Dynamic impacts of Hadley circulation on Saharan Desert warming amplification

Alejandro Manuel Ayala
University at Albany, State University of New York, alejandro.m.ayala317@gmail.com

The University at Albany community has made this article openly available. Please share how this access benefits you.

Follow this and additional works at: https://scholarsarchive.library.albany.edu/legacy-etd

Part of the Atmospheric Sciences Commons

Recommended Citation
https://scholarsarchive.library.albany.edu/legacy-etd/2857

This Master's Thesis is brought to you for free and open access by the The Graduate School at Scholars Archive. It has been accepted for inclusion in Legacy Theses & Dissertations (2009 - 2024) by an authorized administrator of Scholars Archive. Please see Terms of Use. For more information, please contact scholarsarchive@albany.edu.
Dynamic Impacts of Hadley Circulation on Saharan Desert

Warming Amplification

by

Alejandro Manuel Ayala

A Thesis
Submitted to the University at Albany, State University of New York
In Partial Fulfillment of
the Requirements for the Degree of
Master of Science

College of Arts and Science
Department of Environmental and Atmospheric Sciences
2022
ABSTRACT

Changes in temperature due to climate change are not spatially uniform, and deserts and other drylands, which are greatly underrepresented in climate studies, are warming at a much faster rate than much of the globe with increasing concentrations of greenhouse gases. This strong warming amplification over deserts, termed Desert Amplification (DA), is most pronounced over the world’s largest and driest Sahara Desert and the Arabian Peninsula. The Sahara and Arabian deserts are formed in the subtropical subsiding branch of the Hadley Circulation (HC) and so the changes in large-scale subsidence associated with adiabatic heating could impact the DA dynamically. While there is evidence to suggest that thermodynamic impacts such as stronger warming-enhanced large-scale water vapor feedback over drier ecoregions may play a major role in this warming, the dynamic impacts of HC change have yet to be examined with respect to DA. Using two widely used reanalysis datasets, MERRA2 and ERA5, Zonal Mean Meridional Stream Function (ZMMSF) is examined in conjunction with vertical velocity (omega) to assess the strength and location changes of the boundaries of HC and subsidence over the Sahara and compare these changes with the corresponding global values. Results show that changes in HC are not uniform across seasons or when averaged globally versus regionally. There is a strong agreement between the two datasets for weak intensification of both ZMMSF and omega globally during DJF, while both are weakening during JJA. For the Sahara however, there is weaker certainty in weakening of ZMMSF and omega during DJF, but strong certainty of weakening during JJA. These results suggest that changes in HC cannot account for DA over the Sahara as the changes in HC between 1980 and 2019 are either negligible or act in a way that would weaken DA, not strengthen or result in it.
ACKNOWLEDGMENTS

First and foremost, I would like to extend my sincerest thanks to my advisor Dr. Liming Zhou and to my co-advisor Dr. Brian Rose for their invaluable advice, continuous support, and immense patience during my Master’s Thesis research. Their vast knowledge and constructive feedback greatly improved the overall quality of my research. Additionally, I must thank the National Science Foundation grant number AGS-1952745 for funding this project. I would also like to thank all the members in the Zhou research group for all the suggestions that have added a great deal of content to my analysis. Finally, I would like to express my gratitude to my parents, and the rest of my family. Without their support over the past few years, it would have been impossible for me to complete my study.
## CONTENTS

ABSTRACT .................................................................................................................................... ii

ACKNOWLEDGMENTS .............................................................................................................. ii

CONTENTS................................................................................................................................... iv

1. Introduction ............................................................................................................................. 1

2. Data and Methods.................................................................................................................... 8

   2.1 Study Region ..................................................................................................................... 8

   2.2 Reanalysis Datasets ........................................................................................................... 8

   2.3 Methods ............................................................................................................................. 9

      2.3.1 Characterization of Hadley Circulation ...................................................................... 9

      2.3.2 Omega in HC ............................................................................................................ 11

   2.4 Data Processing ............................................................................................................... 12

      2.4.1 Seasons for Analysis ................................................................................................. 12

      2.4.2 Irrotational Wind ....................................................................................................... 13

      2.4.3 Trend Analysis .......................................................................................................... 13

3. Results and Discussion .......................................................................................................... 15

   3.1 Cross-Section Analysis .................................................................................................... 15

      3.1.1 Hadley Circulation Metrics ........................................................................................ 15

      3.1.2 Mean Omega in HC ................................................................................................ 19
1. Introduction

As global temperatures continue to rise due to anthropogenic climate change, the impacts observed on regional scales are not uniformly distributed. One such example is dry lands, where warming rates have increased much faster than other regions in low and middle latitudes (Zhou et al. 2015, Wei et al. 2017). The strongest warming rates seen over the driest ecoregions such as the Sahara Desert and Arabian Peninsula suggest an amplified warming mechanism over deserts (Athar 2013; Zhou et al. 2016). This warming amplification over deserts is known as Desert Amplification (DA) (Zhou 2016; Zhou et al. 2016; Zhou 2021). While there has been a small number of studies regarding DA using reanalysis and climate model datasets over the Sahara Desert, much of the in situ observational analysis has been conducted only over the Arabian Peninsula (Zhou 2021). This is in part because data and observations are far more plentiful for the Arabian Peninsula than over the Sahara Desert. Given that the Sahara is the largest hot desert on the planet, it has become increasingly important to study climatic changes in this region.

The detection and attribution of DA is still in its early stages, with current studies focused mostly on the detection of DA and less on the attribution of DA. One major thermodynamic cause hypothesized for DA is stronger large-scale greenhouse effects over drier deserts in response to increasing greenhouse gases (GHGs) as DA enhances linearly with the global mean GHGs radiative forcing (Zhou 2016). Increasing GHGs enhance downward longwave radiation forcing reaching the surface because of a warming and moistening climate globally. Over the deserts where the air is arid and has very limited water vapor content, the temperature increases are extremely sensitive to increases of water vapor because the greenhouse effect is roughly
proportional to changes in the logarithm of the GHGs concentration (e.g., Myhre et al., 1998; IPCC, 2007; Dessler and Davis, 2010; Zhou, 2016, Wei et al., 2017). Therefore, increasing water vapor content could lead to enhanced warming, consistent with increasing water vapor concentrations over the past 40 years over deserts (Pu and Cook 2012). Additionally, this greenhouse effect has a diurnal asymmetry in the warming associated with DA relating in some part to the changes in the planetary boundary layer height (Zhou 2021; Evan et al. 2015). Further confirmation of this hypothesis, however, is needed as it is challenging to disentangle the complex cause and effect from a fully coupled land-atmosphere system (Zhou 2016; 2021).

The Sahara and Arabian deserts are formed in the subtropical subsiding branch of the Hadley Circulation (HC) and so the changes in large-scale subsidence associated with adiabatic heating could impact the DA dynamically. Interestingly, the dynamic impacts of HC change have yet to be examined with respect to DA. HC is a component of atmospheric circulation that acts to transport excess equatorial energy and angular momentum poleward (Lu et al. 2007; Nguyen et al. 2012). This phenomena results from the uneven heating of the earth’s surface, as the equatorial regions receive far more incoming solar radiation than the poles. While much of this energy is transported poleward through ocean currents (e.g., Atlantic Meridional Overturning Circulation), a fraction is transported through the atmosphere via HC, which is characterized by multiple rotating air cells that each has a convective branch, subsiding branch, poleward branch, and equatorial branch. While there are multiple components (cells) that pertain to the atmospheric overturning circulation (i.e., Ferrel Cell, Polar Cell) that exist in both the Northern and Southern Hemisphere, this thesis will focus primarily on the Northern Hemisphere.
Hadley Cell (NHHC), which is the component of HC that pertains to most to the formation of deserts experiencing DA, such as the Sahara.

NHHC is one of the primary causes behind the subsidence that forms the Saharan and Arabian deserts in the subtropics. This circulation exists almost entirely over the tropics, with convection near the equator, southerly flow aloft, subsidence in the subtropics (between 20° and 40° North) and northerly flow near the surface. Because NHHC exists for most of the year in roughly the same location (there is slight variance both throughout the year and between years), there is a persistent area of subsidence over the subtropics known as the subtropical high (Sun et al. 2017). Precipitation requires clouds, and clouds need convection (upward vertical motion) to form, and the subtropical high associated with HC inhibits both in the subtropics. Thus, the subsiding north branch of the NHHC is one of the primary drivers for the formation and sustenance of the deserts and arid regions in the subtropics, given that subsiding air typically inhibits cloud formation and thus limits rainfall potential (Wu et al. 2009; Nguyen et al. 2013). The strength of the subsidence in the northern branch is proportional to the overall intensity of the cell, thus measuring the total mass balance of air through the cell will be important. HC has a high degree of seasonality, depending on the meridional temperature gradient or the difference in temperature between the equator and pole. NHHC becomes strongest when the meridional temperature gradient is strongest is greatest, which typically happens during the northern hemisphere winter months of December, January, and February (DJF). In contrast, NHHC becomes incredibly weak or even disappear during the northern hemisphere summer months of June, July, and August (JJA) (Oort and Yienger, 1996; Dima et al. 2003), when the meridional temperature gradient is weakest.
While subsidence may explain why there are deserts in the subtropics, it does not directly tie to the amplified warming of these dry regions associated with DA. The link between the subsidence associated with HC and DA is adiabatic heating in the troposphere (Zhou et al. 2016). As air descends, such as through the subsiding branch of the NHHC, the pressure of the air must rise, thus the volume of the air decreases. This results in work being done on the air which raises the internal energy, thus heating the air. In other words, the atmosphere is warmed adiabatically by subsiding compression from the overlying air at the dry adiabatic lapse rate. This warming effect may be stronger in the lower troposphere than the upper troposphere because the air must travel a longer distance from the tropopause, the top of the ascending branch of the Hadley Cells, where the air spreads out and descends in the subtropics. Incidentally, Wei et al., 2017 and Zhou 2021 found that warming associated with DA is skewed towards the surface and lower troposphere. This suggests the possibility that adiabatic heating could play an active role in DA. Intensification of HC would result in stronger subsiding air and greater adiabatic heating, and if this intensification is happening over the Sahara and near the surface, it could be a potentially significant driver behind DA.

Multiple studies using a variety of methods have found that global HC is expanding poleward and weakening in both hemispheres over recent decades (e.g., Hu and Fu 2007; Lu et al. 2007; Davis and Rosenlof 2012; Nguyen et al. 2013), with the primary cause of the expansion being anthropogenic GHG emissions (Hu et al. 2013). The rate of this expansion is not fully agreed upon, with estimates having this expansion rate to be anywhere between 2 and 4.5 degrees of latitude since 1979. This expansion has the northern boundary of the NHHC moving farther
north, and the southern boundary of the Southern Hemisphere HC moving farther south. A globally poleward expanding Hadley Cell results in the subtropical high shifting poleward along with the HC, and thus the region of subsidence associated with desert formation should also shift (Lu et al. 2007). This leads to a poleward trend in the location of deserts globally, along with a broadening and weakening of the area deserts cover given that the entire cell, including the section with subsidence, expands. Therefore, on a global scale, HC expansion causes a weakening of the subsiding branch of the NHHC which would cause the adiabatic heating to be smaller. However, while the Sahara does cover a massive portion of land, it does not encompass the entire globe, so studying regional HC over the Sahara and comparing with the global HC are necessary.

Regional studies of HC differ from those on a global scale. For example, Chen et al. (2014) used the vertical shear of divergent meridional winds to calculate HC regional intensity over multiple regions, including northern Africa. This study found that while there is still great uncertainty across multiple reanalysis datasets, which is expected, many regional Hadley Cells experienced intensification, differing from the weakening of the global Hadley Cell. An additional example is Schwendike et al. (2015), who used a similar method of breaking apart the atmosphere into the orthogonal overturning circulations (the local Hadley and Walker circulation). While this is done over the entire globe, it allows for observations of regional changes, and one specific region of interest noted in that paper is equatorial Africa, which is near where the Sahara is located. Here, it was discovered that mass-flux was decreasing while also shifting southward, which again differs from changes in the global HC. These studies show that
on a regional scale, HC can differ from what is observed globally, so a regional study of HC over the Sahara is crucial to understanding the ties between HC and DA.

There have been several analyses regarding Hadley Circulation both globally and regionally, but none of them have focused primarily on the Sahara, where surface temperatures have risen 2-4 times greater than the mean of the tropics over a 34-year period between 1979 and 2012 (Cook and Vizy 2015). This is concerning because the Sahara is the largest hot desert on earth, covering more than 9 million square kilometers and nearly one third of the African continent. This means that changes here will have major impacts over a large region. Not only is the Sahara itself large, but deserts cover over 30% of surface land globally (Zhou 2016; Wei et al. 2017), so they play a major role in regional and global climate and ecosystems. Additionally, the Sahara is one of the world’s largest sources of dust, contributing to nearly half of all dust in the oceans and over 180 million tons in the atmosphere each year (Goudie and Middleton 2001). This dust can play a major role as an atmospheric pollutant and in terms of the radiation budget, as it reflects a large amount of shortwave radiation back to space (Li et al. 1996; Knippertz and Todd 2012; Vizy and Cook 2017), in addition to impacting cloud formation and Atlantic hurricane activity (Bretl et al. 2015). The Sahara plays a major role in both regional and global climate, so studies of changes to the region including DA are incredibly important. One major challenge for the Sahara is the lack observations of important climatological variables over this region, with satellite measurements being the primary mode of information gathering.
Subtropical deserts are strongly tied to the subsiding branch of HC, and thus the intensity and location of these deserts are incredibly sensitive to the strength and location of the subsiding branch of the NHHC and the corresponding descending air. If HC is strengthening at a regional level over the Sahara, then subsidence would increase and further inhibit cloud formation and strengthen adiabatic heating, which could account for some of the warming associated with DA. However, if HC is weakening regionally over the Sahara, then subsidence would weaken thus enhancing cloud formation and reducing adiabatic heating. Lastly, if there are little to no significant changes in HC, other factors will have dominant roles in causing the DA. Using reanalysis data to calculate metrics associated with HC in conjunction with vertical velocity in pressure coordinates (omega), the aim of this thesis is to examine whether there are any major changes in the strength of HC and subsidence over the Sahara and how these changes may contribute to the warming associated with DA.
2. Data and Methods

2.1 Study Region

The Sahara Desert is one of the largest deserts on Earth. It covers over 30% of Africa and plays a major role in the climate of northern Africa and surrounding regions. To encompass this large region, data between the longitudes of -20° W and 40° E and the latitudes of 10° N to 35° N is used to represent the Sahara, while plots and figures may include latitudes between -60° S and 60°N to show a broader area. This covers most of northern Africa and includes the Sahel, which while not being part the Sahara Desert experiences similar, though not as strong, arid conditions. When referring specifically to peak subsidence relating to the Sahara, the latitudes between 20°N and 30°N are used.

2.2 Reanalysis Datasets

This analysis uses two widely used high-resolution reanalysis products with monthly data ranging from 1980 to 2019. The first of these two is the Modern Era Retrospective analysis and Applications, Version 2 (MERRA 2), which uses assimilated observations and the Goddard Earth Observing System (GEOS) to produce a global analysis at an hourly resolution from January 1980 to the present (Gelaro et al. 2017). While the temporal resolution is hourly, only monthly mean products will be used. With a resolution of 0.625° x 0.5° there are 576 points of longitude and 361 points of latitude. There are 42 pressure levels ranging from 1000 hPa to 10 hPa, but only those under 100 hPa are used in this analysis. While there are a variety of climatological fields available, only the zonal and meridional components of the horizontal total
wind field (U and V) and vertical velocity in pressure coordinates (omega) are used. The second reanalysis dataset used is the ECMWF Reanalysis 5th Generation (ERA5), which is an assimilation of many global estimations of historical observations. ERA 5 has hourly approximations of many ocean, land, and atmospheric climate variables between 137 vertical levels, and like MERRA 2 only those under 100 hPa are used, along with the same variables. ERA 5 has a slightly higher spatial resolution than MERRA 2 at a 0.5° x 0.5° resolution. It is to be expected to see some differences between the two reanalyses as they use different assimilation models and different sources for observations. For example, data-sparse regions (such as the Pacific Ocean or the Sahara) will be filled in differently, and this can lead to noticeable differences on a global scale (Song and Zhang 2007).

2.3 Methods

2.3.1 Characterization of Hadley Circulation

HC is not a metric that can be measured directly, however there are a variety of different ways to quantify it (Nguyen et al. 2012). One such quantity is Zonal-Mean Mass Streamfunction (ZMMSF), the measure of meridional overturning mass. This quantity is a useful metric for quantifying HC because simple metrics of ZMMSF are associated with attributes of HC (Oort and Yienger 1996; Dima and Wallace 2003; Nguyen et al. 2013). Thus, ZMMSF will be the method used to quantify HC in this thesis.

\[
\psi(p, y) = \frac{2\pi \alpha \cos(y)}{g} \int_{p}^{p_s} V(p, y) \, dp
\]  

(1)
As seen in Equation 1, ZMMSF is the vertically integrated zonal-mean meridional wind; \( a \) is the radius of the Earth; \( g \) is gravity; \( y \) is latitude; \( P \) is pressure heights; \( P_s \) is the surface pressure; and \( V \) is the zonally averaged meridional wind. The vertical integration is done for all pressure levels under 100 hPa, as HC does not extend into the stratosphere and 100hPa is a close approximation of the tropopause. This is because the tropopause acts as an upper boundary for HC due to the stability of the stratosphere, and the vertical velocity associated with HC is not strong enough to penetrate it. The zonal mean aspect of the meridional wind is important, because when averaged over a global domain, mass is conserved due to there being no meridional boundaries since it is continuous. However, over a regional domain such as the Sahara, there are meridional boundaries and thus mass can no longer be assumed to be conserved. To overcome this as described by Zang and Wang 2013, the total wind field can be broken into irrotational and non-divergent components, with the former relating to overturning circulation. This is because divergent circulation is linked to vertical motion and convection, and thus overturning circulation (Schwendike et al., 2014). This can easily be accomplished using a Python library called Windspharm by Andrew Dawson, 2016, which will be discussed in greater detail in Section 2.4.2.

Basic attributes of ZMMSF correlate to indices of HC. The sign of ZMMSF will dictate the direction of the circulation, where positive values correspond to clockwise rotation and negative to counterclockwise rotation. Since the cells of HC are the opposite sign of their neighbors (SH Hadley cell -, NH Hadley Cell +, NH Ferrell Cell -, etc.), this means there must be a latitude where the sign of ZMMSF reaches zero in between the positive and negative values. This change in sign identifies the cell boundaries, which are defined as the zero isoline of ZMMSF averaged...
between 400 and 600 hPa. As shown in Stachnik and Schumacher 2011, the boundary is not strongly tied to the chosen pressure heights. For the NHHC, the boundary closer to the equator is the southern boundary and the one farthest from the equator is the northern boundary. The distance between the northern and southern boundaries of the cell will be referred to as the NHHC width, which differs from other papers’ definitions of ‘width’, or width of the tropics, which may use this term to describe the distance between the descent of the NHHC and of the Southern Hemisphere Hadley Cell (Stachnik and Schumacher 2011). The strength of the cell is highly correlated to the maximum intensity of the cell (Oort and Yienger 1996), thus the intensity of the circulation is given by the vertical mean of the maximum values between 200 and 900 hPa. These heights are chosen for determining intensity to avoid impacts from the upper and lower boundaries of the surface and tropopause respectively.

2.3.2 Omega in HC

Omega is an additional quantity that can be used to measure the strength of HC. While it does not measure the meridional aspect of HC, it directly correlates to the vertical branches of HC which in this case is more important with respect to DA. In addition, ZMMSF alone does not account for other means of vertical motion, such as those associated with Walker Circulation, where omega accounts for all sources of vertical motion, thus omega is a crucial quantity when measuring subsidence. Here, omega data are taken from the ERA5 and MERRA-2. An important note to bring up is given that omega and ZMMSF are not and cannot be measured by direct observations, there will always be some measure of uncertainty as to whether results drawn from these metrics can be trusted. While this is true, these are the primary means of measuring
overturning mass balance and vertical velocity, so they must be used to answer the questions posed by this thesis.

2.4 Data Processing

2.4.1 Seasons for Analysis

While warming associated with DA is present on a large scale across all seasons (Vizy and Cook 2017) and thus is not dependent on time of year, Hadley Circulation is highly dependent upon the time of year (Dima et al. 2003). This is because the primary driver for HC is the uneven heating of the earth, where the equatorial region receives far more solar energy than the higher latitudes. In the summer Hemisphere, where the meridional temperature gradient is weakest due to solar heating near the poles producing warm temperature comparable to lower latitudes, HC will be incredibly weak and may even disappear entirely in that hemisphere. In the winter Hemisphere however, the meridional temperature gradient is much stronger because temperatures near the poles are significantly lower than temperatures near the equator, causing HC to be incredibly strong. However, when averaging HC annually, these seasonal differences are smoothed out and HC can be seen easily in both hemispheres, which isn’t useful for finding trends. Thus, only the Northern Hemisphere winter season of DJF and summer season of JJA will be examined here.
2.4.2 Irrotational Wind

While the tropopause and surface act as vertical boundaries, regional ZMMSF has non-zero mass flux at the eastern and western boundaries, and thus conservation of mass cannot be assumed (Zhang and Wang 2013). To overcome this, the total wind field can be decomposed into the non-divergent and irrotational components, where only the irrotational component of the meridional flow is associated with HC and thus is used to calculate ZMMSF. This is because ZMMSF can only defined for an irrotational (divergent) wind field, so by calculating the irrotational wind and using only the meridional component of that irrotational wind, ZMMSF can be calculated. This represents overturning in a pressure-latitude plane for just one sector, in this case the Sahara, even though that sector is exchanging mass with its neighbors. This, however, does exclude vertical motion in the zonal direction, or Walker Circulation, so it does not provide a full picture of vertical motion, thus omega is used in addition to ZMMSF. In Python, where most of the code has been written, there is a library called Windspharm where one of the functions takes input of the global total wind field and outputs the non-divergent and irrotational components of the wind. The one drawback of this method is that it requires a global wind field with no gaps in the data (i.e., missing data). While ERA5 fits this requirement, near the surface and poles in the MERRA 2 data there are missing values, thus data smoothing must be done to decompose the wind field. The data smoothing can easily be done using a simple MATLAB routine as described in Garcia (2010).

2.4.3 Trend Analysis

The primary means of observing data in this thesis are through vertical cross-section of ZMMSF and Omega averaged over seasons, and long-term trend analysis. Both require, to some
extent, a statistical analysis of the data over the period between 1970 to 2019. This is done by calculating a linear least-squares regression of the data over time. This results in the slope of the regression (i.e., linear trend), the intercept, and the p-value of two-tailed student’s t-test which can be used in assessing the statistical significance of the trend. For vertical cross-sectional data, the least squares regression is taken at each grid point and calculated across the entire timeframe. In the figures demonstrating this, the upper plots show the contours of the specific variable being shown (ZMMSF or Omega), while in the lower plots the filled contours show the trend of the regression, and the dots indicate the significance value. This will be explained in greater detail in section 3.1.1. For the time-series plots, linear least-squares regression is used to calculate the slope and intercept used in creating the regression lines (dashed) in addition to also calculating the p-value for significance.
3. Results and Discussion

3.1 Cross-Section Analysis

3.1.1 Hadley Circulation Metrics

The Northern Hemisphere winter season of DJF has stronger Hadley Circulation than the rest of the year because the meridional temperature gradient, the driver for the circulation, is maximized. Figure 1 shows the DJF vertical cross section of ZMMSF averaged over all longitudes (globally) and temporally from 1980-2019 in the upper two plots, while the lower two show the linear trend of ZMMSF at each vertical and latitudinal grid point of their respective upper plots. The left two plots show data from MERRA2 while the right two show data for ERA5. The solid black lines indicate the latitude of maximum intensity for each cell and the vertical green and red lines show the vertically averaged bounds of each cell, where red lines are specifically NHHC bounds. The dots in c) and d) indicate points with a trend that is statistically significant at p < 0.05. During DJF, globally there is a strong NHHC that reaches from the northern hemisphere subtropics down into the southern hemisphere equatorial region. An area near the northern edge of the HC, centered roughly over 15° N, has a statistically significant positive trend indicating a strengthening of the cell in this region. This is true for both datasets, though the location is slightly different in each. Additionally, the strength of this positive trend is much stronger in the MERRA2 data than the ERA 5, though in both cases the magnitude of the change is significantly smaller than the actual streamfunction values. This strengthening of the Hadley Cell in this region indicates that the subsiding branch of the Hadley cell is increasing. Omega over the same season (DJF) and averaged globally is shown in Figure 2, where the HC
bounds are carried over from Fig 1 so omega can be compared to the extent and boundaries of HC in the same season and region. As expected, there is upward motion at the southern end of the HC near the equator, and subsidence at the northern end over the subtropics. The trends for omega are positive in roughly the same locations as in Figure 1, indicating that specifically omega is becoming more positive, and thus subsidence is enhancing over this region during DJF, with the magnitude of the increase being less than 1% the value of omega. This is consistent with Nguyen et al. (2013) showing that the globally averaged Hadley Cell has been enhancing at a rate of about 0.1% each year over recent decades, especially during the winter. Additionally, these enhancements in stream function and subsidence would lead to weaker adiabatic heating at these latitudes.

While the DJF ZMMSF and Omega seem to agree with past work on a global scale, when averaged just over the Sahara longitudes, results are quite different. Figure 3 is like Fig 1 in showing ZMMSF, however it is averaged only over the Sahara longitudes. There is similarly a large NHHC that stretches from the sub-tropics into the southern Hemisphere, however the most intense section of the cell is not as broad. In the ZMMSF trend plots, over the Sahara latitudes there is a negative trend, indicating a weakening in the HC. This trend is present in both the MERRA2 and ERA5 datasets but only statistically significant in the MERRA2. The negative trends are also incredibly small in magnitude compared to the mean data values, by almost 3 orders of magnitude. The omega for the same spatial and temporal mean as Fig 3 is in Figure 4, and similarly has a negative trend in subsidence over the Sahara latitudes that is also present in both datasets but is only significant in MERRA2, along with being incredibly weak. Both the stream function and omega plots indicate a weakening of ZMMSF and subsidence respectively.
over the Sahara Desert region during DJF. These changes over the Sahara DJF, while two orders of magnitude smaller than average values, are opposite to those of the global DJF, and thus where the global change would lead to dryer and warmer conditions, the Sahara changes in stream function and subsidence lead to the opposite conditions, which makes cloud formation and rain more likely.

The northern hemisphere summer months, or JJA, are when the NHHC is weakest, as this is when the meridional temperature gradient is smallest. These weaker ZMMSF and omega values for JJA NHHC are important, because any changes to them will have a greater impact than DJF, where the subsidence and streamfunction are already large. This can very clearly be seen in Figure 5, which shows the global ZMMSF JJA, which has a NHHC that is incredibly small and weak compared to its southern hemisphere counterpart. The trends in stream function for the two datasets are also quite small but are negative over the Sahara latitudes, indicating a weakening of the circulation. This negative trend is statistically significant in the MERRA2, but insignificant in the ERA5. The global omega for this same season is shown in Figure 6, where the subsidence over the Sahara latitudes is far weaker than that in any of the DJF plots. There is a significant negative trend in subsidence over the Sahara latitudes for the MERRA2 plot, but in ERA5 there is no significant trend.

The Sahara-longitudinal mean of ZMMSF for JJA is shown in Figure 7, which has a NHHC that is more well-defined than the global JJA NHHC. The trend for stream-function is statistically significant and negative for both reanalysis datasets. Additionally, the magnitude of
the trend is much greater for Sahara JJA than for any of the other streamfunction trend values. **Figure 8**, which shows omega for the same season and region as Fig 7, also has much stronger values for omega than the global JJA counterpart. Both MERRA2 and ERA5 indicate a statistically significant negative trend in omega over the Sahara latitudes, which when coupled with the ZMMSF data indicate that stream-function and subsidence over the Sahara, when averaged over the Saharan longitudes, has weakened for JJA between 1980 and 2019.

When averaged globally, the cross-section results show that subsidence is enhancing during DJF, which agrees with past work. These changes are quite small however, as they account for less than 1% of the total value for omega over the 40-year period. When averaged specifically over the Sahara however, subsidence trends are negative and weakens at a proportionally small magnitude. Thus, there appears to be slight enhancement of Northern Hemisphere Hadley Cell globally during DJF but a slight weakening of Northern Hemisphere Hadley Cell over the Sahara during DJF. During the summer months of JJA, the Northern Hemisphere Hadley Cell is much weaker, and as such any changes in the Hadley Cell are much weaker or nonexistent. However, unlike DJF where there was a difference between enhancement and weakening when averaged globally and regionally respectively, during JJA when a change in Stream Function or omega was present, aside from a single instance, it was always negative. In both DJF and JJA however, there were negative trends present when averaged over the Sahara in nearly all figures, indicating a consistent weakening trend.
3.1.2 Mean Omega in HC

The last cross-section is Figure 9, which shows the trend, and mean of DJF, JJA and annual mean omega, but averaged over just the Saharan latitudes and longitudes at each pressure height. Plots a) and b) show the change in omega for MERRA2 and ERA5 respectively with the stars on each line indicating statistical significance. In the former, all three seasons do show relatively strong negative trends, compared to ERA5, with the strongest values closest to the surface. Additionally, most of the data points are statistically significant for MERA2. As for the latter, while most of the points do have negative trends, points closer to the surface in ERA5 do show a positive trend, though this trend is incredibly weak and not statistically significant. Like MERRA 2, the only points that are significant are the strongest negative values, even if they are weaker than MERRA2. For the mean in omega in plots c) and d), as is expected over the Sahara omega is positive at all pressure levels for 3 seasons except near the surface for JJA. This is because during JJA the northern extent of the Southern Hemisphere Hadley Cell stretches into the Northern Hemisphere, like how the NHHC does during DJF. This pushes the convective branch of both cells farther north. Additionally, the greater surface warming of the summer months strengthens the Sahara low in the lower troposphere and causes dry convection (Evan et al. 2015), which also acts against subsidence.

3.2 Long-Term Trends

3.2.1 Intensity of Hadley Circulation

As previously stated, the maximum intensity of ZMMSF is an indicator of the overall strength of a Hadley Circulation cell. Thus, measuring the seasonal anomaly of the maximum
intensity between 1980 and 2019 gives an approximation of strengthening or weakening with
time in the NHHC. Figure 10 shows DJF maximum ZMMSF intensity seasonal anomaly time
series for both datasets averaged over the Sahara and globally in plot a), and latitude of
maximum intensity in plot b), where the seasonal anomaly is the difference between the given
value and the climatological value for that season between 1980 and 2019. The trend and its
statistical significance values for each of these lines are in Table 1. The trend lines of MERRA2
Global, MERRA2 Sahara, ERA5 Global and ERA5 Sahara representing dataset and regional
means are hereafter referred to as M Global, M Sahara, E Global and E Sahara, respectively.
Each of the slopes for the seasonal anomaly of intensity in plot a) are positive, but only the
MERRA2 global trend is statistically significant. For the latitudes in plot b), all but MERRA2
Sahara are positive, but both M Sahara and ERA5 global are significant. Figure 11, like Fig 10,
shows the ZMMSF seasonal intensity and latitude, but for JJA instead of DJF. Contrary to DJF,
all the trends for the intensity are negative, though both slopes over the Sahara are an order of
magnitude larger than the global trends, in addition to being significant. The trend for latitude of
maximum intensity is positive for all four, and the only one not significant is M Global. These
together show that the overall strength of the NHHC appears to be strengthening both globally
and regionally over the Sahara during DJF but is weakening during JJA. Additionally, aside from
one instance, the location of the maximum intensity is moving north both during DJF and JJA,
which may indicate an expansion of the Hadley Cell.

3.2.2 HC Bounds and Width

The boundaries of a cell show the northern and southern extent, and they define where
the convection and subsidence will be located. Figure 12 shows the bounds and width of the
NHHC for the DJF season, where plot a) shows the latitude of the northern and southern bounds and plot b) shows the width of the NHHC in kilometers. Table 2 has the trend and its statistical significance of each of the time series lines for both DJF and JJA. The northern boundary trend for both MERRA2 Global and Sahara is positive (northward) while both for ERA 5 are negative (southward) and none are significant. The southern boundary slopes are positive for all excluding M Global, and only M Sahara is statistically significant. These lead to widths that are shrinking in all but M Global, with M Sahara being the only significant trend in width. Figure 13 shows boundaries and width like Fig 12 but for JJA instead of DJF, with the trend and its significance value also in Table 2. All but M Global for the norther boundary are negative, however M Global is the only significant slope. For the southern boundary, all are positive, and both Sahara slopes are significant. These make widths that, other than M Global, are all decreasing, and all but E Global are significant. The northern boundary of the NHHC is tied closely to the location of the subsidence, thus movement of the northern bound may lead to changes in the location of subsidence. For example, a poleward expanding NHHC will have a northern boundary that also moves farther north. The poleward branch of the NHHC is also the subsiding branch, thus the subsidence must also move further north. This would lead to the aridity and desert conditions to move further north from the subtropics, bringing entirely different climatic conditions to locations that don’t normally experience them. The opposite would be true if the northern boundary moved to the south. The data show however that any trends are incredibly small and not statistically significant, thus there should be no major changes.
3.2.3 Omega in HC

Lastly, the time series of omega is shown for DJF in Figure 14. Like Fig 10, plot a) shows the seasonal anomaly of the maximum in omega while plot b) shows the latitude of the maximum. All but M Sahara have a positive slope, and both Global slopes are statistically significant. For the latitudes, all but M Global are positive and none are significant. Figure 15 shows maximum omega values and latitudes but for JJA. All the anomalies in maximum omega for JJA are negative, and only E Global is not significant while the other three are. All the latitudes are negative, but none are significant. In DJF, both Global trends in omega are positive and significant while the Sahara trends neither agree nor are they significant, which shows global intensification of subsidence and no trend in the Sahara. In JJA however, since all are negative and most are significant, there is very strong evidence for weakening of subsidence both globally and regionally. These results are consistent with the changes in ZMMSF mentioned before, which makes sense as a strengthening Hadley Cell would most likely have stronger subsidence, with the opposite being true for a weakening HC.
4. Summary and Conclusion

While many aspects of climate have been changing under the preface of anthropogenic climate change, deserts, especially the Sahara Desert, have warmed substantially more than other regions in the low and middle latitudes (Zhou et al. 2015). Recent studies suggested that thermodynamic impacts such as stronger warming-enhanced large-scale water vapor feedback over drier ecoregions play a major role in this desert amplified warming (Zhou et al. 2016; 2021). However, other potential processes, such as the dynamic impacts relating to HC, still need to be examined given the role HC plays in the formation and sustenance of deserts and arid regions. HC, or more specifically the subsiding branch of the HC, leads to adiabatic heating in the subtropics that warms and dries the air, so changes in HC may play a major role in the amplification of warming deserts, and more specifically the Sahara. To address this question, two widely used reanalysis datasets, ERA 5 and MERRA2, were used to quantify changes in ZMMSF and vertical velocity from 1980 to 2019. Results suggest that changes in HC in recent decades most likely play a very limited role in DA. It was shown that HC and omega are enhancing globally during DJF, which reinforces past work, but are slightly weakening globally during JJA, changing by less than one tenth of one percent. More importantly, HC and omega over the Sahara are shown to be weakening over this same period, albeit at a very small rate, in both DJF and JJA. These results are shown both in the cross-section seasonal analysis and in the time-series trend analysis. Weakening of HC and omega leads to a decrease in adiabatic heating and thus a decrease in warming over the Sahara. Therefore, these changes in HC cannot be responsible for the increase in temperatures over the Sahara associated with DA.
These results are useful in determining the relative contribution of HC to the DA but are not fully conclusive. Firstly, only two reanalysis datasets were used, and the addition of more observational and reanalysis and climate model datasets could be useful in corroborating these results. Long-term climate model simulations could be used to extend the timeframe both into the past and into the future for a more robust verification of these results, as currently reanalysis data only goes back 40-50 years. Second, only the seasons of JJA and DJF were analyzed in this thesis, however the transition season of March April May (MAM) and September October November (SON) could also be studied. Lastly, while these results do give useful information for the Sahara, there are other deserts and arid ecoregions experiencing DA and thus regional studies of HC over all such ecoregions would be useful in determining whether these results are a global phenomenon or only specific to a handful of deserts. DA is an ongoing research topic, so there is still much to study and learn about this phenomena.


DOI: [http://doi.org/10.5334/jors.129](http://doi.org/10.5334/jors.129)


Equation 1:

\[ \psi(p, y) = \frac{2\pi \cos(y)}{g} \int_{p}^{P_s} V(p, y) dp \]

FIGURES

Figure 1: The top two panels (a and b) show the globally (all latitudes) averaged DJF ZMMSF from 1980 to 2019 for MERRA2 and ERA5 respectively, while the lower two panels (c and d) show the linear trends of ZMMSF for these datasets over the same period. The red vertical lines indicate NH HC bounds while green vertical lines indicate bounds for other cells. Solid black lines indicate the latitude of maximum intensity for each level in each cell, where bold lines are for the NH HC specifically. The dots in the lower panel indicate the trends that are statistically significant at \( p < 0.05 \).
Figure 2: Like Figure 1 but for omega. The vertical lines are the same cell bounds from Figure 1 thus the red lines are the DJF global HC bounds.
Figure 3: Like Figure 1 but averaged over the Sahara latitudes (20 W to 40 E) instead of globally.
Figure 4: Like Figure 2 but averaged over Sahara instead of globally.
Figure 5: Like Figure 1 but averaged over JJA instead of DJF.
Figure 6: Like Figure 2 but averaged over JJA instead of DJF.
Figure 7: Like Figure 4 but averaged over JJA instead of DJF.
Figure 8: Like Figure 6 but averaged over Sahara instead of Globally.
Figure 9: Plots a) and b) show the vertical cross section of the change in omega from 1980-2019 for the DJF, JJA and Annual seasons and averaged spatially over the Sahara (20-30°N, -20-40°E) with MERRA2 on the left and ERA5 on the right. Plots c) and d) show the climatological omega over the Sahara. Stars indicate the trends that are statistically significant at $p < 0.05$. Note that all significant trends for both datasets are negative.
Figure 10: Plot a) shows the DJF seasonal anomaly for the maximum intensity of ZMMSF while b) shows the latitude of maximum ZMMSF intensity for both MERRA2 (M) and ERA5 (E). The solid lines show the actual values, while the hashed lines are the linear trend of the data between 1980 and 2019. The trend and its p-value for each line are in Table 1.
Figure 11: Like Figure 10 but averaged over JJA instead of DJF.
Figure 12: Plot a) shows the DJF northern and southern boundaries of the northern hemisphere Hadley Cell while b) shows the annual width of the cell (distance between bounds in kilometers) for 1980-2019.
Figure 13: Like Figure 12 but for JJA instead of DJF.
Figure 14: Like Figure 10 but for Omega instead of ZMMSF.
Figure 15: Like Figure 14 but for JJA instead of DJF.
TABLES

Table 1: 1980-2019 time-series linear regression slopes of ZMMSF. M and E indicate data from MERRA2 and ERA5 reanalysis respectively. Global is averaged over all longitudes, while Sahara is only averaged between 20W and 40E. Intensity is vertical mean of maximum ZMMSF intensity, while latitude is vertical mean of the latitude of maximum intensity. Asterisk (*) indicates p-value less than 0.05, and thus is statistically significant.

<table>
<thead>
<tr>
<th></th>
<th>DJF Intensity Slope (10(^{-9}) kg/s)</th>
<th>DJF Latitude Slope (° N)</th>
<th>JJA Intensity Slope (10(^{-9}) kg/s)</th>
<th>JJA Latitude Slope (° N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M Global</td>
<td>6.17e-01*</td>
<td>2.10e-02</td>
<td>-4.42e-02</td>
<td>1.23e-02</td>
</tr>
<tr>
<td>M Sahara</td>
<td>1.50e-01</td>
<td>-3.10e-02*</td>
<td>-6.44e-01*</td>
<td>1.90e-02*</td>
</tr>
<tr>
<td>E Global</td>
<td>1.90e-01</td>
<td>2.90e-02*</td>
<td>-1.56e-02</td>
<td>2.15e-02*</td>
</tr>
<tr>
<td>E Sahara</td>
<td>1.59e-02</td>
<td>4.92e-03</td>
<td>-2.05e-01*</td>
<td>7.98e-03*</td>
</tr>
</tbody>
</table>

Table 2: Like Table 1, but for northern/southern boundaries and for HC width (distance between N and S boundaries).

<table>
<thead>
<tr>
<th></th>
<th>DJF N-Bound Slope (° N)</th>
<th>DJF S-Bound Slope (° N)</th>
<th>DJF Width Slope (km)</th>
<th>JJA N-Bound Slope (° N)</th>
<th>JJA S-Bound Slope (° N)</th>
<th>JJA Width Slope (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M Global</td>
<td>8.30e-03</td>
<td>-1.50e-02</td>
<td>2.57e+00</td>
<td>1.19e-01*</td>
<td>1.59e-02</td>
<td>1.14e+01*</td>
</tr>
<tr>
<td>M Sahara</td>
<td>3.20e-02</td>
<td>1.37e-01*</td>
<td>-1.02e+01*</td>
<td>-1.35e-02</td>
<td>3.58e-02*</td>
<td>-5.45e+00*</td>
</tr>
<tr>
<td>E Global</td>
<td>-1.17e-04</td>
<td>4.48e-03</td>
<td>-5.08e-01</td>
<td>-3.77e-02</td>
<td>7.04e-03</td>
<td>-4.95e+00</td>
</tr>
<tr>
<td>E Sahara</td>
<td>-7.34e-03</td>
<td>2.39e-02</td>
<td>-3.45e+00</td>
<td>-1.81e-02</td>
<td>3.10e-02*</td>
<td>-5.42e+00*</td>
</tr>
</tbody>
</table>

Table 3: Like Table 1, but for omega instead of ZMMSF.

<table>
<thead>
<tr>
<th></th>
<th>DJF Intensity Slope (Pa/s)</th>
<th>DJF Latitude Slope (° N)</th>
<th>JJA Intensity Slope (Pa/s)</th>
<th>JJA Latitude Slope (° N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M Sahara</td>
<td>-5.60e-05</td>
<td>4.57e-03</td>
<td>-2.07e-04*</td>
<td>-2.70e-02</td>
</tr>
<tr>
<td>E Global</td>
<td>5.65e-05*</td>
<td>2.67e-02</td>
<td>-1.67e-05</td>
<td>-4.46e-02</td>
</tr>
<tr>
<td>E Sahara</td>
<td>1.14e-05</td>
<td>3.25e-02</td>
<td>-1.31e-04*</td>
<td>-3.10e-02</td>
</tr>
</tbody>
</table>