WARMING AT THE AGULHAS REGION
DURING THE GLOBAL SURFACE WARMING ACCELERATION
AND SLOW-DOWN

by

Lu Han

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I dedicate this thesis to my family and friends for their unconditional love and support.
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ABSTRACT

This study investigates the interannual to decadal ocean heat content evolution of the upper 700m in the last three decades at the Agulhas region and emphases on exploring its difference between the global surface warming acceleration and slowdown periods. The Agulhas region is a stagnation point of three circulation systems, the South Atlantic Ocean subtropical gyre, the Indian Ocean subtropical gyre, and the Subtropical Front of the Antarctic Circumpolar Current in the Southern Ocean, and it’s the linkage between two ocean basins, the Indian Ocean and the Atlantic Ocean. At this region, the ocean never stops or slows its warming even during the global surface warming slowdown. Besides the warming surface, the deeper layer (200-700m) gains more heat primarily as a result of the deepening isopycnals (heaving), possibly induced by the saltier upper layer water, also with a relatively small contribution of the changes along the isopycnals (spice). The most pronounced isopycnal sinking locates at the Return Current and the neighbouring Subtropical Front region, while the isopycnals shoal at the upper layer of the Agulhas Current. Due to the altered wind pattern at the Indian Ocean and Southern Ocean, less heat comes along the Agulhas Current during the slowdown period, and the broadening Return Current moves the warm and saline subtropical water southward, which is subducted into the deeper layer by the reclining isopycnals.
Chapter 1
INTRODUCTION

1.1 Global Surface Warming Slow-down

The anthropogenic emission of CO$_2$ contributes to the continuously increasing of greenhouse gasses (GHG), which can trap more heat in the earth system. The annual mean atmospheric concentration of CO$_2$ at Mauna Loa, Hawaii, increased from about 315ppm in 1960s to 396ppm in 2013 [13]. GHG is increasing and the ocean heat uptake is unabated, however, from 1998 to 2013, global mean surface temperatures (GMST) increased at a smaller, compared to the latter half of the 20th Century. The inter governmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) reported this period as the “global warming hiatus” [13]. During this time period, the warming rate has stalled 0.05 degree/decade, compared to 0.12 degree/decade, since 1951 (Figure 1.1).

Why has the global warming rate reduced for nearly 15 years when there is increasing GHGs? The mechanisms for this hiatus are not well understood yet. From the external forcing of earth climate system, solar activity decreases, volcano activity increases, water vapor increases in the stratosphere [38] and aerosols concentration also rapidly increase in stratosphere and troposphere [38] [19] are possible reasons for generating hiatus. On the other hand, the internal variability of the climate system is believed to play an important role in the climate hiatus [31] [20] [39][9]. In 2016, Xie et.al [41] has distinguished anthropogenic changes from nature variations to attribute climate variability during the global warming hiatus by analyzing climate model simulations with and without anthropogenic increases in greenhouse gas concentrations. No consensus has been reached on the mechanism, such as where the heat goes and what triggers the hiatus.
The world ocean plays an important role in climate variability due to its large thermal inertial[5]. Different scientists argue different ocean basins hide the most heat. The recent hiatus has been suggested as a part of the La Nina-like cooling Pacific Decadal Oscillation (PDO) [20] [39]. A pronounced strengthening in Pacific trade winds over the past two decades has been found to be sufficient to account for the cooling of the tropical Pacific and a substantial slowdown in surface warming through increased subsurface ocean heat uptake. At the same time, the accelerated trade winds have increased equatorial upwelling in the central and eastern Pacific, lowering sea surface temperature there, which drives further cooling in other regions [9]. In addition to the Pacific effect, some other studies suggested that Atlantic sank the heat that could have heated the surface and initialized the hiatus by driving easterly wind anomalies over the Indo-western Pacific as Kelvin waves and westerly anomalies over the eastern Pacific as Rossby waves [6] [27]. And more recently, the Indian Oceans role has been highlighted to accumulate more heat from Pacific through the Indonesia Throughflow [24][32]. Liu et al. [28] has also emphasis the deep heat penetration in the Southern Ocean and the South Atlantic. Moreover, a large El Niño event ends in 1998, which led to an higher starting temperature and moving back the start point just one or two years means a rate of change close to the long-term trend. The time period chosen for the hiatus is important[10], and the so-called “hiatus” is more of a decadal climate fluctuation or variation[25][26]. Additionally, some researchers can find no evidence of the surface warming hiatus in an updated global surface temperature analysis [18]. A redistribution of heat [32][24] is not really a global warming hiatus, and the term should be used with caution. Climate scientists have reached a consensus that rather than “global warming hiatus”, the GMST rising slowdown is a result of increased heat uptake and redistribution. “Global surface warming slowdown” is suggested to be a more appropriate term to describe this period[42]. The slowdown is significant enough and triggered more research to improve the understanding of nature[10].
Figure 1.1: Estimated changes in annual global mean surface temperatures (°C, color bars) and CO₂ concentrations (thick black line) since 1880. The changes are shown as differences (anomalies) from the 1901 to 2000 average values. Carbon dioxide concentrations since 1957 are from direct measurements at Mauna Loa, Hawaii, whereas earlier estimates are derived from ice core records. The scale for CO₂ concentrations is in parts per million (ppm) by volume, relative to a mean of 320ppm, whereas the temperature anomalies are relative to a mean of 13.9°C (57°F) [39].
Figure 1.2: Strongly simplified sketch of the global overturning circulation system. The global structure of the thermohaline circulation cell associated with North Atlantic Deep Water production. The circles with interior dots indicate regions where water upwells from deeper layers to the upper ocean and the yellow ellipses indicate sinking regions[21].
1.2 The Agulhas Current System

Heat distribution in the ocean in highly associated with the horizontal wind-driven circulation and vertical overturning circulation\cite{9}\cite{36}. The overturning circulation is related to the water density in the ocean. Taking the acknowledged Atlantic Meridional Overturning Circulation (AMOC) for example, northward warm and saline water cools at Nordic and Labrador Seas and becomes denser, sinking to deeper layer, and donates a southward flow of cold water at depth. Deep water formation in the Southern Ocean contribute to the production of Antarctic Bottom Water (AABW), flowing northward near the bottom (Figure 1.2). The greater Agulhas System around South Africa forms a key component of the global ocean circulation, which feeds the upper arm of the AMOC through the leakage of warm, saline water from the Indian Ocean to the south Atlantic Ocean \cite{1}\cite{29}. The Agulhas System has drawn a growing interest from global physical oceanographers for its important role in the global ocean circulation and climate. The Agulhas Current flows to the southwest along the east coast of South Africa as a narrow, fast boundary current. As the western boundary current of the Indian subtropical gyre and one of the strongest western current in the world, it transports the Indian Ocean water into the Agulhas Region. Climate models show an intensification and poleward shift of subtropical western boundary currents in a warming climate\cite{43}. However, a more recent study proves that the Agulhas Current is broadening instead of strengthening since the early 1990s based on satellite and in situ data\cite{2}. After the current separates from the continent, it loops anti-clockwise around the south of Africa and feeds back into the Indian Ocean as the eastward Agulhas Return Current. This loop is known as the Agulhas Retroflection \cite{11}. Instabilities, interaction with the bathymetry, mesoscale dynamics generate rings, mesoscale eddies, and filaments, transporting some of the water from the region into the Atlantic Ocean\cite{37}\cite{4}. This part of water is called Agulhas Leakage. Theory suggests its variability is associated with the large-scale wind field, in particular with the position of the maximum Southern Hemisphere westerly winds \cite{8}\cite{1}. In essence, if the westerlies shift southwards, the leakage from the Indian Ocean to the Atlantic increases, while a
northward shift would reduce the leakage [7]. Other than the local effect, a model study suggests Agulhas leakage increases with an open Indonesian Throughflow comparing to a closed one [23]. (Figure 1.3)

The goal of this study is investigating the heat distribution at the Agulhas region during the global warming slowdown, its difference from the global warming acceleration period and possible warming mechanism.

Figure 1.3: Mean values over the 1993-2012 period of the sea surface height above geoid in the Agulhas Region (color, in m), and associated with mean geostrophic currents (black vectors). The altimeter products were produced by Ssalto/Duacs and distributed by Aviso, with support from Cnes (http://www.aviso.altimetry.fr/duacs/).
Chapter 2
DATA AND METHODOLOGY

2.1 Data

2.1.1 Sea Surface Temperature Data

SST data is provided by the NOAA National Centers for Environmental Information (NCEI), formerly the National Climatic Data Center (NCDC), which has been used to compute the SST trend in Agulhas Region to investigate the surface warming. The data is an optimally interpolated SST (OISST) daily and monthly averaged product. The basic daily OISST methodology is described in Reynolds et al. 2007[33], but minor modifications were introduced in the current version, version 2 [34]. The product combines in situ and satellite SST with an additional simulated SST for ice-covered regions. The temporal coverage of the data is 1981 to the current date. The spatial coverage is a 0.25 latitude by 0.25 longitude global grid [https://www.ncdc.noaa.gov/oisst].

2.1.2 Ocean ReAnalysis Pilot 5 (ORAP5)

This data is used to investigate the temperature and salinity (TS) structure and calculate the heat ocean content (OHC) at the Agulhas Region. Ocean ReAnalysis Pilot 5 (ORAP5) is a new eddy-permitting ocean reanalysis that has been implemented at European Centre for Medium-Range Weather Forecasts (ECMWF) based on Nucleus for European Modelling of the Ocean (NEMO) 3.4.1, including a prognostic thermal-dynamic sea-ice model (LIM2). It spans the period 1979 to 2013. It has a horizontal resolution 0.25°x0.25° and 75 vertical levels, with variable spacing (the top level has 1 meter thickness). The data was assimilated on this model via NEMOVAR in its 3D-var FGAT mode method with a 5 days assimilation window, the assimilated data
includes some parameters: Temperature and Salinity profiles from the EN3 v2a XBT bias corrected database (1958-2009), including XBT, CTD, Argo, Mooring, and from real-time GTS thereafter. It also assimilates along track altimeter sea level anomalies (SLA) and global trends from AVISO. SST comes from a combination of NOAA and OSTIA products. Sea surface temperature (SST), sea surface salinity (SSS), and global mean sea-level trends are used to modify the surface fluxes of heat and freshwater [45].

2.1.3 Wind Stress Data

The surface wind stress was calculated using the NCEP/NCAR Reanalysis-1 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/[17]. The monthly means are available from 1981 to present, with a global spatial coverage of 2.5 latitude by 2.5 longitude and 17 layers of wind velocity. The wind stress was computed using the wind velocity 10 m (1000 hPa) above the surface following the method detailed by Large et al.[22].

2.2 Methodology

2.2.1 Heaving and Spice Decomposition

The ocean is not layered with depths, but with densities. Potential density depends on the chosen reference pressure and the reference pressure varies with locations. With correct reference pressure, isopycnal can work as an isentropic surface, along which water parcels can move adiabatically, that is, without external input of heat or salt. When isopycnal serves as a boundary between difference water masses, at which the heat can move with it, along it, and even across it. In this study, ocean temperature change at a fixed depth are considered due to heaving and spice variability. Heaving is the temperature change due to isopycnal motions subjected to no heat and salinity exchange with the environment and spice is a change along a neutral density surface. And we followed the decomposition method introduced by Bindoff & McDougall 1994 [3] and updated by Hkinen et al. 2016 [12]

\[
d\theta/dt|_z = d\theta/dt|_n - dz/dt|_n d\theta/dz + R
\]
\[
dS/dt|_z = \frac{dS}{dt}|_n - \frac{dz}{dt}|_n\frac{dS}{dz} + R
\]

The potential temperature changes at a certain depth \((d\theta/dt|_z)\) are divided into a change along a neutral density surface \((d\theta/dt|_n)\), called spice, a change due to neutral density surface motions \((dz/dt|_n)\) subjected to no heat and salinity exchange, heaving, and residue, a change cross neutral density surface. At a well stratified environment, the residue should be near zero. Neutral density surface here is an isopycnal with same potential density to a nearly continuously varying reference pressure, an approximation to the isentropic surface\([30]\). The neutral density values is computed, using software available online at [http://www.teos-10.org/preteos10_software/neutral_density.html][16] Total heat content change and its heave and spice components are computed by integrating potential temperature changes times volume, density, and heat capacity of seawater.

\[
dOHC = \int_{dep} C_p\rho V d\theta dz
\]

### 2.2.2 Hilbert-Huang Transform

The Hilbert-Huang Transform (HHT) is used to the ORAP5 reanalysis data. The HHT is a recent method for decomposing a time series into intrinsic mode functions (IMF) along with a trend, and obtain instantaneous frequency, which can be applied to nonstationary and nonlinear data \([14]\). This transform is the result of empirical mode decomposition (EMD) and the Hilbert spectral analysis (HSA). The purpose of EMD is to reduce a complicated data set into a finite and generally small number of intrinsic mode functions (IMF). The process to identify an IMF is as follows: (1) identifying the local extrema; (2) connect all the local maxima by a cubic spline line as the upper envelope; (3) repeat the previous procedures for the local minima to produce the lower envelope. Having obtained the decomposed IMFs, Hilbert transform is performed on each IMF to compute the instantaneous frequency. This gives us both the amplitude and the frequency of each component as functions of time. This frequency-time distribution of the amplitude is known as the Hilbert spectrum.
We applied HHT to the OHC, its heaving part and spice part time series using the updated Ensemble Empirical Mode Decomposition (EEMD). Mode mixing due to IMF mode rectification is one of the major problems of EMD, which can cause aliasing in the time-frequency distribution and can cause an individual IMF to lose its physical uniqueness. In order to address this issue, Huang and Wu [15] introduced an advanced version of EMD called EEMD. This algorithm that works as follows: (1) add a white noise series to the data, (2) decompose the data plus noise into IMFs, (3) repeat the first two steps with different white noise, and (4) obtain the ensemble mean of the IMFs for the results [15].
Chapter 3
RESULTS

In this study, we analyzed the sea surface temperature data and the ORAP5 reanalysis data from 1984 to 2013. To understand the heat revolution during the global surface warming acceleration and slowdown, 1984-1998 is chosen to represent the acceleration period and 1999-2013 for the slowdown.

3.1 Surface Warming

The Greater Agulhas System shows a warming trend at the surface in the past three decades, along with a warming in the Indian Ocean and the South Atlantic Ocean (Figure 3.1). Only on the coastal area are a few upwell-like cooling spots.

Figure 3.2 shows the SST time series averaging over 36°S to 45°S and 10°E to 35°E, a domain standing for most of Agulhas System [35]. Seasonality is the dominant signal of the SST. To remove the strong seasonal variability, EEMD is applied on this data set. Low frequency signal, (IMF4-7 and the residue trend) is plotted. A sudden temperature (about 1°C) increase happens around 1998 and 1999, with small increase both before and after these years, showing a step-like warming. But still during the slowdown period, the surface temperature increases faster than than the acceleration period, which is opposite to the global mean surface temperature.

Separated into two periods, the warming patterns are different during the global surface warming acceleration and slowdown. During the acceleration period, fastest warming happens 10 – 20°E and 40 – 45°S, southwest of the retroflection. During the slowdown period, the warming moves westward into the South Atlantic Ocean, with a larger magnitude. (Figure 3.3) The coastal area cools down. Even though a cooling trend happens at the core Agulhas Region during the Slowdown, it is still warmer
during the slowdown than the acceleration period (Figure 3.4). And the strongest warming signal locates at the Agulhas Region.

Figure 3.1: SST trend in the last three decades (1984 - 2013).
Figure 3.2: SST time series from 1984 to 2013, averaging over 36°S to 45°S and 10°E to 35°E. The light grey line is the original data and the black line is the IMF4-7 plus residue trend computed from EEMD.
Figure 3.3: SST trend during (a) the Global Surface Warming Acceleration (1984-1998), and (b) Slowdown (1999-2013)
Figure 3.4: Mean temperature of (1999-2013) minus that of (1984-1998). The black contour is 0.3°C.
3.2 OHC Evolution and its Decomposition

The sea surface temperature only reveals the surface signal, but could not give much information about what’s going on in the deeper layer. In this case, ocean heat content (OHC) is a better indicator about the heat distribution in the ocean. The OHC is computed into three layers, 0-200m, 200-700m, and 700-1500m. As shown in Figure3.5, the rate of heat accumulation is much stronger during the slowdown period and most of the signal is at the upper 700m. At the Agulhas Region, 200-700m layer shows a larger warming trend. Also, seasonal variability is dominant in the upper 200m layer. Other than that, the heaving and spice decomposition method does not apply well in the strong mixing condition[3]. Thus, in this study, we focus on investigating the heat evolution and distribution within the 200-700m layer.

At this layer (200-700m), the warming moves to the Return Current region and gets stronger during the slowdown period comparing to the previous 15 years. The Retroflection area and the leakage area show slight cooling signal, while the Agulhas Current is slightly warming.(Figure3.5)

In the last three decades, the ocean gains more heat at this region. And the heat uptake is faster during the slowdown period than the acceleration, which is similar with but larger than the sea surface temperature signal. Figure3.6 shows the averaged OHC integrated between 200m and 700m at the Agulhas Region ($OHC_t$) and its two decomposed components, heaving and spice ($OHC_h$ and $OHC_s$). Heaving keeps increasing during both of the two periods. But the spice has a larger positive trend during the slowdown period comparing to the acceleration period, which is also true for the total OHC.

EEMD is applied to all the three signals ($OHC_t$, $OHC_h$ and $OHC_s$) into different time scales, yielding IMFs shown in Figure3.7,3.8,3.9. The IMFs are displayed in ascending order of time scales, as directed result of EEMD sifting process. For $OHC_t$ and $OHC_s$, the first two IMFs are seasonal variability; IMF3-4 are interannual variability, IMF5-7 are decadal variability, and the last mode is long term nonlinear trend. Since using this 30-year data, the largest time scale can be resolved is 15 years. In
the EEMD result of $OHC_h$, IMF5 is interannual (5 year) instead of decadal like that of $OHC_t$ and $OHC_s$. Both of the residue trends of $OHC_t$ and $OHC_h$ are increasing for the three decades, while the $OHC_s$ trend decreases during the acceleration and increases during the slowdown. For each decomposition, the significance of each resulting IMF was determined by calculating the spread function for the 99% and 95% confidence limit levels [40]. The energy spread of white noise can be calculated and has a Gaussian distribution with a standard deviation. For any defined confidence level, the spread lines, which bound the energy of the white noise with upper and lower limits, can be calculated. If the energy density of any IMF is above the upper spread line, then that IMF contains information at that confidence level.

For this study, the IMFs with longer time scales and containing a significant portion of variance are isolated to analyze low-frequency variations in response to the surface warming acceleration and slowdown. The highest frequency IMFs the $OHC_t$, IMFs 1-2 account for 4.05% of the total variance; the interannual IMFs, IMFs 3-4 account for 6.99% of the total variance; the decadal IMFs, IMFs 5-6 each account for almost 10%. Table (3.1) The IMFs 2-4 of the $OHC_h$ account for 26.96%, the most of the total variance, despite the residual long term trend, which is more than 46%. While for $OHC_s$, the dominant mode is IMF 5, taking up 21.3% of the total variance. IMFs 1-4 are removed to provide a better depiction of larger time scale modulations. The heaving process induced OHC change is much larger than that induced by spice. But the $OHC_t$ shows more similar changing cycle to the $OHC_s$, rather than the $OHC_h$. (Figure 3.10)

To better understand the different temporally scaled signals’ contribution to the total variance of the original data, we performed the Hilbert spectral analysis on the IMFs with time scales longer than one year, IMFs 3-7. The Hilbert Spectrum of $OHC_t$, $OHC_h$ and $OHC_s$ are shown in Figure 3.11, 3.12 and 3.13 respectively. The color scale represents the nondimensional energy present at any particular frequency and temporal location. Dark blue indicates zero energy and dark red indicates a high energy. In Figure 3.11, the maximum energy is found around and lower than 0.1 cpy. As mentioned before, as a result of the limited length of data, the longest time scale
can be resolved is 15 years (0.067 cpy). Therefore, the dark red signal in this figure at 0.02 cpy should not be taken into account. Some strong decadal variation can be found during the acceleration period, and dissipates after 1998, during the slowdown. However, no strong low frequency signal shows in the Hilbert spectrum of $OHC_h$. A maximum energy is found at 0.1 cpy from 1985 to 1995 and 2008 to 2012 in the spectrum of $OHC_s$, Figure 3.13. The heaving process contributes more interannual variability, while the spice process modulates the decadal oscillation.
Figure 3.5: OHC trend during the acceleration and slowdown periods at different layers. The unit is $J/m^3\ Decade$, which is the area averaged OHC trend normalized by the depth for better comparison.
Figure 3.6: The averaged OHC at the Agulhas Region and its heaving and spice components. The black line is the total OHC, the blue line is the heaving part and the red line is the spice part.
Figure 3.7: EEMD of the total OHC ($OHC_t$) (200-700m) at the Agulhas region. IMFs with seasonal to decadal time scales, and the residual of the decomposed signal. The IMFs are plotted in order from high to low frequency. The x axis is time in years. The y axis has units of $J/m^2$. The IMFs have the mean removed, while the residual preserve the mean location.

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Figure 3.8: EEMD of the heaving component ($OHC_h$) (200-700m) at the Agulhas region. IMFs with seasonal to decadal time scales, and the residual of the decomposed signal. The IMFs are plotted in order from high to low frequency. Units is $J/m^2$. 

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Figure 3.9: EEMD of the spice component ($OHC_s$) (200-700m) at the Agulhas region. IMFs with seasonal to decadal time scales, and the residual of the decomposed signal. The IMFs are plotted in order from high to low frequency. Units is $J/m^2$. 

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Figure 3.10: IMFs 5-7 plus the trend of $OHC_t$, $OHC_h$, and $OHC_s$. The dash lines are the original monthly data, same as Figure 3.6. The solid lines are their IMF5-7 plus trend. Black is the total; blue is the heaving; and red is the spice.
Figure 3.11: The Hilbert spectrum of IMFs 3-7 of the $OHC_t$ at the Agulhas Region show the change in frequency and energy throughout the record length. The color of the Hilbert spectrum indicates the nondimensional energy of the signal ranging from low energy (dark blue) to high energy (dark red).
Figure 3.12: The Hilbert spectrum of IMFs 3-7 of the $OHC_h$ at the Agulhas Region show the change in frequency and energy throughout the record length. The color of the Hilbert spectrum indicates the nondimensional energy of the signal ranging from low energy (dark blue) to high energy (dark red).
Figure 3.13: The Hilbert spectrum of IMFs 3-7 of the $OHC_s$ at the Agulhas Region show the change in frequency and energy throughout the record length. The color of the Hilbert spectrum indicates the nondimensional energy of the signal ranging from low energy (dark blue) to high energy (dark red).
3.3 OHC Spatial Variability

The Agulhas Region does not change uniformly. The warm saline Indian water comes from the Agulhas Current (AC), forms a retroreflection around the south tip of South Africa and returns back to the Indian Ocean via the Return Flow (RC). To better understand the heating mechanism in the Agulhas region, these three regions are studied separately. As shown in Figure 3.14, the AC region locates at $30^\circ E - 40^\circ E$, $20^\circ S - 35^\circ S$; the Retro region locates at $10^\circ E - 20^\circ E$, $36^\circ S - 41^\circ S$; the RC region locates at $20^\circ E - 40^\circ E$, $36^\circ S - 42^\circ S$.

The temperature change has also been decomposed into the heaving and spice components and integrated from 200m to 700m into $OHC_t$, $OHC_h$ and $OHC_s$ in all these three regions. Also EEMD and Hilbert spectral analysis are applied to all the three signals at the three regions.

At the AC region, $OHC_t$, $OHC_h$ and $OHC_s$ all show an increase during the acceleration and decrease during the slowdown in the residual long term trend, but the increase of $OHC_s$ during the acceleration is weaker than the other two, shown in Figure 3.15, 3.16, 3.17. The interannual IMF, IMF4 of the heaving component takes most of the variance, which shows a off chart warming since 2007. This explains the filtered decadal variation of $OHC_h$ in Figure 3.18 fails to present the increase after 2007. The heaving component and spice component show opposite changing pattern from 1990 to 1998 and from 2004 to 2003. All three Hilbert spectrum show maximum energy at the decadal time scale, and very low level of energy at the interannual time scale, which is also shown in the Hilbert spectrum. Very limited energy can be found at the decadal time scale.

At the Retro region, the $OHC_t$ and $OHC_h$ show a slight warming, while $OHC_s$ has a cooling trend in the last three decades (Figure 3.22, 3.23, 3.24). There is a sudden and steep decrease of both $OHC_t$ and $OHC_h$ (Figure 3.25). The first four IMFs have most of the variance of the $OHC_t$ and $OHC_h$, but the IMFs 5-6 of the $OHC_s$ still take a big portion of the total variance (Table 3.1). A significant amount of annual and interannual variation happens at the region.
At the Return Current region, the $OHC_s$ increases mildly before 1996, and shows a decreasing trend since then, while $OHC_t$ and $OHC_h$ show a high-rate increase in the thirty years (Figure 3.29, 3.30, 3.31). IMFs 4-7 of the $OHC_t$ show very little variability after 1994 and in the long term trend shows the increase gets faster after 1994, which shows similarly the $OHC_s$, except for the sudden decrease starting at 2010. The 5-6 year cycle variation takes most of the variance of the $OHC_h$ other than the long-term trend. Most of the $OHC_s$’s variance concentrates at the decadal and longer than decadal variation. Low frequency energy can only be found at 1994 and during the acceleration in the Hilbert spectrum of the $OHC_h$ and $OHC_s$, respectively.

Figure 3.36, 3.37, 3.38 show the the $OHC_t$, $OHC_h$ and $OHC_s$ difference between the slowdown and acceleration periods. The Agulhas Current region loses heat in total, with less heaving input, but a little more spice induced heating. Part of the Retroflection region gains heat, while its northwest part, where connecting to the leakage area loses heat. This pattern is also shown by the heaving component ($OHC_h$). The Return Current contributes to most of the heating in the Agulhas Region. Heaving is ruling at this region, while spice contributes more at the warmer region south to the Return Current.
Figure 3.14: The locations of the chosen regions. The blue box is the Agulhas Current region (AC); the green box is the Retroflection region (Retro); the yellow box is the Return Current region (RC); the white box represent the greater Agulhas System, aka the Agulhas Region. Background color represents mean values over the 1993-2012 period of the sea surface height above geoid, and black vectors represent mean geostrophic currents.
Figure 3.15: EEMD of the total OHC \((OHC_t)\) (200-700m) at the Agulhas Current (AC) region. IMFs with seasonal to decadal time scales, and the residual of the decomposed signal. The IMFs are plotted in order from high to low frequency. Units are \(J/m^2\).
Figure 3.16: EEMD of the heaving component ($\text{OHC}_h$) (200-700m) at the AC region. IMF's with seasonal to decadal time scales, and the residual of the decomposed signal. The IMFs are plotted in order from high to low frequency. Units is $J/m^2$. 
Figure 3.17: EEMD of the spice component ($OHC_s$) (200-700m) at the AC region. IMFs with seasonal to decadal time scales, and the residual of the decomposed signal. The IMFs are plotted in order from high to low frequency. Units is $J/m^2$. 
Figure 3.18: IMFs 5-7 plus the trend of $OHC_t$, $OHC_h$, and $OHC_s$ at the AC region. The dash lines are the original monthly data, same as Figure 3.6. The solid lines are their IMF5-7 plus trend. Black is the total; blue is the heaving; and red is the spice.
Figure 3.19: The Hilbert spectrum of IMFs 3-7 of the $OHC_t$ at the AC Region show the change in frequency and energy throughout the record length. The color of the Hilbert spectrum indicates the nondimensional energy of the signal ranging from low energy (dark blue) to high energy (dark red).
Figure 3.20: The Hilbert spectrum of IMFs 3-7 of the $OHC_h$ at the AC Region show the change in frequency and energy throughout the record length. The color of the Hilbert spectrum indicates the nondimensional energy of the signal ranging from low energy (dark blue) to high energy (dark red).
Figure 3.21: The Hilbert spectrum of IMFs 3-7 of the $OHC_s$ at the AC Region show the change in frequency and energy throughout the record length. The color of the Hilbert spectrum indicates the nondimensional energy of the signal ranging from low energy (dark blue) to high energy (dark red).
Figure 3.22: EEMD of the total OHC \((OHC_t)\) (200-700m) at the Retroflection region. IMFs with seasonal to decadal time scales, and the residual of the decomposed signal. The IMFs are plotted in order from high to low frequency. Units are \(J/m^2\).
Figure 3.23: EEMD of the heaving component ($OHC_h$) (200-700m) at the Retroflection region. IMFs with seasonal to decadal time scales, and the residual of the decomposed signal. The IMFs are plotted in order from high to low frequency. Units is $J/m^2$. 
Figure 3.24: EEMD of the spice component ($OHC_s$) (200-700m) at the Retroflection region. IMFs with seasonal to decadal time scales, and the residual of the decomposed signal. The IMFs are plotted in order from high to low frequency. Units is $J/m^2$. 
Figure 3.25: IMFs 5-7 plus the trend of $OHC_t$, $OHC_h$, and $OHC_s$ at the Retroflection region. The dash lines are the original monthly data, same as Figure 3.6. The solid lines are their IMF5-7 plus trend. Black is the total; blue is the heaving; and red is the spice.
Figure 3.26: The Hilbert spectrum of IMFs 3-7 of the $OHC_t$ at the Retroflection Region show the change in frequency and energy throughout the record length. The color of the Hilbert spectrum indicates the nondimensional energy of the signal ranging from low energy (dark blue) to high energy (dark red).
Figure 3.27: The Hilbert spectrum of IMFs 3-7 of the $OHC_h$ at the Retroflection Region show the change in frequency and energy throughout the record length. The color of the Hilbert spectrum indicates the nondimensional energy of the signal ranging from low energy (dark blue) to high energy (dark red).
Figure 3.28: The Hilbert spectrum of IMFs 3-7 of the $OHC_s$ at the Retroflection Region show the change in frequency and energy throughout the record length. The color of the Hilbert spectrum indicates the nondimensional energy of the signal ranging from low energy (dark blue) to high energy (dark red).
Figure 3.29: EEMD of the total OHC \((OHC_t)\) (200-700m) at the Return Current region. IMFs with seasonal to decadal time scales, and the residual of the decomposed signal. The IMFs are plotted in order from high to low frequency. Units are \(J/m^2\).
Figure 3.30: EEMD of the heaving component ($OHC_h$) (200-700m) at the Return Current region. IMFs with seasonal to decadal time scales, and the residual of the decomposed signal. The IMFs are plotted in order from high to low frequency. Units is $J/m^2$. 

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Figure 3.31: EEMD of the spice component \((OHC_s)\) (200-700m) at the Return Current region. IMFs with seasonal to decadal time scales, and the residual of the decomposed signal. The IMFs are plotted in order from high to low frequency. Units is \(J/m^2\).
Figure 3.32: IMFs 5-7 plus the trend of $OHC_t$, $OHC_h$, and $OHC_s$ at the Return Current region. The dash lines are the original monthly data, same as Figure 3.6. The solid lines are their IMF5-7 plus trend. Black is the total; blue is the heaving; and red is the spice.
Figure 3.33: The Hilbert spectrum of IMFs 3-7 of the $OHC_t$ at the Return Current Region show the change in frequency and energy throughout the record length. The color of the Hilbert spectrum indicates the nondimensional energy of the signal ranging from low energy (dark blue) to high energy (dark red).
Figure 3.34: The Hilbert spectrum of IMFs 3-7 of the $OHC_h$ at the Return Current Region show the change in frequency and energy throughout the record length. The color of the Hilbert spectrum indicates the nondimensional energy of the signal ranging from low energy (dark blue) to high energy (dark red).
Figure 3.35: The Hilbert spectrum of IMFs 3-7 of the $OHC_s$ at the Return Current Region show the change in frequency and energy throughout the record length. The color of the Hilbert spectrum indicates the nondimensional energy of the signal ranging from low energy (dark blue) to high energy (dark red).
Table 3.1: IMF information for each data set. This table shows the variance of each mode as a percentage of the variance of the original time series.
Figure 3.36: The mean $OHC_t$ (200-700m) during the slowdown (1999-2013) minus that during the acceleration (1984-1998).
Figure 3.37: The mean $OHC_h$ (200-700m) during the slowdown (1999-2013) minus that during the acceleration (1984-1998).
Figure 3.38: The mean $OHC_s$ (200-700m) during the slowdown (1999-2013) minus that during the acceleration (1984-1998).
3.4 Isopycnals’ Vertical Migration and Temperature Change at Isopycnals

Deepening isopycnals are the dominant contribution to the warming at the Agulhas Region, with maximum sinking occurring at Antarctic Intermediate Water (AAIM) and Central Water (CW) ($\sigma = 26.8 - 27.8$). The zonal and meridional averaged heaving trends from 1984 to 2013 are shown in Figure 3.39, 3.40, with red indicating sinking and blue indicating shoaling. The most pronounced deepening happens at the Agulhas Region, mainly at the deep layer of the Return Current and upper layer of its adjacent Subantarctic Zone with a trend larger than 15 m/decade, while the pycnocline and the layer below it show a slight shoaling signal at the Agulhas Current (about 200-700m (Figure 3.41)).

Isopycnals of $\sigma = 26.5, 27, 27.5$ are chosen to represent different water masses, Subtropical Mode Water (STMW), Central Water (CW) and Antarctic Intermediate Water (AAIM), respectively. These three potential density surfaces’ depth difference between the slowdown and acceleration periods is shown in Figure 3.42, 3.43, 3.44 for the spacial variability of isopycnals’ sinking and shoaling. The density surface of 26.5 sinks as much as 40 meters at the Return Current and shoals at the Agulhas Current during the slowdown period, comparing to the previous acceleration period. Isopycnals of 27 and 27.5 both show a strong deepening at this region, and the scale is twice that of 26.5. The isopycnal 27.5’s sinking is stronger than that of 27. Häkkinen et.al (2016)[12] claims that the strongest deepening happens at isopycnal of 27 at the southern hemisphere and the deeper layer is pushed down by this layer, comparing to which, heaving at the Agulhas Region is stronger and deeper than most of the other locations on earth.

It’s notable that warming along isopycnals occurs mostly at the upper layer, which is opposite to the maximum heaving. During the slowdown period, the isopycnal of 26.5 warms the most at the Return Current and strongest warming signal of 27 locates at the subtropical front area. The temperature increase along the isopycnal of 27.5 is much milder, which is less than one third of 26.5.
Figure 3.39: Zonal average sinking/shoaling trends [(m/decade); positive downward] of the potential density surfaces for the Agulhas Region in the last three decades. The black contour is 15m/decade.
Figure 3.40: Meridional average sinking/shoaling trends [(m/decade); positive downward] of the potential density surfaces for the Agulhas Region in the last three decades. The black contour is 15m/decade.
Figure 3.41: Climatology density distribution at (a) 20°E, (b) 40°E. The black contour is average potential density. The background color is the density difference between the slowdown and acceleration periods.

Figure 3.42: Sinking/shoaling change of the potential density surfaces 26.5 from 1984-1998 to 1999-2013 at the Agulhas Region.
Figure 3.43: Sinking/shoaling change of the potential density surfaces 27 from 1984-1998 to 1999-2013 at the Agulhas Region.
Figure 3.44: Sinking/shoaling change of the potential density surfaces 27.5 from 1984-1998 to 1999-2013 at the Agulhas Region.
Figure 3.45: Zonal average potential temperature trends [°C/decade] along the potential density surfaces for the Agulhas Region in the last three decades.
Figure 3.46: Meridional average potential temperature trends [°C/decade] along the potential density surfaces for the Agulhas Region in the last three decades.
Figure 3.47: Potential temperature change of the potential density surfaces 26.5 from 1984-1998 to 1999-2013 at the Agulhas Region.
Figure 3.48: Potential temperature change of the potential density surfaces 27 from 1984-1998 to 1999-2013 at the Agulhas Region.
Figure 3.49: Potential temperature change of the potential density surfaces 27.5 from 1984-1998 to 1999-2013 at the Agulhas Region.
3.5 Temperature Change with Depth

In this section, we explore the vertical profiles of the averaged temperature change and their heaving and spice components from the acceleration period 1984-1998 to the slowdown period 1999-2013 at the Agulhas Region and other defined regions (Figure 3.50). A positive spice means a warming isopycnal and a positive heaving means a deepening isopycnal. The total warming at the Agulhas region weakens with depth. Its heaving component has a peak at 200m and a larger one at 600m, then decreases to zero at 1500m. Its spice component reaches the peak at 100m then decreases to zero at 700m and remains near zero in the deeper layers, and it is larger than the heaving at the upper 400m. The three small regions all show different changing patterns from the bigger area and each other. At the Agulhas Current region, only the water upper than 250m and lower than 1200m is warmer during the slowdown, which is consistent with the OHC decrease at 200m to 700m. Its heaving component reaches a minimum at 600m and a maximum at 1000, which is opposite with its spice component. The spice component in the top 200-700m is warming and cooling below 700m. 250-800m layer at this region is the only place where shows a sign of shoaling isopycnals. The water column at the Retroflection region has a similar pattern to that at the Agulhas Current region. But the total temperature change is positive at each depth and the minimum of its heaving component is at 300m and its maximum is at 700m. The total warming at the Return Current region resembles that at the larger area. Its heaving component reaches the maximum warming at 800m and is always larger than its spice component. The T-S diagram at the Agulhas region is shown in Figure 3.51. During the slowdown, the surface water is getting saltier, while the deep water is getting warmer.
Figure 3.50: Total potential temperature change ($^\circ$C) from the acceleration (1984-1998) to the slowdown (1999-2013) divided into heaving and spice for the study areas. The black line is the total temperature change; the blue line is the heaving component; the red line is the spice component; the grey dash line is the residue of total minus heaving and spice.
Figure 3.51: Averaged T-S Diagram at the Agulhas Region. Blue dots represent the temperature and salinity during the acceleration (1984-1998) and red dots represent the slowdown (1999-2013).
Chapter 4

CONCLUSION AND DISCUSSION

In this study, the analysis of reanalysis ocean heat content at the Agulhas Region reveals heat distribution at the upper 700m, where the largest heat gain has occurred, in the last three decades, including the global surface warming acceleration and slowdown periods. The OHC decomposed into heaving and spice after Bindoff and McDougall (1994)[3], Häkkinen et.al (2016)[12], Zhang and Yan (2017) [44] provide a framework to understand the mechanism of the deep warming at this region. The total OHC, its heaving component and spice component are analyzed by applying EEMD and HHT in an effort to better understand the heat evolution. The Agulhas Region is warming in the last thirty years, with a larger magnitude in the later fifteen years (the global surface warming slowdown) comparing to the acceleration and more heat accumulates at the deeper layer (200-700m). In the region averages, the dominant contribution to the heat content at 200-700m comes from the deepening of isopycnals and the maximum deepening occurs at 600m. The isopycnals themselves are also warming up, but mainly at the surface and phase out with depth. The spice component shows a strong decadal cycle, while the heaving component’s most significant frequency is 5-6 years. The total OHC contains large changes from isopycnals sinking and shoaling (heaving), but its decadal variation is regulated by the spice component. During the slowdown period, the upper layer water is saltier, which might contribute to the isopycnals sinking.

The Agulhas region is where three circulation systems adjacent to: the South Atlantic Ocean subtropical gyre, the Indian Ocean subtropical gyre, and the Subtropical Front of the Antarctic Circumpolar Current in the Southern Ocean. Different locations can be affected by different circulation induced warming mechanisms. The Agulhas Current is the western boundary current of the Indian Ocean subtropical gyre.
The sea surface temperature of the current is higher during the slowdown. However, the deeper layer here is cooling. The isopycnals are warming but shoaling, which agrees with Beal et al. (2016)[2], which suggests the Agulhas Current is not strengthening but broadening. The Retroflection region is where the current leaves the coast, returns, and forms leakage, feeding warm and saline water to the South Atlantic subtropical gyre. This region warms a little, but the leakage pathway to the South Atlantic Ocean northwest to it shows a slight cooling trend, which suggests more water reaching this region returns instead of leaking into the Atlantic. The Return Current flows by the Subtropical Front of the Antarctic Circumpolar Current in the Southern Ocean. And here occurs the strongest warming at the Agulhas Region. The maximum isopycnal deepening here reaches deeper than 800m. The isopycnal warming (spice) is relatively strong as well comparing to the other two regions. Sea surface temperature also shows the largest difference between the slowdown and the acceleration at this region. At this region, more heat is gained and taken into the deeper ocean by the potent heaving.

Other than the saltier upper layer water, another possible explanation of this big difference between the slowdown and acceleration periods is the local wind pattern change and the change at the Indian Ocean, shown in Figure 4.1. The east wind at the tropical Indian Ocean is weakened during the slowdown. Even though with a stronger Indonesian Throughflow (ITF), the upstream heat input of the Agulhas Current can decrease. Also, the southeast wind at the leakage area gets weaker, less leakage leaves this region feeding into the South Atlantic. The Return Current would take more Agulhas Water back into the Indian Ocean. And the warm saline subtropical water can be subducted into the deeper layer by the strong having at this region. At each location, the residue is relatively strong at the surface and only exit at the mixing layer (about upper 200m).
Figure 4.1: Sea Level Pressure (SLP) and wind trend during (a) the Global Surface Warming Acceleration (1984-1998), and (b) Slowdown (1999-2013). The background color is the SLP trend, and the unit of the colorbar is mbar/decade. The black vector represents the wind trend, with a unit of m/s \cdot decade.


## Appendix A

### LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>greenhouse gases</td>
<td>GHG</td>
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<tr>
<td>global mean surface temperatures</td>
<td>GMST</td>
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<tr>
<td>The inter governmental Panel on Climate Change</td>
<td>IPCC</td>
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<td>Fifth Assessment Report</td>
<td>AR5</td>
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<tr>
<td>Pacific Decadal Oscillation</td>
<td>PDO</td>
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<tr>
<td>Atlantic Meridional Overturning Circulation</td>
<td>AMOC</td>
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<td>Antarctic Bottom Water</td>
<td>AABW</td>
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<td>Sea Surface Temperature</td>
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<td>NOAA National Centers for Environmental Information</td>
<td>NCEI</td>
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<tr>
<td>National Climatic Data Center</td>
<td>NCDC</td>
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<td>optimally interpolated SST</td>
<td>OISST</td>
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<tr>
<td>heat ocean content</td>
<td>OHC</td>
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<tr>
<td>European Centre for Medium-Range Weather Forecasts</td>
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