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Critical Review for ANTA 602
Global linkages and influences – the Antarctic Circumpolar Current and the Thermohaline Conveyor Belt

Introduction:

This review assesses the available literature and documents a contemporary understanding of the oceanic thermohaline circulation system and the oceanic currents that surround Antarctica, with an emphasis being placed on the Antarctic Circumpolar Current. The review then focuses on an assessment of the role of the Antarctic Circumpolar Current within the world-wide Thermohaline 'Conveyor Belt'.

In addition, the review also critically assesses key papers that outline the possible impacts of climate change on the Antarctic Circumpolar Current and the Thermohaline Conveyor Belt.

Discussion:

1. *Oceanic thermohaline circulation*

Oceanic currents are driven predominantly by the wind, the density of seawater, tides and the earth's rotation (Rahmstorf, 2002). The density of seawater is determined by salinity and temperature. The colder or saltier seawater becomes the denser it becomes. Differences in density cause seawater to move vertically through the water column with cold or salty, dense seawater moving downwards through the water column and less salty or warmer water moving upwards in the water column (L. Carter, Professor of Marine Geology, Victoria University Wellington, personal communication, November 17, 2009¹; Van Aken, 2007).

The cyclical movement of seawater around the globe due to differences in density is referred to as the thermohaline² circulation (L. Carter, personal communication; Van Aken, 2007).³

These convection currents of the thermohaline circulation system (THC) are a product of the environmental conditions that exist at the various locations throughout the globe.⁴ A basic explanation of the THC is provided by Chester (2000); Kunzig (2000); Kunzig and Broecker (2009); Rice (2000) and Thomas (2004) and a more thorough explanation is provided by Carmack (1990); Clarke, Church and Gould (2001); Deacon

¹ Hereafter referred to as "(L.Carter, personal communication)".

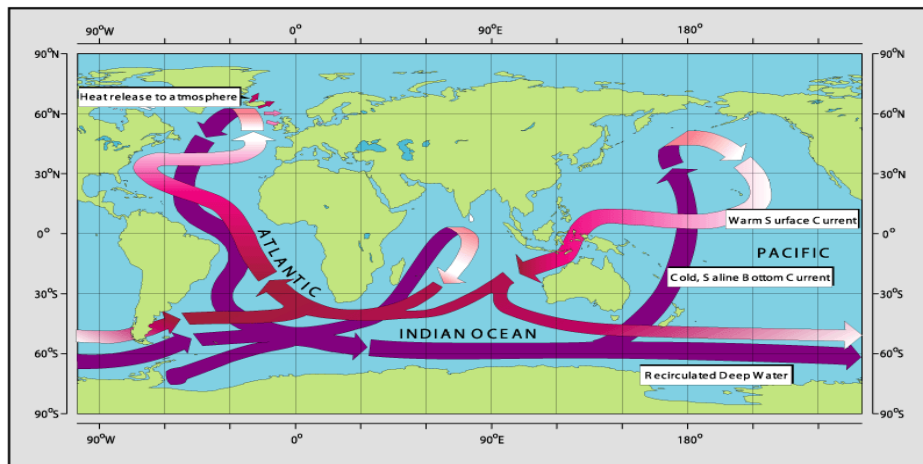
² From the Greek words for heat and salt (Kunzig & Broecker 2009).

³ It is also known as the Meridional Overturning Circulation (Fry, 2008; Schmittner, Chiang & Hemming, 2007; Van Aken, 2007) and it is often referred to as a 'Conveyor Belt' or in particular, the 'Broecker's Conveyor Belt' (Kunzig & Broecker, 2009).

⁴ Refer to Figure 1 below.

(1977); Hogg (2001); Lehman, Wright and Stocker (1993); Millero and Sohn (1992); Patterson and Whitworth (1990); Pedlosky (1996); Thompson, Crease and Gould (2001); Tyler (1995) and Van Aken (2007). A merger of these all these sources⁵ indicates that air-sea interaction at higher latitudes around the poles causes surface seawater to cool and increase in salinity⁶ thus gaining density, forcing the water to descend to abyssal depths where the atmosphere no longer has a direct impact upon it and where it spreads away horizontally to lower latitudes.

**Figure 1. Schematic map of the THC.
From Schmittner et al (2007).**



The rush of water that dives to the Atlantic abyssal plains off Greenland is described by Kunzig as being more powerful than the Niagara Falls and as it progresses south this current of water pulls with it currents that originate from the Labrador Sea (Kunzig, 2000). As this mass of water moves further south it is joined by pulses of very salty water from the Mediterranean Sea. The three sources of water slowly mix together vertically to form what is then known as North Atlantic Deep Water (“NADW”).

The NADW makes its way south until it is integrated in with the deepwater of the Antarctic Circumpolar Current.⁷ Bottom/deep waters that are able to make their way north, away from the influence of the Antarctic Circumpolar Current⁸ will eventually make their way back to the surface at some point due to the greater penetration of solar heat in lower latitudes and due to upwelling in shallower waters of the Pacific, Indian and Atlantic Oceans (Fine, 1993; Kunzig, 2000; Kunzig & Broecker, 2009; Van Aken, 2007).

The warm, surface waters of the Pacific and Indian Oceans make their way west, thanks to the easterly trade winds that operate in the tropics, to join the warm surface

⁵ In order to describe this system in basic terms to set the scene for this literature review.

⁶ This is discussed in more detail in section 3 below.

⁷ This is discussed in more detail in section 3 below.

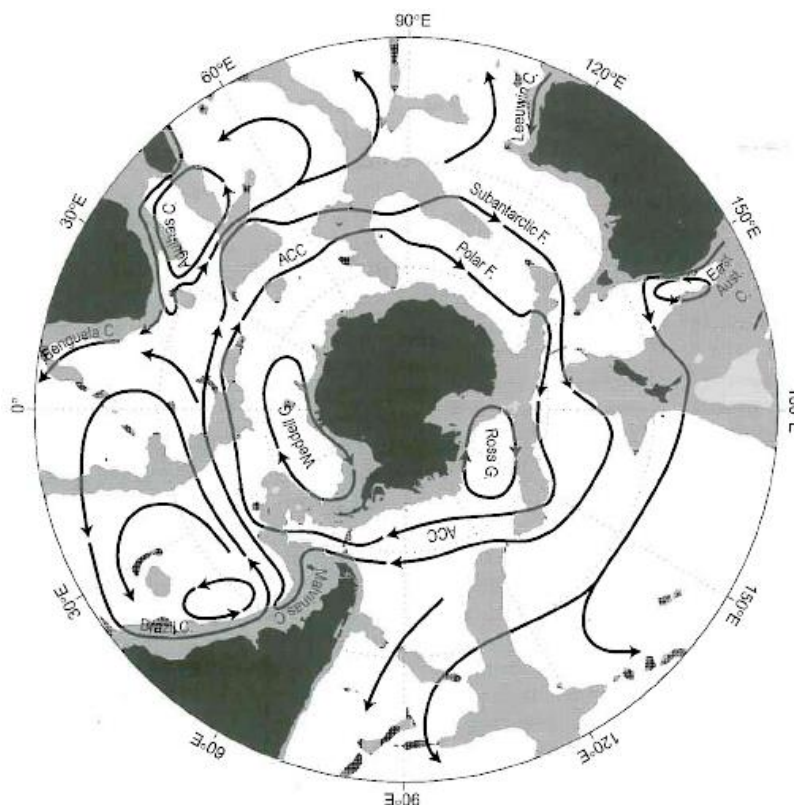
⁸ This is discussed more in section 2 below.

waters of the Atlantic to then head north and east into the North Atlantic via the Gulf Stream where they are cooled and the cycle starts all over again (Doos, 1995; Rahmstorf, 1996).⁹

2. Oceanic currents surrounding Antarctica

Antarctica is an isolated continent that maintains its glacial climate due to the currents¹⁰ encircling it preventing the warmer waters of the Subtropics or Subantarctics from reaching it directly¹¹ (Rintoul, Hughes and Olbers, 2001). Priddle (1993) states that in the coastal marine area immediately adjacent to the Antarctic mainland, the prevailing winds are easterly and this drives waters to the west. This is known as the Antarctic Coastal Current¹² (Rintoul et al., 2001). Two notable cyclonic gyres exist in this zone also.¹³ These gyres operate against this east wind drift.

Figure 2. Schematic map of the major currents around Antarctica.
From Rintoul et al (2001).



Thermohaline stratification in the water column of the Coastal Current is dominated by Antarctic Bottom Water (“AABW”), Lower Circumpolar Deep Water (“LCDW”) and

⁹ We know about the convection currents of the THC thanks to the early, and ongoing, work of oceanographers. Refer to Appendix 1 for a brief history of the work of some notable oceanographers in developing this understanding of the THC.

¹⁰ That are uninterrupted by land barriers.

¹¹ As shown in Figure 2.

¹² Also known as the East Wind Drift or the Antarctic Slope Front.

¹³ The Ross Gyre and the Weddell Gyre.

Upper Circumpolar Deep Water (“UCDW”) as well as the NADW¹⁴ that is being lifted to the surface to be cooled to balance the flow of water moving to lower latitudes at the bottom and surface layers¹⁵ (Baines, & Condie, 1998; Rintoul et al., 2001). There can be several varieties of AABW¹⁶ (Jones, Nelson & Treguer, 1990). LCDW and UCDW are created from ‘recycled’ or rejuvenated NADW (Jones et al., 1990; Whitworth, Orsi, Kim, Nowlin & Locarnini, 1998).

Further north out to sea the prevailing winds are westerly and this drives the water to the east, in an irregular band, around Antarctica – this current is known as the Antarctic Circumpolar Current (“ACC”)¹⁷ (Rintoul et al., 2001). The catalyst for the birth of the ACC was the separation of Antarctica from South America.¹⁸ Oceanic and atmospheric conditions changed – prevailing westerly winds encircling Antarctica created the immense ACC that now flows through the southern parts of the Pacific, Indian and Atlantic Oceans (L. Carter, personal communication; A. Clarke, Marine Ecologist, personal communication, November 24, 2009).¹⁹

The ACC is the world’s largest current,²⁰ 150 times the flow of all the world’s rivers combined (Fyfe & Saenko, 2005). Kunzig (2000) describes the ACC as carrying 800 Amazon Rivers.²¹ The ACC carries 130 Sverdrups of water (130million m²/second) through the Drake Passage (L. Carter, personal communication; Rintoul et al., 2001).

The ACC consists of a number of circumpolar fronts. The two main fronts are the Polar Front and the Subantarctic Front.²² As shown in Figure 3, thermohaline stratification in the water column of the ACC is dominated by AABW, LCDW and UCDW as well as the ascending NADW. Antarctic Intermediate Water (“AAW”) also comes into play at this point. AAW forms from overlying water²³ or subantarctic surface water when these sink when cooled by the polar conditions (Iudicone, Madec, Blanke & Speich, 2008; Jones et al., 1990).

The band where the Coastal Current and the ACC diverge is known as the Antarctic Divergence (Hince, 2000). This zone is characterized by large-scale upwelling of UCDW and NADW (Laws, 1989; Rintoul et al., 2001). The divergence causes some surface water to eddy south back towards the Antarctic Continent where it is cooled, possibly to the point that it becomes AABW (L. Carter, personal communication).

¹⁴ Refer to Figure 3 below.

¹⁵ The movement of these layers is referred to in greater detail below.

¹⁶ Weddell, Ross and so on.

¹⁷ Also known as the West Wind Drift or simply the Polar Front.

¹⁸ Through the development of the Drake Passage.

¹⁹ Hereafter referred to as “(A. Clarke, personal communication)”.

²⁰ The ACC takes about 8-9 years to circle the globe (Hince, 2000).

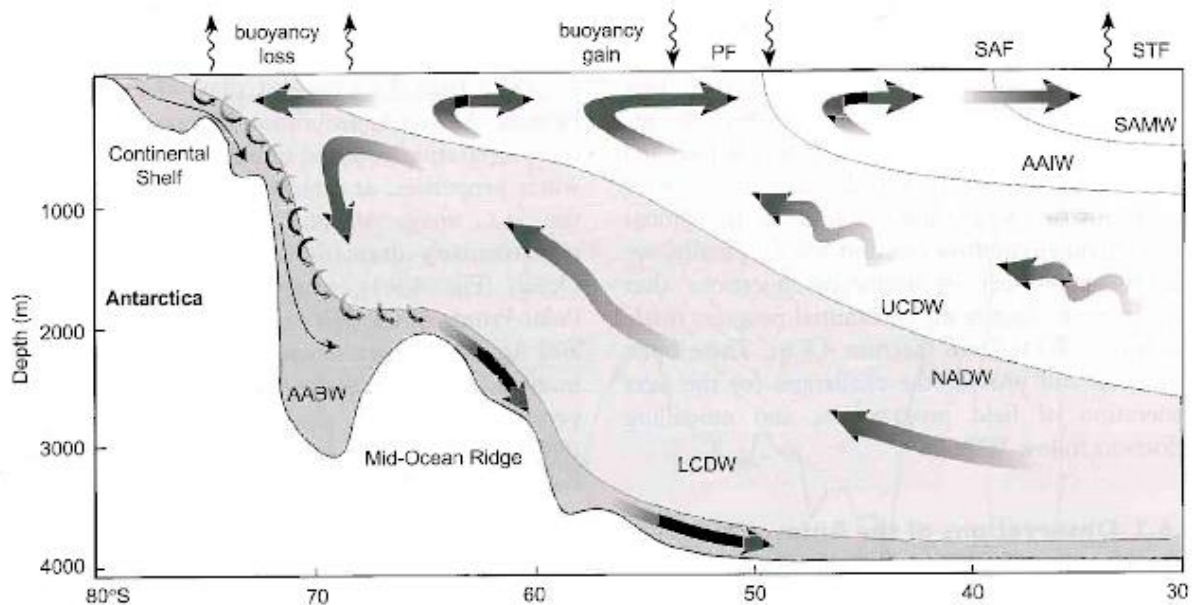
²¹ Compared to the 80 Amazon Rivers carried by the NADW current.

²² But these in turn can be analysed in greater detail to reveal sub-fronts such as the Southern Front and the Southern Boundary.

²³ Winter water.

The boundary where the warmer Subantarctic surface water meets the colder, denser Antarctic surface water is known as the Antarctic Convergence.²⁴ This zone is dominated by the conversion of Subantarctic Mode Water (“SAMW”) to AAIW (Kunzig 2000; Rintoul et al., 2001) and by the eddying of this AAIW north to lower latitudes when it escapes the forces of the ACC (Fine, 1993).

**Figure 3. Schematic view of the THC in the Southern Ocean
From Rintoul et al (2001).**



3. *The role of the Antarctic Circumpolar Current in the Thermohaline Conveyor Belt*

The ACC connects each of the world’s ocean basins, permitting the THC to exist (Busalacchi, 2004; Piepenburg, 2005; Rintoul et al., 2001). The ACC plays the role of mixmaster or centrifuge in the THC (Kunzig, 2000), churning up the oceanic currents that reach it, mixing them in with its own cold, dense waters and scattering them north again to lower latitudes as they eddy off the ACC whirlpool (Van Aken, 2007). The AABW component of the ACC is so cold and dense it even forces the NADW, which has made its way south along the east coast of South America, to eddy its way towards the surface to be cooled again and mixed in with the LCDW and UCDW (Rintoul et al., 2001).

The ACC is the provider of AABW to ventilate and refresh a substantial component of the world’s oceans (Rintoul et al., 2001). Carmack (1990); Carmack and Foster (1977); L. Carter, personal communication; Foster and Carmack (1977); Grassl (2001); Hofmann & Klinck (1998); Kunzig (2000); MacAyeal (1984); McPhee, Kottmeier and Morison (1999); Nicol, Worby and Leaper (2008); Rahmstorf (2002); Rintoul (1998); Rintoul et al (2001); B. Storey, Director of Gateway Antarctica, University of Canterbury, personal communication, November 25 (2009)²⁵ and Stossel, Yang and

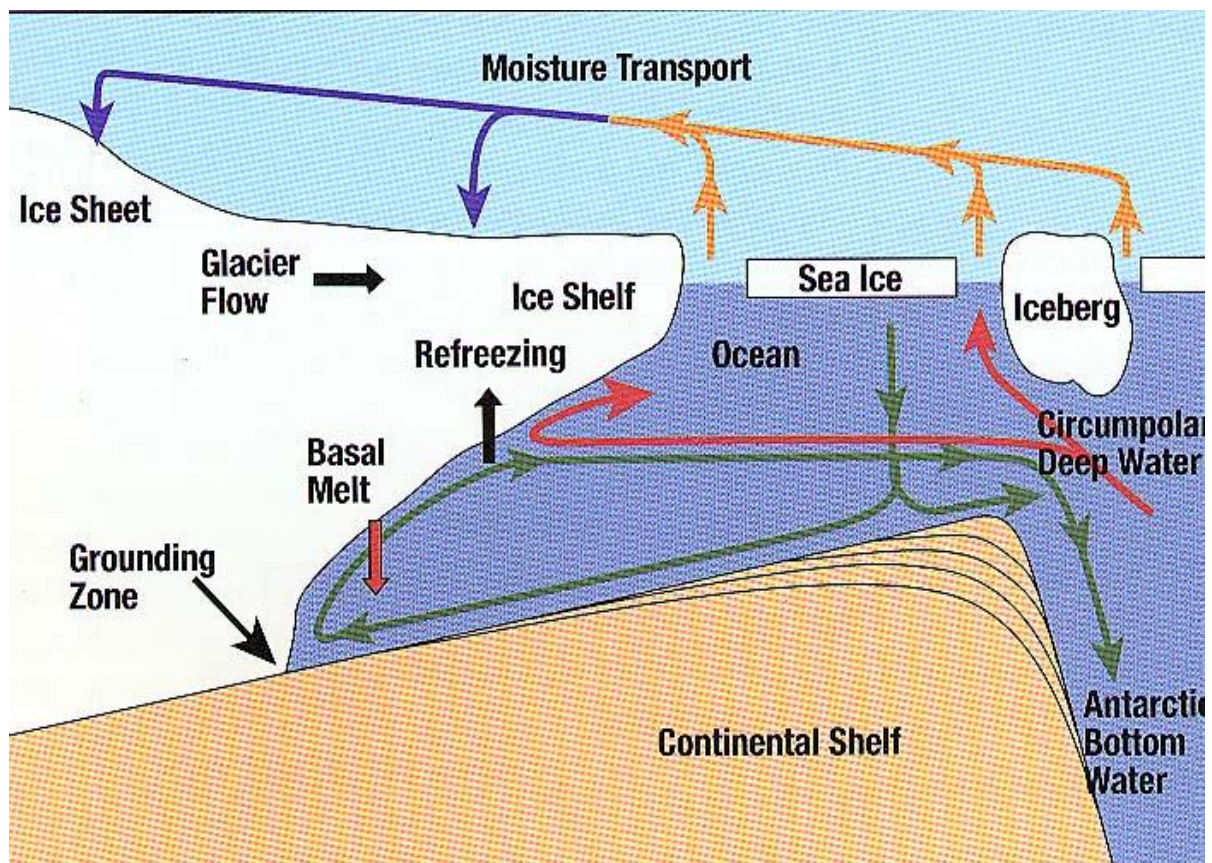
²⁴ Or simply the Polar Front.

²⁵ Hereafter referred to as “(B. Storey, personal communication)”.

Kim (2002) all outline the importance of Antarctic ice shelves,²⁶ and sea-ice in cooling the sea water in the Weddell Sea and Ross Sea, and increasing its salinity²⁷ making it super dense and forcing it to the very bottom of the ACC, along abyssal plains.²⁸ Kellogg (1987) states that cryosphere variations is the key influence on the formation of and source areas for AABW and NADW.²⁹ This deep penetrating local convection creates a dense reservoir of extremely cold water (Van Aken, 2007) that is critical to creating the pressure required to drive the conveyor belt sufficiently for NADW to complete its journey home to the Greenland coast (Rintoul et al., 2001).

The ACC also acts as a barrier preventing warmer waters of the Subtropics or Subantarctics from directly reaching Antarctica, keeping Antarctica isolated and cold thus perpetuating the development of ice shelves and sea ice that are crucial to cooling the waters that supply AABW to the Southern Oceans (L. Carter, personal communication).

Figure 4. Schematic view of the influence of ice shelves and sea ice on the THC.
From B.Storey, personal communication, November 25, 2009.



²⁶ Which are unique to Antarctica.

²⁷ When sea-ice forms, that is associated with the ice-shelf, it loses its salt content to the underlying water (L. Carter, personal communication; Whitworth et al., 1998).

²⁸ Refer to Figure 4 from the B.Storey lecture of November 25, 2009.

²⁹ The role of the Weddell Gyre and Ross Gyre, in eddying surface water back from the ACC to feed these shelves, is crucial (Assman, Hellmer & Beckman, 2003; Fusco, Budillon & Spezie, 2009; Gordon, 1998; Rintoul et al., 2001).

4. *Possible impacts of climate change on the Antarctic Circumpolar Current and the Thermohaline Conveyor Belt*

(a) *The case for climate change impacts on the ACC and THC*

The literature that highlights possible climate induced changes in Antarctica, which may in turn lead to impacts on the ACC and THC, tends to focus on four key themes – warming around the Antarctic Peninsula specifically, ice shelf/sea ice loss generally, temperature increases/decreases for East Antarctica and changes to the ACC itself.

(i) Warming around the Antarctic Peninsula

It should be noted that the literature acknowledges that direct observations of climate change are sparse³⁰ and so often, reconstructions of past oceanic conditions need to be carried out through ice and sediment core analysis or climate models (Rahmstorf, 2002; K. Sinclair, Glaciologist, Geological and Nuclear Sciences, personal communication, November 23, 2009³¹). However, recent findings from direct observations indicate that the Antarctic Peninsula is warming rapidly (Montes-Hugo et al., 2009; Steig et al., 2009; Walsh, 2009).³²

It is clear from direct observations that the Antarctic Peninsula is one of the three fastest warming areas in the world (A. Clarke, personal communication; Clarke et al., 2006; Meredith & King, 2005; Stammerjohn, Martinson, Smith & Iannuzzi, 2008; Walsh, 2009) with a regional warming of 2.5°C since the 1940/50s (K. Sinclair, personal communication) and a mass loss increase by 140% since 1992 (Rignot et al., 2008).³³ Temperature increases are predicted to continue on the Antarctic Peninsula (B. Storey, personal communication).

(ii) Ice shelf/sea ice loss generally

Ice shelves are a key indicator of change as they are exposed to both oceanic and atmospheric changes (K. Sinclair, personal communication). And as A. Clarke and B. Storey state, the ice shelves also play an important role in buffering the ice sheets and glaciers from the effects of climate change (A. Clarke, personal communication; B. Storey, personal communication). When ice shelves are lost this leads to the accelerated loss of glaciers and ice sheets and this acceleration (or dynamic thinning) can endure for decades after ice-shelf collapse (Peck, Barnes, Cook, Fleming & Clarke, 2009; Pollard & DeConto, 2009; Pritchard, Arthern, Vaughan & Edwards, 2009; Rignot et al., 2008).

³⁰ Almost entirely post-IGY period.

³¹ Hereafter referred to as "(K. Sinclair, personal communication)".

³² These papers also indicate that there are signs of a significant temperature increase on the outer edge of the Ross Ice Shelf as well.

³³ This warming on the Peninsula has led to ice shelf collapses (eg, Larsen B and Wilkins), the retreat of glaciers and ice sheets and an increase in sea surface water temperature with consequent reduction in sea ice production (A. Clarke, personal communication).

The loss of the ice shelves in the Amundsen/Bellingshausen Sea, for example, has led to an increase in dynamic thinning of adjacent glaciers (Hellmer, Jacobs & Jenkins, 1998; Pritchard et al., 2009; Rignot et al., 2008) and an increase in sea surface temperatures and a marked reduction in winter sea ice production since the 1930's. The winter sea ice forms later and melts earlier, decreasing in extent by 10% per decade (A. Clarke, personal communication; Clarke et al., 2006; King, Firing and Joyce, 2001; Stammerjohn et al., 2008).

B. Storey states the mass balance of glaciers in the Ross Sea area are increasing and the glaciers in the Weddell Sea are in equilibrium, whereas the mass balance of the glaciers in the Amundsen/Bellingshausen Sea area are decreasing due to the loss of the ice shelf from this area – this makes the Amundsen/Bellingshausen Sea area the most vulnerable and unstable component of the West Antarctic Ice Sheet (“WAIS”) (B. Storey, personal communication).

As a result, B. Storey is predicting a continued reduction in the WAIS (B. Storey, personal communication).³⁴ These predictions for the WAIS are supported by Conway, Hall, Denton, Gades and Waddington (1999) which shows the WAIS has retreated 1300km since the Last Glacial Maximum (LGM) and by Pollard and DeConto (2009) who refer to the high frequency of glacial/interglacial cycles that have occurred in the WAIS.

Gammelsrod et al (1994) state that Weddell Deep Water has also increased in temperature (0.7°C between 1977 and 1992/93) and that Ice Shelf Water (ISW), once dominant in the Filchner Depression and the Berkner Shelf, is no longer found. This may indicate future mass balance reductions for glaciers in WAIS.

(iii) Temperature increases/decreases for East Antarctica

A. Clarke believes there is no ‘significant’ records of warming for the East Antarctic Ice Sheet (“EAIS”) (A. Clarke, personal communication). This view is supported by Anderson, Shipp, Lowe, Wellner and Mosola (2002) who state that the WAIS and EAIS have not advanced or retreated in concert. The view expressed by A. Clarke is also supported by Wingham, Shepherd, Muir and Marshall (2006) that states there has been a mass gain for East Antarctica and this gain also exceeds the mass loss for West Antarctica.

However, Rignot et al (2008) state there has been a small loss of mass in the EAIS and A. Brown refers to yet to be published data from Muto et al that suggests the EAIS has warmed by 0.1-0.2°C per decade since the IGY (A. Brown, United States Antarctic Program, personal communication, December 4, 2009). This is consistent with the results presented by Turner et al (2005).³⁵

³⁴ These predictions could not be made confidently prior to the advent of satellite-based laser altimetry (Oppenheimer, 1998).

³⁵ Climatic models also suggest that both the West and East Ice Sheets are vulnerable to climate change caused by increasing atmospheric CO₂ levels (Huybrechts & Wolde, 1999).

(iv) Changes to the ACC itself

Gille (2002) states that there have been temperature increases in the Southern Ocean³⁶ at ~700 to 1000m depths (0.17°C between the 1950s and the 1980s) and that these are concentrated in the ACC. Clarke et al (2006) and Hattermann and Levermann (2009) state there has been a weakening of the ACC with climate change. Fyfe and Saenko (2005) state there has been a consequential southward shift of the ACC by approximately 50km.

(b) *Possible impacts from these climate induced changes*

In terms of possible impacts, again, the climate change literature tends to focus on key themes – the difficulty in predicting change, the reduction in AABW (and/or NADW) production leading to THC changes and changes to the ACC itself.

(i) Difficulty in predicting change

It is very difficult to predict climate-change induced impacts on the ACC or THC because these systems are a far more complicated array of gyres, eddies and countercurrents than can be described in this review. Many components of the ACC and THC are still poorly understood and the world's oceans are such a key players in driving climate systems that this also makes predictions difficult (Carter & Cortese, 2009; Kunzig & Broecker, 2009; Rahmstorf, 2002; Wunsch, 2007).³⁷ Global scale observations are clearly needed (Wunsch, 2001).

Predicting change will also be very difficult because humans have altered these environments so much already (A. Clarke, personal communication; Clarke & Crame, 1992). And Broecker (1987) suggests that we do not have sufficiently recent environmental markers to guide us with predicting the super-interglacial conditions we are creating for ourselves.

Although many scientists believe there is a low likelihood of rapid climate change due to the collapse of the THC (Arnell, Tompkins & Adger, 2005; Kunzig & Broecker, 2009). Broecker (1987) and Broecker (1997) state there is evidence in sediment core samples that suggests climate change impacts may cause sudden rather than gradual shifts in the THC.

(ii) Reduction in AABW or NADW production leading to THC changes

B. Storey suggests there will be changes in the THC if or when sea temperatures rise sufficiently (B. Storey, personal communication). Grassl (2001) states that changes to the formation of AABW may lead to abrupt changes in the THC but he bases this statement on work conducted in the Arctic region.

³⁶ Which exceed the average increases for all other oceans.

³⁷ For example, changes in sea surface temperature will alter the heat and freshwater evaporation exchange with the atmosphere which in turn may either lead to climate stability or variability (Rahmstorf, 2002; Van Aken, 2007).

Using sediment core samples, it has been demonstrated that NADW formation all but ceased in meltwater events in the past (Clark, Pisias, Stocker & Weaver, 2002; Rahmstorf, 2002; Sarnthein et al., 1994; Seidov & Haupt, 1997; Seidov, Sarnthein, Statterger, Prien & Weinelt, 1996). This could occur to AABW, LCDW and UCDW with continued ice-shelf collapse and loss of sea ice³⁸ (Kellogg, 1987; Seidov, Barron & Haupt, 2000; Stossel et al., 2002).

The loss of certain currents such as the AABW or NADW may severely alter the THC conveyor belt leading to less or no inter-hemisphere mixing of currents and then possibly the upheaval of climate with the Southern Hemisphere warming and the Northern Hemisphere cooling (Kunzig & Broecker, 2009; Rahmstorf, 1997; Rahmstorf, 2002; Sarnthein, Grootes, Kennett & Nadeau, 2007; Seidov et al., 2000; Van Aken 2007; Vettoretti, d'Orgeville, Peltier & Stastna, 2009).

It may be assumed that cooling in the Northern Hemisphere will lead to an increase in NADW production,³⁹ however, analysis of sediment samples has shown that NADW production slows during glacial maximums due to ice shelf formation out to the edge of the continental shelf (Broecker, 1987; Rahmstorf, 2002; Sarnthein et al., 1994; Seidov et al., 1996).⁴⁰ It has been suggested that the same occurs for AABW during glacial maximums (Kellogg, 1987).

A positive feedback loop may develop with reduced AABW production⁴¹ where a warmer Southern Ocean leads to a warming of the atmosphere, exacerbating global warming and ice-shelf collapse and thus reducing the development of AABW further still (Meredith & King, 2005; B. Storey, personal communication).

(iii) Changes to the ACC itself

B. Storey stated that the Drake Passage would need to be closed to shut down the ACC itself (B. Storey, personal communication) and Boning, Dispert, Visbeck, Rintoul and Schwarzkopf (2008) states that the ACC is insensitive to decadal change due to wind stress. However, the findings of Clarke et al (2006); Fyfe and Saenko (2005) and Hattermann and Levermann (2009) suggest that the ACC will be warmer which could increase ice shelf and sea ice melting and thus hasten the demise of the THC.

Conclusions:

Thanks to the work of oceanographers, substantially progress has been made in developing our understanding of the THC and ACC. It is clear from this work that the ACC is a critical component of the THC.

The literature that highlights possible climate induced changes in Antarctica, which may in turn lead to impacts on the ACC and THC, tends to focus on four key themes –

³⁸ Which are so crucial to the development of AABW especially.

³⁹ Which could compensate for the loss of AABW production.

⁴⁰ NADW forms south of Iceland during glacial maximums, rather than where it is currently forms in the Nordic Sea.

⁴¹ Resulting from ice-shelf collapse and loss of sea ice.

warming around the Antarctic Peninsula specifically, ice shelf/sea ice loss generally, temperature increases/decreases for East Antarctica and changes to the ACC itself.

Current research findings demonstrate that there is great uncertainty about the nature and extent of climate change and indeed the impacts of climate change on the ACC and THC. In terms of possible impacts, again, the climate change literature tends to focus on key themes, such as the reduction in AABW (and/or NADW) production leading to THC changes and changes to the ACC itself.

More research is required and more data needs to be collected. Use of climate models and ice/sediment core analysis is essential but direct observations will be critical. Increased collaboration amongst scientists of all nations will greatly assist.

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Appendix 1: Developing our understanding of the THC – a brief history

Van Aken (2007) acknowledges the work of Italian Luigi Ferdinando in the 17th century, stating that Ferdinando was the first to make reference to oceanic flow being driven by differences in density from his observations of the flow of the Bosphorus. Kunzig (2000); Kunzig and Broecker (2009) and Van Aken (2007) all credit the work of Captain Henry Ellis, skipper of the British slave ship *Earl of Halifax*, with the earliest recorded identification (in 1751) of varying water temperatures with depth. Whilst at sea in the tropics near the Azores, Ellis identified and recorded the existence of a cold water layer a mile deep.

Benjamin Thompson Rumford (also known as Count Rumford) was the first to grasp how convection currents might operate in the ocean (in the 1790's approximately). Rumford recognised the significance of the recordings made by Captain Ellis. Rumford's theory was that cold water must be flowing along the bottom of the ocean from higher latitudes and that warmer surface water currents must be travelling towards the poles. He believed there was no other way that Captain Ellis could have recorded the existence of such cold water in the tropics (Zunzig, 2000).

In subsequent decades, oceanographers made little progress on developing an understanding of ocean physics but data collection continued never the less. In the 1870's, the British ship *Challenger* followed the work of Captain Ellis in a systematic manner by taking measures of temperature movement at varying depths right across the world. Rice (2000), a British author, states that the first substantive, world-wide study of oceanography was carried out by the HMS *Challenger* from 1872-1876. The German vessel *Meteor* then recorded extensive density measurements in the Atlantic between 1925 and 1927 (Kunzig, 2000). Kunzig (2000) states that it was the measurements taken by the *Meteor*, above all others, that led to the understanding we have today regarding the thermohaline system that exists in the Atlantic.

Kunzig (2000); Kunzig and Broecker (2009) and Wunsch (2001) then refer to the work of American Henry Stommel in the mid-1940's onwards, regarding his findings on the Gulf Stream and on his predictions about the deep currents that operate in the Atlantic (now known as the North Atlantic Deep Water). Wunsch (2001) refers also to the important oceanographic work conducted by Sverdrup in the 1940's.