Abrupt Climate Change and Multistability of the Thermohaline Circulation

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Abstract

Ice core records suggest that the Earth's climate has undergone rapid, catastrophic shifts on multiple occasions in geologically recent times. The multiplicity of steady states found in fluid convection models has led many to speculate that the changes may have been caused by transitions between different stable modes of ocean current patterns. This paper reviews analytical and numerical modeling of multistability in the thermohaline circulation with particular reference to bifurcation analysis. The relevance of these models to paleoclimate data and contemporary observations is discussed.

1 Introduction: Challenges to Uniformitarianism

The foundation of the modern earth sciences is generally taken to be the work of James Hutton, who based his theories on the doctrine that the earth's features can be explained as the result of the same slow processes that occur today gradually directing massive change over the course of enormous spans of time, an idea known as uniformitarianism. This postulate was adopted by all of the earth sciences, and has been enormously successful and scientifically satisfying. However, over the past 30 years climatologists have had to back away from the assumption of gradual, linear changes as new types of data have indicated that the climate has undergone large changes occurring much faster than was thought possible.

The earliest serious objection to uniformitarianism in climatology was the recognition in 1837 by Agassiz that many confusing geological features were well-explained by positing a period of the past during which much larger portions of the earth were covered by ice. In his time, many of Agassiz's colleagues dismissed his theories as heretical vestiges of catastrophism, but later work has demonstrated that ice ages fit within a gradualist view of the earth. Deep-sea sediments have allowed us to produce a convincing timeline of glaciation, and the results broadly confirm the theories of Milankovitch, who suggested that slow changes in the shape of the earth's orbit are responsible [1].

In the 1970s, a remarkable effort to dig up and analyze deep ice cores in Greenland brought an exciting twist. The records of snow accumulation contained in the cores confirmed the sediment observations, but also showed "miniature ice ages", periods of accumulation intermediate between the glacials and interglacials [2], later christened Dansgaard-Oeschger oscillations. These episodes came and went too quickly to register in the deep-sea sediments, which have a time resolution limited by the shifting caused by worms, and in fact too quickly to be satisfactorily explained within the uniformitarian paradigm.

There was speculation from early on that Dansgaard-Oeschger oscillations might be evidence of the existence of multiple stable states of the climate, and interest in the physical mechanism for this soon alighted on the thermohaline circulation [3]. It is well known that in the presence of a thermal gradient, fluids transition from a uniform to a convecting state at a critical Rayleigh number. This fact, together with the important role played by the thermohaline circulation in controlling the climate, made it a natural locus for bistability and the subject of intense research that continues today.

2 Background on the Thermohaline Circulation

The very definition of the thermohaline circulation is a controversial matter [4]. This paper will follow Rahmstorf [5] by taking the thermohaline circulation (THC) to be that part of the circulation of ocean waters "driven by fluxes of heat and freshwater across the sea surface and subsequent interior mixing of heat and salt." The other main drivers of ocean circulation are tides and the wind. The THC is not a physically separate entity, and cannot be measured independently of the other components of the general circulation, though it can be modeled independently. Much of this paper specifically concerns the Atlantic meridional overturning circulation (AMOC), which is the physically observable circulation pattern that is believed to be the chief manifestation of the THC in the Atlantic ocean.

The global THC forms a large loop through all of the oceans, but the AMOC is especially interesting and important. On the surface, Atlantic currents flow mostly north carrying warmer equatorial waters to high latitudes. In the north the water is cooled, and some of it changes phase. The North Atlantic experiences a net excess of evaporation over precipitation annually, and together with the formation of sea ice this increases the salinity. The resulting cold, salty water is denser than its surroundings, and it falls to a deeper level of the ocean. This descent occurs not throughout the bulk, but only at a few discrete locations in the Labrador Sea and the Greenland Sea, labelled as stars in figure 1. Remarkably, the ocean circulation is stratified – rather than a linear decrease in temperature with depth, there are distinct layers with sharply different temperatures flowing above one another. The North Atlantic deep water (NADW) flows southward at a depth of 2-4 km [6], underneath and contrary to the warm surface water (the NADW is in turn undercut by the Antarctic Bottom Water, an even colder and denser mass that forms in the Weddell and Ross seas). In the southern hemisphere much of the NADW rises and flows northward to complete the cycle, though some portion passes through the Indian and Pacific oceans at depth before returning after hundreds of years to the Atlantic surface.

The AMOC has several important effects on the global climate. It is responsible for a significant portion of total heat transport to the North Atlantic [3]. The absence of this heat would have severe effects in itself and these would be amplified by the increased formation of sea ice, as the greater albedo of the enhanced ice cover would alter the Earth's radiation budget significantly, further cooling the planet. Also, the ocean contains significant amounts of carbon dioxide so the disruption of currents could have unforseen effects on the composition of the atmosphere with further implications for climate. Detailed simulations of an AMOC shutdown find that the Northern Hemisphere would cool $1-2^\circ$ on average, and up to 8° locally in Central and Northern Europe. Global net primary productivity of vegetation would decrease by 5%, surely resulting in the starvation of multitudes [8].

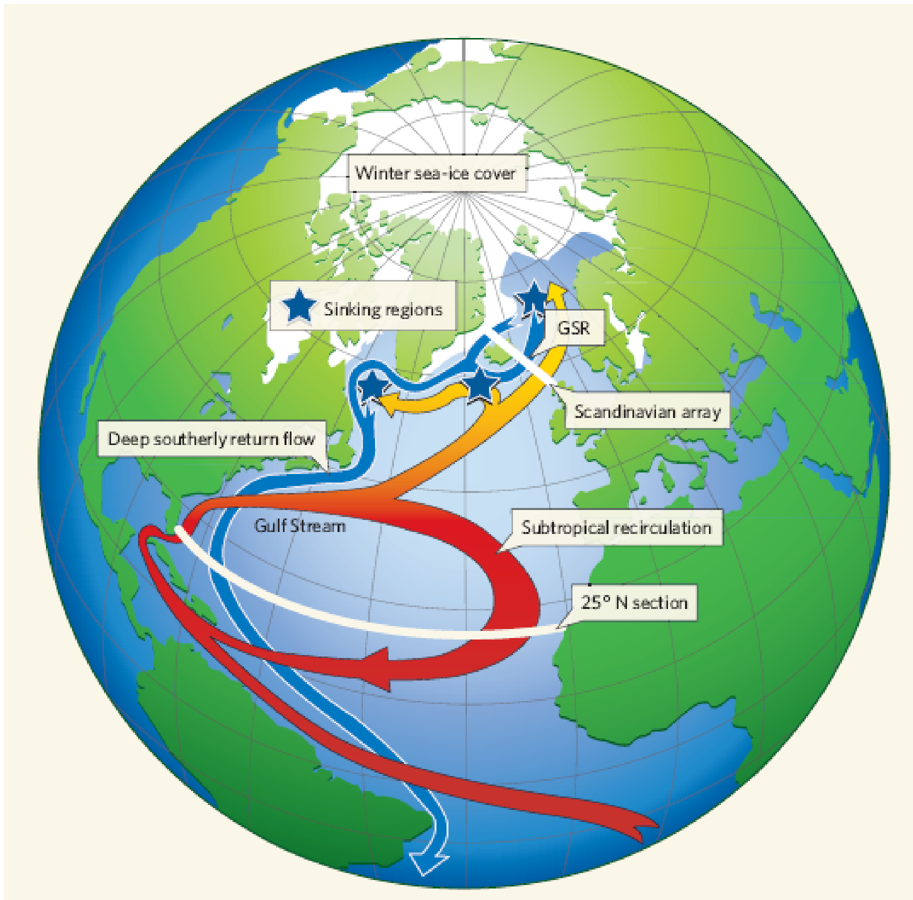

Figure 1: A schematic depiction of the AMOC. Warm surface currents (red) flow north, while cold deep water (blue), formed at sites labeled by stars, flows south. Two circulation observation arrays are drawn in as white lines. The GSR is the Greenland-Scotland Ridge, an undersea topographical feature. From [7].

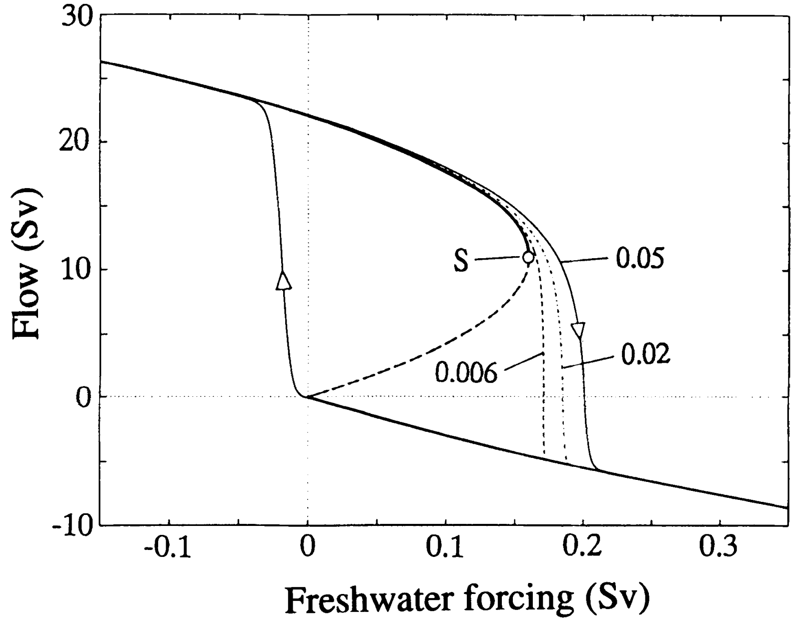

Figure 2: The Stommel bifurcation diagram in the context of ocean circulation. Flow is measured in sverdrups(Sv); 1 Sv = $10^6 m^3 s^{-1}$. From [10].

3 Numerical and Analytical Studies

3.1 Early Box Models

The foundational paper on the analysis of the THC is by Stommel [9], who proposes and analyzes three simple "box models". This paper culminates in the analysis of the equilibrium solutions of a system in which two vessels connected to reservoirs are joined by a capillary that exchanges heat and salt. In the particular case considered, one reservoir is warm and salty, the other cold and fresh. The flow through the capillary is proportional to the difference in density of the two water masses, which is taken to be a linear function of temperature and salinity. Upon substituting the equation of state into the equations governing the evolution of the water masses, Stommel finds two coupled nonlinear equations. In some parameter regimes there are three steady state solutions, two of which are stable. These two stable modes have opposite directions of flow, which he interprets as a competition between temperature and salinity effects on density.

Stommel's analysis of the bifurcations is not very general or sophisticated (a full bifurcation diagram given by later workers is presented in figure 2), and he devotes much of his attention to a particular numerical example that may not be relevant to reality. However, the basic bifurcation he observes is found in modified form in more realistic models, and he presciently noted that "the system is inherently fraught with possibilities for speculation about climate change." He suggests that a slight change in parameters or a perturbation into another basin of attraction could send the flow in estuaries or oceans into very different steady states. In the context of the THC, Stommel's bifurcation leading to the reversal of the flow direction was the original proposed mechanism of THC disruption leading to abrupt climate change [3], but more accurate models have found other steady states.

3.2 General Circulation Models

The increased interest in the THC generated by speculation surrounding its role in paleoclimate change prompted investigators to move beyond simple box models, and improvements in computational resources made semi-realistic simulations of ocean circulation feasible. A notable work investigating bifurcations in the THC numerically is by Bryan [11], who observes the emergence of asymmetric circulation in a system with equatorially symmetric boundary conditions and geometry. Bryan's simulation is an example of a general circulation model (GCM), a broad class of commonly-used simulations which directly simulate the fundamental equations of motion on a grid. This GCM uses a finite difference method to predict the temperature and salinity in a three-dimensional rectangular grid, representing an idealized Atlantic Ocean. The basic model has a fixed salt flux at the surface, with heat flux determined by a newtonian cooling law, and the inital conditions are equatorially symmetric.

Previous work with box models had led to speculation that equatorially symmetric circulation would be unstable to infinitesimal asymmetric perturbations towards an asymmetric circulation. Bryan finds that in fact there is a basin of attraction for the symmetric state, but it is unstable to relatively small finite perturbations. In various experiments it is found that the addition or subtraction of freshwater stops the formation of deep water and thus halts the THC, with the establishment of a pole-to-pole circulation mode thereafter. Overturning circulation in both the clockwise and counter-clockwise directions are stable. The time needed to establish the asymmetric mode depends strongly on the sign of the freshwater input, with an increase in salinity taking much longer to reestablish convection than a decrease.

Bryan's work is compelling evidence for the spontaneous breaking of equatorial symmetry in ideal thermohaline circulation, but as the author notes there are many reasons to question the applicability of the results to reality. The model neglects important climate components, notably the effects of sea ice and the coupling to the atmosphere. Feedback effects on the salinity flux are not accessible with these boundary conditions. It is also unclear whether multistability would be maintained under asymmetric boundary conditions and geometry, such as obtain in the real world.

An improved GCM addresses some of these shortcomings by coupling a realistic atmosphere to the ocean and applying realistic geometries and boundary conditions [12]. In this paper Manabe and Stouffer find two stable modes, one with an AMOC rotating in the same direction as is observed in reality, and one with no AMOC. This is later reinterpreted as a weak reverse AMOC [13], and claimed to be a manifestation of the Stommel bifurcation. The authors speculate that the realistic geography is responsible for the weakening of the reverse AMOC solution, but no systematic investigation is attempted. A comparison of temperature distributions in the AMOC and no-AMOC states is shown in figure 3.

High computational costs prevented Manabe and Stouffer from seeking a detailed understanding of the bifurcations in their model. A thorough investigation of this topic in a simplified coupled ocean-atmosphere GCM finds the bifurcation diagram shown in figure 4 by slowly changing the freshwater flux in the north Atlantic. Like Manabe, Rahmstorf finds a Stommel bifurcation, but his AMOC state shows extra structure. There are multiple circulation patterns possible, corresponding to deep water formation in different locations. Rahmstorf also locates a Hopf bifurcation, a transition to a steady oscillation of the AMOC strength with a period of 22 years. The threshold to pass the Stommel bifurcation is found to be about 0.06 Sv, a much lower figure than found in previous studies. Rahmstorf notes that this route to a bifurcation is rather slow, with AMOC shutdown occuring gradually over hundreds of years. He considers shifts in deep water formation sites to be a more plausible mechanism for rapid climate change, and finds that a pulse of only 0.015 Sv directly into the Labrador Sea is enough to shut down regional convection.

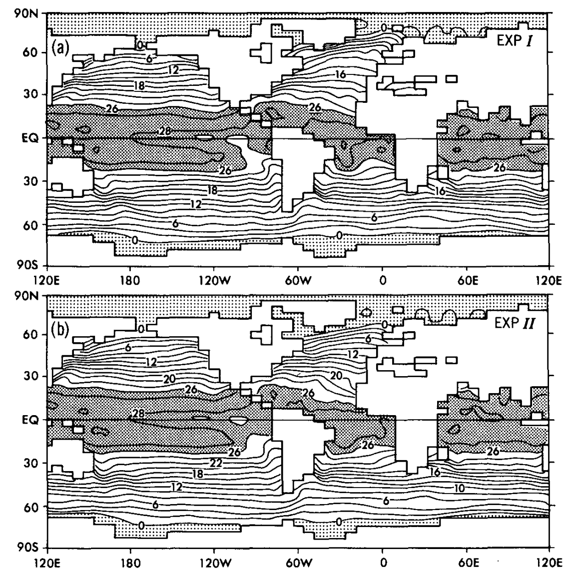

Figure 3: Temperature distributions in two steady states of a GCM model. Top panel has AMOC, while bottom panel does not. It can be seen that without the AMOC, the North Atlantic is considerably colder. From [12].

3.3 Boussinesq Models

Much of the work of the previous section aims at finding multistability in models that are as realistic as is computationally feasible. These efforts are strongly linked to climate change research; indeed, the work of Manabe and Stouffer seems to be a mere

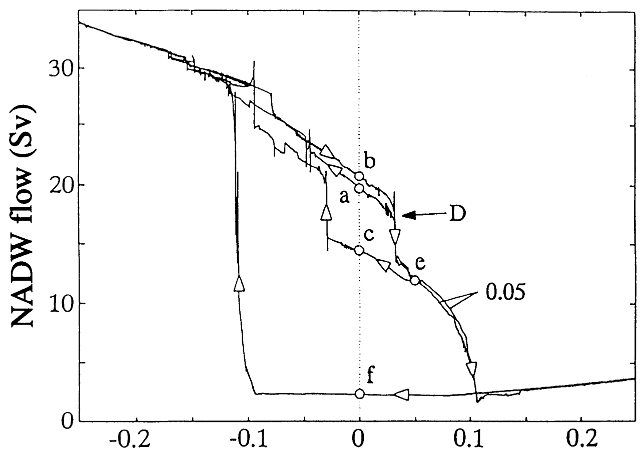

Figure 4: Points a, b, and c are AMOCs with deepwater formation in different locations. Point f is a stable solution lacking the AMOC. D labels the Hopf bifurcation. The x-axis is freshwater forcing in Sv. From [10].

sideline in an extremely ambitious investigation of the greenhouse effect. Another line of research explores a simpler model in greater analytic detail, with more concern for the connections to fluid mechanics and bifurcation theory. Quon and Ghil [14] study a two-dimensional Boussinesq model coupled to a salinity field, an extension of Rayleigh-Benard convection that is reported to be much more difficult and somewhat understudied. The symmetric to antisymmetric transition found by Bryan is investigated as a function of the Rayleigh number and salt flux. The question of boundary conditions weighs heavily on many people interested in this problem, because observations of oceanic salt input are scanty and different types of boundary conditions produce qualitatively different results. Quon and Ghil find that the symmetric state is always stable when the surface salinity is fixed; bifurcations only occur when a salt flux is prescribed, which the authors consider to be a more realistic condition. The transition is also found not to occur in the absence of a salinity field, i.e. in regular Rayleigh-Benard convection.

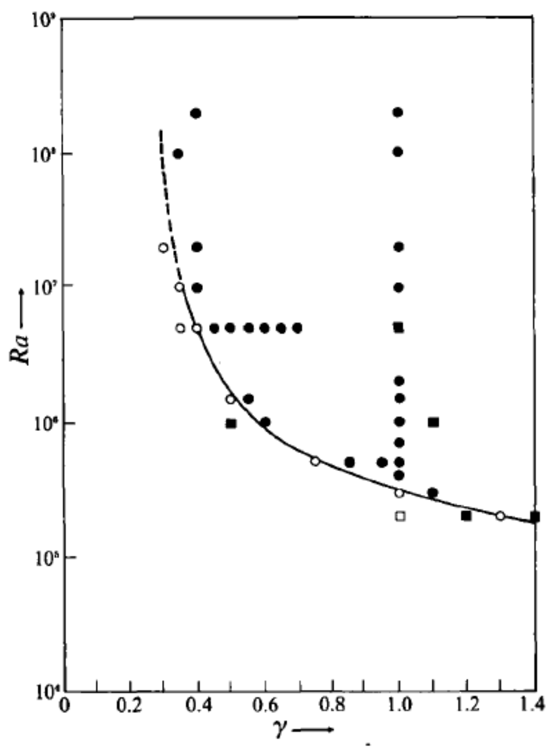

Figure 5: Neutral stability curve in the Ra-γ plane, from [14].

In their simulations a symmetry breaking bifurcation is found to occur when either the Rayleigh number or salt flux is increased. Previous workers had only noticed the latter bifurcation because of their use of high Rayleigh numbers appropriate to actual ocean conditions. Quon and Ghil numerically determine a neutral stability curve (figure 5) and find a supercritical pitchfork bifurcation curve for the salt flux γ (figure 6). They are keen to point out that the transition to asymmetry is not as abrupt as previous work had implied – their stable dominant cell grows gradually as the Rayleigh number is increased.

Cessi and Young [15] analyze the small aspect ratio limit of the problem and produce for the salinity field an amplitude equation that displays multiple stable equilibria. However, the result is only possible because of various unrealistic assumptions, in particular a very low Rayleigh number and a very high vertical diffusion that is incompatible with the observed stratification of the ocean.

A series of papers by Dijkstra and coauthors use more advanced numerical methods to probe the bifurcation structure of the 2D Boussinesq model in detail. In [16] they find a Hopf bifurcation in the system, consistent with the GCM results of Rahmstorf and others. These authors have a particular interest in the effects of aymmetric boundary conditions on the symmetry breaking transitions, a problem they refer to as "imperfection theory". In [17] they investigate the model in an equatorially asymmetric geometry meant to approximate the Atlantic basin. It is found that the supercritical pitchfork bifurcation of Quon and Ghil becomes detached, producing a new stable branch associated with a weak northern-ocean-sinking THC, again consistent with GCM results.

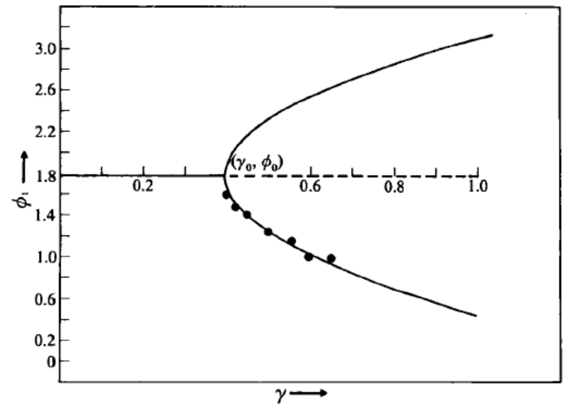

Figure 6: Bifurcation curve in γ, from [14].

4 Observational Data

4.1 Ice Cores and Ocean Sediments

The transformative advance that made abrupt climate change a topic of serious research was the acquisition of deep ice cores chronicling the past 300,000 years. The first such core was drilled in 1968 at Camp Century, a U.S. army base in the far north of Greenland. Methods were developed to infer surface temperatures from the ratio of oxygen isotopes in the ice, and the observed fluctuations were suggestive but inconclusive; the orthodox response was to attribute them to local events. In 1981 the Greenland Ice Sheet Program team finished drilling a 2035 meter core at a site in southern Greenland called Dye 3, and the correlation with the Camp Century data was stunning (figure 7). Further confirmation of the most recent abrupt climate change event (called the Younger Dryas) by lake sediments and pollen records in Europe convinced researchers of the global significance of the data.

The tie between the Dansgaard-Oeschger (DO) oscillations and the AMOC was suggested by CO_2 fluctuations found by Oeschger, the ocean's role as a carbon reservoir, and the known bistability of fluid convection models. The CO_2 oscillation turned out to be an artefact [18], but the relationship remained compelling. Carbon isotope ratios in deep sea foraminifera shells provided early evidence that NADW formation was in fact suppressed during the Younger Dryas [19]. North Atlantic sediment data compiled since then suggests that the AMOC has displayed three distinct modes: a strong AMOC as we enjoy today, a weaker AMOC where NADW formation is shifted south, and a mode without AMOC [6]. Shifts between these modes are found to correlate well with the DO oscillations [20], but cause and effect are difficult to disentangle.

4.2 Recent Observations

All of the speculation about the possible dramatic effects of changes in the AMOC might induce one to pay closer attention to the current state of the ocean circulation. Direct ongoing measurements of circulation in the Atlantic have only begun recently with the inauguration of the RAPID circulation monitoring system and the results have been controversial. In 2005, Bryden et al. [21] reported observations of the circulation at all depths along the 25° N latitude running from Florida to North Africa, made with regularly spaced permanant devices running along cables from the surface to the ocean floor. This early data was compared with intermittant measurements made in previous decades, and a 30% decrease in AMOC circulation over the past 50 years was claimed. The authors acknowledged that the changes were uncomfortably close to the uncertainties associated with unknown natural variability and local eddies, but felt that suggestive patterns in the depth profiles of the temperature and circulation strengthened the case for a real decline. The paper triggered a flurry of popular distress.

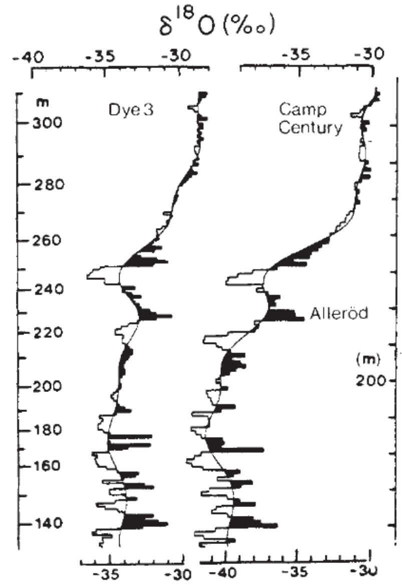

Figure 7: Comparison between the Camp Century and Dye 3 ice cores, from [2].

After observing the circulation over a longer timespan, the RAPID collaboration found that the AMOC naturally displays huge seasonal variations, rendering the previous results meaningless [22]. Bryden's results were judged to be merely a particularly low fluctuation, and the net effect was to underscore how little is known about the actual state of the Atlantic circulation. Bryden himself maintains that the aforementioned depth profiles and independent measurements indicating freshening of deep water in the Bahamas still suggest a 10-15% decrease in the AMOC. Presumably future reports by the RAPID collaboration will resolve some of the confusion.

5 Conclusions

Much is uncertain about the THC/AMOC, its steady states, and its role in past climate change, but some important results have been established. General thermohaline flow has been shown to display spontaneous symmetry breaking from an equatorially symmetric state, resulting in a bistable system for realistic parameter values. When imperfections like asymmetric geography or surface conditions are imposed, the bifurcation diagram changes to resemble that found in GCM models, yielding a set of steady states compellingly similar to those attested to by paleoclimate records. Although causation has not been established for past events, simulations indicate that changes in the AMOC could have serious effects on surface temperatures. Thus, while further study is needed to resolve the questions of paleoclimatologists, improved monitoring and modeling of the current AMOC are necessary to understand the threat posed by abrupt climate change.

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