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Otto Pettersson's ideas on general ocean circulation

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Originally a physical chemist, Pettersson became deeply interested in physical and chemical oceanography (hydrography) when analysing measurements of the "Vega" expedition in 1878–1880 around Eurasia. He wrote a paper on ice conditions in which he displayed fascination for the relationship between the system of ice formation in the Arctic Ocean and the melting far to the south. At the turn of the century, he published his hypothesis stating that melting ice caused deepwater movements. A 10-year heated debate began between Pettersson and Nansen, who favoured atmospheric cooling and (possibly) ice formation as the cause of deepwater flow. Pettersson was skeptical of Zöppritz's hypothesis that the wind, apparently driving the equatorial surface currents, would be able to penetrate to the bottom and thereby drive deep currents. When Ekman presented his theory in 1902, in which the wind current was shown to be very shallow, Pettersson was pleased. When the same author demonstrated three years later that the wind in the presence of coasts could make its influence felt at the greatest depths, Pettersson protested. Concerning the recent appreciation of the North Atlantic Oscillation, there is a link back to Pettersson. His article in 1896 was highly appreciated by Meinardus because it connected the Gulf Stream Extension variations with a meteorological parameter (air temperature). Meinardus, however, showed atmospheric pressure to be a much more practicable tool. In the opinion of the present author, Pettersson had an early but realistic view of the currents of the Nordic Seas. Later, however, he found that a pattern complying with his ice-melting hypothesis also explained the transport of Arctic plankton to the Skagerrak.

Keywords: deepwater formation, Gulf Stream, ice melting, ocean circulation, Otto Pettersson, thermohaline force, wind force.

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Introduction

In my Centenary lecture in Stockholm in 1999, I referred to Otto Pettersson as the Father of ICES, and perhaps ICES was his greatest achievement. He was, however, also a producer of many scientific articles in most branches of oceanography. In that context, he is less well remembered, possibly because he asserted views that differed from the mainstream.

Pettersson began his scientific career as a physical chemist in Uppsala in 1874 and was professor in general chemistry in Stockholm during the period 1884–1909. He authored some 60 papers on "pure" chemistry in the period 1870–1895. As a kind of side-track, he presented his first tentative ideas in 1878 on the role of ice in the oceans. In 1881, he was asked to process the hydrographic measurements made during the Swedish "Vega" expedition along the Siberian coast, when Nordenskiöld was the first to sail the Northeast Passage. In doing this, Pettersson became so interested in the complex nature of ocean ice problems that he wrote a separate article on the subject. He later enlarged the scope of his inquiry to embrace the role of ice melting within general ocean circulation, a point referred to later.

Even before the "Vega" work, Pettersson observed that his lifelong friend, Gustaf Ekman, had measured temperature and salinity in connection with the new herring period, which began in the winter of 1877/1878. Pettersson worried that these important observations would not be continued, especially because catches continued to rise each year, making it indisputable that a new herring period had, in fact, arrived. Fortunately, Pettersson's concern resulted in a synoptic survey by five Swedish ships during a winter week in 1890, organized by the two pals, as well as a comprehensive account of it written by them a year later. Thereafter, Pettersson organized a five-country, cooperative survey in 1893–1894, and was the main promoter of ICES between 1897 and 1902.

Finally, Pettersson carried out current measurements in 1907 which, to his surprise, unmasked features that he correctly interpreted as semidiurnal internal tidal waves. Diurnal measurements of temperature and salinity made at Bornö Station (on a Skagerrak fjord) from 1909 onwards also showed the existence of internal movements, including those of semi-monthly and monthly periodicity. Pettersson believed even these to be of tidal character. Gradually his interest was transformed into longer tidal periods which were woven into articles he wrote about climate in the ensuing years.

For the purpose of this paper, the Atlantic Ocean has its northern boundary along the Greenland–Scotland Ridge. North of the Ridge, the Nordic Seas extend as far as the Arctic Ocean. The "Gulf Stream Extension" is defined in the next paragraph.

The Gulf Stream Extension

Pettersson (ca. 1884) is an unpublished manuscript titled "Ocean circulation in the Northern Hemisphere". Although undated, it may have been written in 1884 or 1885 because of a reference to "Boguslawski's recently published Handbook", i.e., 1884. In the manuscript, he demonstrated wide reading; for instance, von Middendorff (1871), on whose opinion of the Gulf Stream Extension he commented:

> He extended the dominions of the water system of the Gulf Stream even to the Siberian Sea because the relatively warm climate of the Taimur peninsula could not well be due to any other source than an influx of warm Atlantic water into the Siberian Sea even in winter.

The water system of the Gulf Stream will henceforth be referred to as the "Gulf Stream Extension". It begins where the cold Labrador Current meets the northern end of the Gulf Stream proper. Its northeasterly continuation, the North Atlantic Current, is broad and not well defined. The Norwegian Current along Norway and its continuation into the Arctic (Quadfasel *et al.*, 1991) are, however, fairly easy to identify.

In connection with the processing of the "Vega" observations, Pettersson searched in vain for "Gulf Stream" water in the data. Actually, the warm nucleus was later found to be positioned much further offshore than the "Vega" course. Nevertheless, claiming that a summer of measurements as insufficient to solve the question, he continued to side with those who believed in the vast climatic influence of the Gulf Stream. In particular, he opposed A. G. Findlay (see Peterson *et al.*, 1996), who announced ca. 1870 that the dimensions of the Gulf Stream and likewise its influence on the climate of Europe had been extremely overrated.

Pettersson (1896) demonstrated the time variations of the Gulf Stream Extension by means of water temperatures measured at coastal stations in the Nordic Seas. These variations were shown to correlate with variations in air temperatures in central Sweden. The German meteorologist Meinardus (1898) applauded this initiative, but suggested using spatial differences of atmospheric pressure instead of coastal water temperatures. What Meinardus (1898) proposed was approximately what we today call the NAO (North Atlantic Oscillation), mediated to us by Walker (1924).

Do wind or thermohaline forces drive ocean circulation?

As demonstrated in Krümmel's *Handbook of Oceanography* (1907–1911) and also described in Peterson *et al.* (1996), there were, by the middle of the 19th century, two schools of thought regarding what drives ocean circulation. One considered that temperature differences between pole and equator drove ocean circulation. The other school pointed to the obvious part played by trade winds in driving equatorial currents. Pettersson can be identified with the first school, referred to as the Thermohaline School, because he considered salinity equal in importance to temperature. The Wind School in 1878 was reinforced when Zöppritz presented a mathematical treatment showing that wind could influence water at the greatest depths of the ocean as long as sufficient time were allowed for what he considered a slow process. Pettersson may have grown skeptical of the wind theory when studying the Swedish scientist Cronander's processing of Kattegat current measurements made in the 1860s. Because the time variations had been very much faster than demanded by Zöppritz's theory, Cronander (1898) drew the conclusion that they could not be caused by wind.

Walfrid Ekman (in a paper written in Swedish) revised Zöppritz's theory by including the influence of the earth's rotation as well as using turbulent coefficients of viscosity. Pettersson was now satisfied that the influence of the wind was limited to a shallow surface part of the ocean and time variations very much faster than in Zöppritz's theory. The satisfaction was short-lived, however, as three years later Ekman (1905) demonstrated that the presence of coasts indirectly allowed the wind to be influential to great depths. This assertion was too much, and Pettersson refused to accept it. Recall that in Ekman's theory, the water is assumed to have a constant density. Oceanographers later combined aspects of the two hypotheses, realizing that thermohaline stratification often significantly modifies the influence of the wind.

Pettersson did not even accept that the fairly shallow Nordic Seas portion of the Gulf Stream Extension could be wind-driven. "How can the wind drive the Gulf Stream Extension when it has been converted to a subsurface current from Spitzbergen to the Siberian islands," he asked. Pettersson at first pretended not to have seen the above-mentioned suggestion by Meinardus (1898) for measuring the strength of the Gulf Stream Extension. He admitted later that he had been unwilling to accept wind forcing since this would have been the consequence of using atmospheric pressure

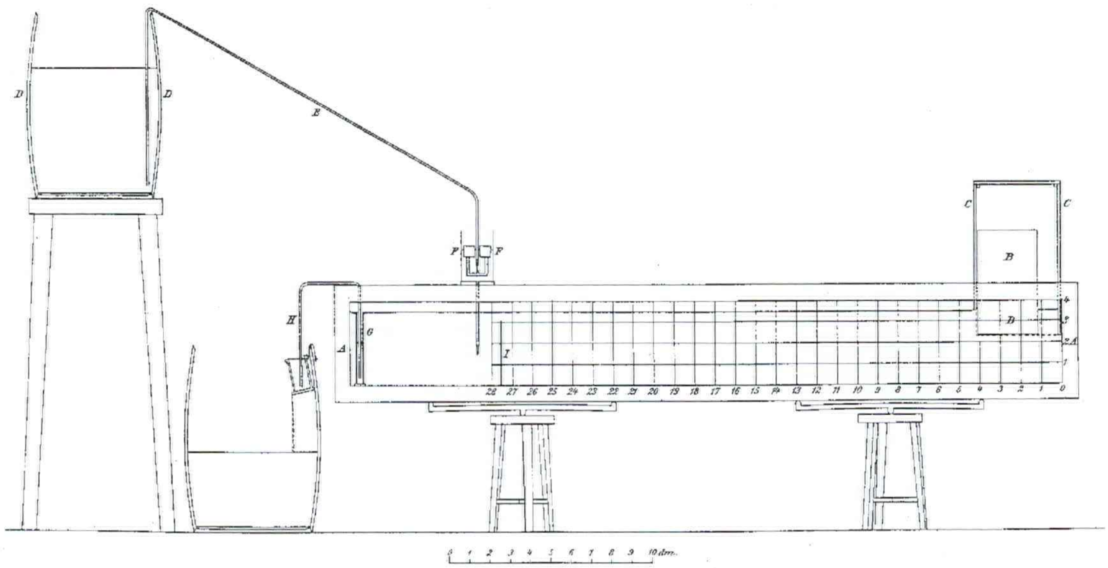

Figure 1. Arrangements for the model experiment carried out by Sandström. A-A represents the rectangular aquarium made of thick plate glass set in a solid wooden frame. The dimensions were 350 cm in length and 40 cm in inside breadth and depth. The ice, B, was put into the water at one end of the tank. The top of the ice, floating freely on the water, was covered with cotton to prevent ice melting from the heat of the air. A barrel, D, was filled morning and evening with water of 30 salinity and 8°C. The water passed from the barrel into the tank through a siphon, E, into which an automatic valve was fitted that transposed the water to the constant level FF. By the use of the glass cylinder G and the siphon H, the water in the tank was kept constantly at the same level, 35 cm above the bottom. The amount of water flowing from the barrel was 12 l per hour. The part of the tank in which the ice was melting was separated from that in which water renewal took place by the partition I, 31 cm in height. By inclining the wall I, passage of the water could be permitted to various degrees. – Reproduced from Sandström (1905).

gradients. Much later, in 1922, Pettersson assumed the cold winter climate in Scandinavia, which he had found prevalent during the herring years of 1880–1897, to be indicative of a retarded Gulf Stream Extension. Still, he did not try to apply Meinardus's method.

Pettersson's thermohaline model

As an associate professor in physical chemistry, Pettersson had to know about the new thermodynamics, including the Carnot cycle theorem of the steam engine. In fact, he may have been the first to apply this theorem to the ocean, as outlined in Pettersson (ca 1884). In a steam engine of the condenser type, water vapour and liquid water are the two acting phases. In the ocean, they correspond to liquid water and ice. In the engine, the latent heat of evaporation plays a significant role; in the ocean, it is the latent heat of ice melting. It is not surprising that Pettersson focussed on the system of the Gulf Stream Extension plus the Greenland–Labrador currents.

Pettersson did not develop these ideas much further. For instance, he did not bother dealing with the problems of pressure. His assistant and colleague Sandström, however, took up the problem thoroughly in a 1908 paper. Sandström is actually one of the few to have investigated the application of the Carnot cycle to oceanography, and is referred to in this respect in most of the older textbooks.

Pettersson's ice-melting hypothesis of deepwater formation

In his 1880s writings, Pettersson proved that pure ice, which moves freely in salt water, must occasionally encounter a surface current. When he resumed the investigation of ice-related problems in 1899, he addressed two new factors: 1) the action of ice cooling warmer water while melting, and 2) cooled water sinking owing to its higher density.

This possibly began with Pettersson's enthusiasm for the results of the Danish "Ingolf" expeditions in 1895 and 1896. A 1900 paper in Swedish includes, in addition to even more "Ingolf" sections than covered in Pettersson (1899), maps of regular Danish ice observations.

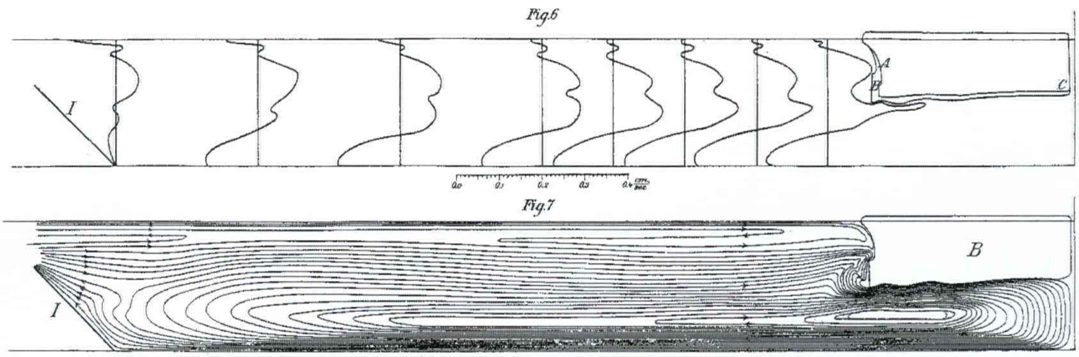

Figure 2. Results of Sandström's experiments carried out with the equipment depicted in Figure 1. His Figure 6 contains some diagrams of velocity, whereas his Figure 7 represents the courses of the water particles constructed from Figure 6. It is evident that a shallow, slow current flows from the ice at the surface. Below, there is a strong current moving towards the ice, and at the bottom, one of great velocity flowing from the ice. – Reproduced from Sandström (1905).

Another important reason why Pettersson adhered tenaciously to this hypothesis is that laboratory simulations were so successful. He performed trials earlier as well, but in 1903 arranged for Sandström to make experiments in the 3.5-m long tank at the ICES Central Laboratory in Kristiania (Figure 1). Water of 30 salinity units and at 8°C was continuously added at the same time that an equal amount of water was removed. Sandström (1905) presented details of an experiment in which the partition "I" was vertical. The resulting pattern was then composed of four currents. A reduction to three currents occurred when the partition "I" was inclined 45° (Figure 2). The warm saltwater attacked the ice at its front, where lighter water was formed, rising and leaving as an out-flowing surface current. Deeper, the warm saltwater flowed inward under the ice at the same time that cooled water sank towards the bottom where it, in turn, became an out-flowing current.

In an attempt to transfer his model results to the real world, Pettersson came into conflict with the traditional idea of the Nordic Seas currents constructed by Mohn (1885). For the North Sea–Skagerrak, Pettersson and Ekman (1891) gave partly differing information. For this area, the conflict became combined with the question of how Arctic plankton species, which the zoologist Aurivillius and the botanist Cleve had discovered in 1894 in the Skagerrak, had arrived there. Figure 3 shows what Pettersson considered to be the typical traditional current concept. It was published in Ekman *et al.* (1907), where the authors, Pettersson included, reported the results of the first five years of the international investigations to the Ministry of Agriculture. The warm inflow to the Skagerrak was not present on Mohn's map or on Helland-Hansen's and Nansen's well-known picture, which, moreover, did not appear in print until 1909. The Norwegian biologists Gran and Hjort, however, did not worry that the Nordic Seas branch of the Gulf Stream Extension in this figure was positioned as a barrier to the inflow of Arctic water. They claimed that Arctic species, after having entered at some extreme current situation, could sink to the bottom of the Skagerrak to survive the summers.

Pettersson, however, found that his ice-melting hypothesis for deepwater formation agreed perfectly well for bringing cold Arctic water into the Skagerrak, at least for part of the year. Already in Pettersson (1899), a current picture (Figure 4) fairly different from the traditional was evident, and it was repeated in many of his subsequent papers. To satisfy the hypothesis, warm Gulf Stream Extension branches were drawn toward the ice in the western Nordic Seas, where Arctic water was made to flow in the opposite direction. In the 1899 paper, he wrote that the ice attracted the warm Atlantic water.

A major discussion arose between Pettersson and Fridtjof Nansen over the general mechanism of deepwater formation, but their disagreement also touched on the reliability of each other's data. Nansen's "Achilles' heel" was his reliance on salinities measured by hydrometric procedure on the "Fram" in the Arctic Ocean. The raw figures were no doubt too low, but when correcting them for surface tension, Nansen (1902) added the extremely large value of 0.7 salinity units. This led to the conclusion that the deep salinity of the Arctic Ocean (35.10) was higher than the salinity of the Nordic Seas (34.95). To account for this difference, Nansen had to suggest a ridge between Greenland and Spitsbergen with a sill depth of roughly 500 m. Pettersson (1907) was satisfied when Nansen hinted at the possibility of equalizing the two salinities and removing the sill.

One of Nansen's counter-arguments to Pettersson's ice-melting hypothesis was the fact that, under the ice, there was, not only in the Arctic Ocean but also in the

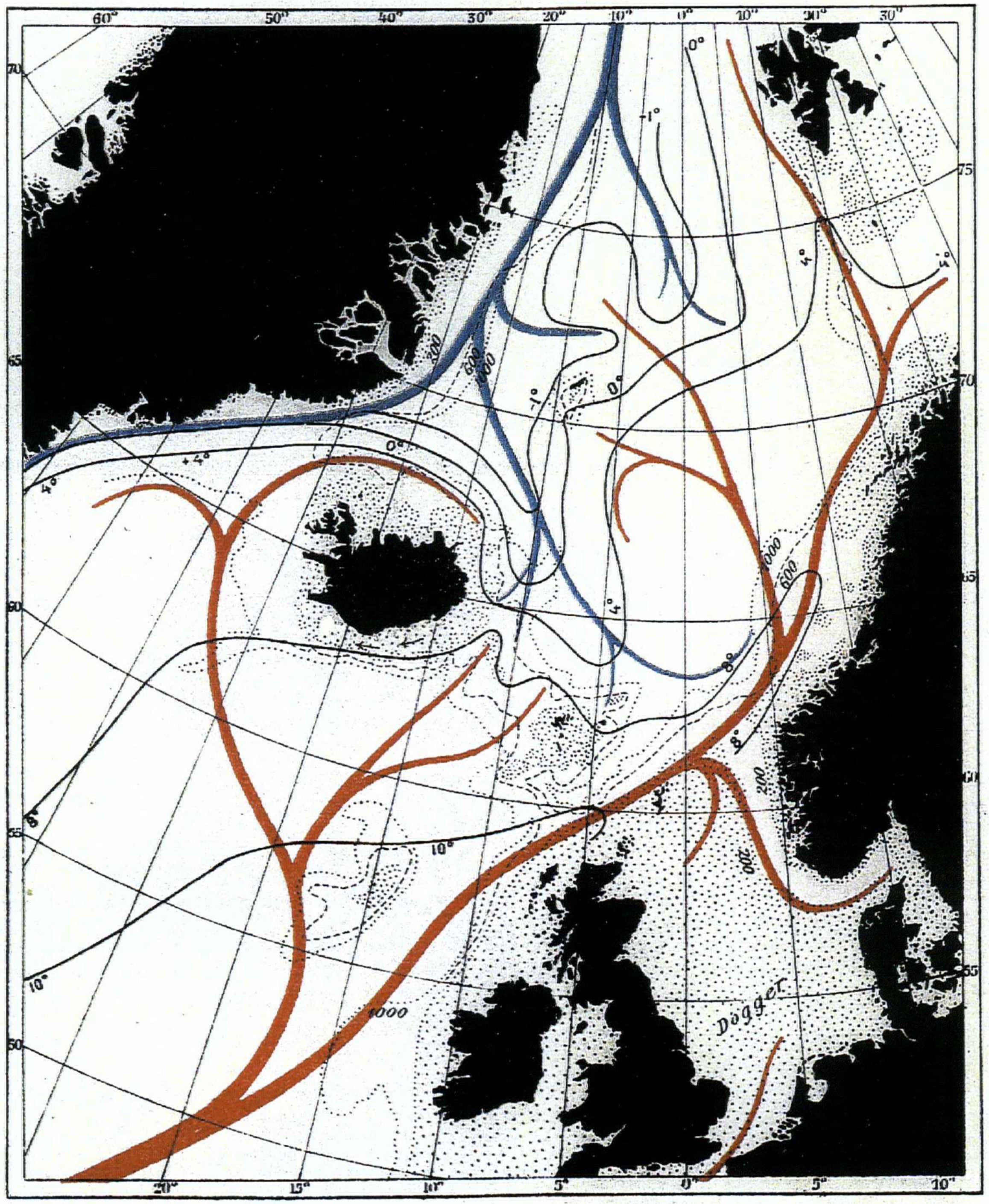

Figure 3. Schematic map of warm (red lines) and cold (blue lines) current branches, at 50–300 m depths, of the Atlantic and the Nordic Seas. Some isobaths in metres and isotherms in °C are also shown. – Reproduced from a colour picture in Ekman *et al.* (1907).

Figure 4. One of many versions of Pettersson's ideas of water circulation in the northern Atlantic. Thick black lines represent warm Gulf Stream Extensions and stripes represent cold Arctic currents. Broken lines of both types indicate deep currents. – Reproduced from Pettersson (1905).

Nordic Seas, usually a fairly thick layer of low salinity water above the saltier Gulf Stream Extension water. Therefore, the cooling at the underside of the ice would occur in water that could not become heavy enough to sink into or through the Atlantic water. Pettersson, however, insisted that "his" process took place over deepwater where the ice had been forced to flow as a countercurrent of the Gulf Stream Extension water. He argued that Nansen's low-salinity water was to be found only on the shelf along Greenland.

Nansen instead favoured atmospheric cooling as the main agent for forming heavy bottom water. He became convinced of this mechanism when he had to account for his discovery of an area in the Greenland Sea that, in winter, lacked not only the low salinity surface water but ice as well (Nansen, 1906). Pettersson (1907) acknowledged the importance of this discovery and went so far as to indicate the area with an "A" on his chart:

> The area [A] would consequently, during some months every year, act like an open window to the bottom of the [Nordic Seas], where it would flow northwards over the hypothetical ridge into the depth of the polar basin and southward toward the southern parts of the [Nordic Seas].

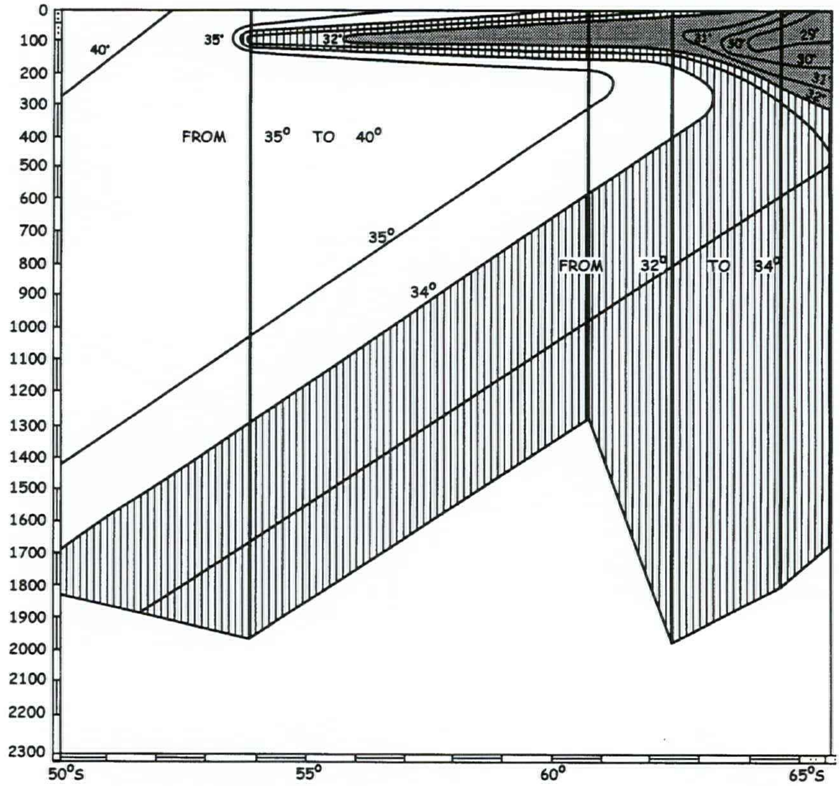

Figure 5. Surface temperatures (in °F) measured by "Challenger" in the Southern Hemisphere (Murray, 1896). – Reproduced from Pettersson (1899). Depths are in fathoms.

Even if the atmospheric cooling mechanism were proven to exist, Pettersson, however, refused to believe it could be the only agent because he argued that it was a much slower process than the ice melting.

Although Welander (1968) praised the laboratory experiments, he also made some critical comments:

> It may be pointed out that the problem ... has not yet been solved theoretically. The proportions of water rising and sinking from a melting body of ice cannot be determined from the balance equations for mass, heat and salt alone, but require a knowledge of detailed diffusion and mixing process at the sea-water interface.

Gade and also Jacobs *et al.*, both in 1979, made theoretical approaches to the diffusion and mixing processes dealing with Antarctic ice of the Ross Ice Shelf, giving credit to Pettersson and Sandström. Antarctic conditions are generally more advantageous for fulfilling the demands of Pettersson's ice-melting hypothesis than those of the Arctic. There are not only the Antarctic Ice Shelves, but the surface layer of low salinity in the Nordic Seas, mentioned above, is also considerably reduced in the Antarctic Ocean. Pettersson (1899) reproduced the Antarctic section (Figure 5) from the Challenger Report. The three-layer system depicted in this section contained the essence of Pettersson's hypothesis. Indeed, if Pettersson had been able to see the longitudinal pole-to-pole sections annexed at the end of Dietrich *et al.* (1975), he would have found in them an excellent demonstration of his ideas.

Antarctic bottom water is still considered to have its birthplace in the Weddell Sea. Foldvik and Gammelsroed (1988) described how they found about 15% of it to be formed by cooling at the underside of the Ice Shelf. They wrote further:

> Since the freezing point of sea water decreases with increasing pressure this cooling is most readily accomplished by melting at the underside of the ice.

Conclusions

Pettersson's ideas of general ocean circulation focused on thermohaline causes owing to his skepticism about the theories of wind-forcing by both Zöppritz and Ekman. Ekman did not allow himself to be goaded into debating with Pettersson, while Nansen, on the contrary, did so, but the difference in their views only concerned the thermohaline mechanism. Pettersson supported ice melting, while Nansen asserted atmospheric cooling.

The battle ended in victory for Nansen, especially as seen today. In most aspects, Nansen's ideas still appear valid, whereas Pettersson's have been reduced to explain smaller-scale phenomena, e.g., in the Antarctic Ocean. Trying to account for this fact, I would like to return to Pettersson's idea of Gulf Stream Extension water being sucked by the ice melting. Such an attraction is currently believed to be exercised by an ocean region of heavy mixing exerted, for instance, by the atmospheric cooling of the Greenland Sea. Consequently, my tentative explanation would be that Pettersson misjudged the mixing capacity exercised by ice melting.

Because Nansen admitted that ice formation played "second fiddle", one may ask why Pettersson did not agree to this "compromise". After all, he comprehensively studied the desalination which sea ice undergoes when ageing. In all probability, desalination at ice formation is a more efficient mixing source than ice melting.

Unlike the case of deepwater formation, Nansen and Helland-Hansen praised Pettersson's work on the connection between Gulf Stream Extension temperature and Scandinavian climate. As explained above, Pettersson's contribution here lay in his strong support for this influence, which was already suspected by earlier authors. His numerical approach seems to have inspired Meinardus to originate the idea of the North Atlantic Oscillation (NAO).

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