Water masses: birth of the idea

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A brief review is presented of the development of the methods and instruments for the measurement of temperature, salinity, and density in the ocean. The main events and circumstances associated with the genesis of the concept of "water masses" in connection with progress in observations are discussed. Among these are: 1) the first findings of the extremes in the vertical distribution of salinity during the "Challenger" Expedition (1872–1876) and the extremes in the vertical distribution of temperature during Nansen's Polar Expedition in 1893–1896; 2) the appearance of the term "water masses" in the book *Norwegian Sea* in 1909; 3) the first examples of the classification of water masses in the northern seas; and 4) the famous report by Helland-Hansen in 1916 and the birth of the oceanographic coordinates and the method for temperature–salinity (TS) analysis. The significant contribution by ICES and its leaders O. Pettersson, F. Nansen, and M. Knudsen in the creation of the preconditions for the appearance, entry, and distribution of the new idea of water masses in oceanography is highlighted.

Keywords: density measurements, salinity, temperature, TS analysis, water masses.

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Introduction

What is the ocean composed of – just water? It is a liquid substance which is transformed in the minds of scientists into various images. Physicists convert ocean water into a continuum or thermodynamic system; modellers – into scalar or vector fields; chemists – into water solutions of organic and inorganic materials; biologists – into a set of ecological factors; and geologists – into minerals and the main agents of marine sedimentation. As a result, this multifaceted picture of the ocean is lacking in unity and interrelationship.

It is probable that the only approach able to compensate for this loss is the idea of water masses as individual water bodies. This concept includes, at once, an effective tool for the division of the ocean into parts and a way of integrating physical, chemical, biological, and geological knowledge.

The history of the development of the concept of "water masses" in oceanography was connected very closely with the formation and activity of ICES, although most of the basic ideas originated many years earlier.

Initial period (before 1872)

Oceanography is an observational science. Any advance in knowledge about the ocean has been generated by the development of equipment and methods of observation. The first measured values from depths in the ocean were of temperature and density. From the middle of the 18th century, the temperature of seawater was measured inside a vessel after it had been hauled up from depth to the surface. Later, some investigators coated their water bottles with an insulating substance so that the temperature might remain unaltered during the process of being hauled up. Attempts were also made to insulate the thermometer itself, but these "slow thermometers" must hang for a very long time (1–2 hours) in the sea to attain an accurate measurement of the temperature of the water. Obviously, such methods could not give an exact result, but it was enough for the first discovery (in the middle of 19th century): "in very deep water all over the globe a uniform temperature of 39°F (4°C) is found to prevail" (Carpenter, 1877). But the new measurements using thermometers protected from pressure gave a new law of temperature distribution: temperature in the ocean falls with increasing depth. The detection of a cold stratum in the low latitudes was explained as evident proof of the existence of cold currents which run from the poles towards the equator.
For determining the density of seawater, two methods were used: direct weighing (pycnometer) and hydrostatic weighing (floating hydrometer or hydrometer of total immersion). Distilled water was used for the calibration of these methods and for the separation of the effects of temperature and salinity on density. As a result, two forms of density appeared in oceanography: 1) density as a function of temperature and salinity, and 2) specific gravity as a function of salinity only. In practical terms, specific gravity was the equivalent of salt content in seawater.

As a result of some series of specific gravity measurements in different parts of the ocean, scientists formed the opinion that its variations were very slight and had little influence on the structure of the ocean.

The content of salt in seawater was considered mainly a chemistry problem during this period. In 1819, A. Marcet made a remarkable discovery about the composition of sea salt. On the basis of 16 samples from oceans and seas he determined only five components. Although the supposition was almost a guess, it was absolutely exact: all samples contained the same ingredients all over the world, and the ingredients had very nearly the same proportions in relation to each other. Nearly 45 years later, G. Forchammer (1865) confirmed this discovery through the analysis of 280 samples that he collected over a period of 20 years. He coined the new terms in the oceanographic lexicon: "salinity" and "chlorine coefficient" (before "saltiness" and "strength" were used). Actually, he had prepared the ground for the new method of salinity determination.

"Challenger" period (1872–1895)

The programme of physical observations in seawater made during the "Challenger" cruise included the determination of temperature and specific gravity. The floating hydrometer was used for specific gravity measurements. The results were reduced to their values at the standard temperature of 60°F.

The instrument for temperature measurement had been chosen on the assumption that temperature fell with increasing depth. This was the maximum-minimum Miller-Casella thermometer with protection from pressure, similar to those employed in meteorology (Six's thermometer). Such a method could obviously not reveal unmonotonic distributions of temperature.

In this way, the temperature and specific gravity of nearly 2000 samples were determined, including 362 measurements at depth (Buchanan, 1877). The results were first represented on the maps of surface distributions and on meridional transects of the Atlantic and Pacific Oceans, respectively.

The most important discoveries concerning the vertical structure of water have been made in the Atlantic Ocean. In the equatorial zone, the sub-surface maximum of specific gravity at a depth of 50–100 m was disclosed. But a more sizable anomaly, an intermediate minimum of specific gravity (salinity), was found at a depth of 800–1000 m between 10°N and 30°S. A third feature was discovered in the North Atlantic: comparatively high specific gravity near the bottom. To account for the specific gravity anomalies, the advective mechanism was proposed.

To find a solution to the problem with salinity, 77 samples of seawater were collected from different parts of the ocean, and in 1884, W. Dittmar published the results of the full analysis of the salt content in seawater (Sverdrup et al., 1942). The laws of constancy of composition and constancy of proportion of salt in seawater were confirmed conclusively and opened up the way to the transformation of salinity from a chemical into a physical value.

It was significant that the data from the "Challenger" expedition were analysed and discussed for more than 50 years (Wüst, 1929).

Nansen's Polar Expedition (1893–1896)

This unique expedition made an outstanding contribution to oceanography in general and also to the progress of ideas about the structure of the ocean. In spite of extremely severe conditions during the expedition, which greatly hampered any observations and restricted the choice of investigative methods, results of exceptional importance were achieved.

Nansen (1902) combined the most-used and novel methods and instruments. Measurement of temperature was carried out by insulated water bottles (Pettersson's and Ekman's) and by reversing deep-sea thermometers (Negretty and Zambra). Since it was impractical to use the titration of chlorine for salinity determination in polar conditions, the solution was found in the combination of the long-established method of calculating salinity from specific gravity measurements (with the use of hydrometers) and the new method of determining salinity by conductivity measurements.

The famous transect throughout the Polar Basin was carried out over two years and seven months and included 18 stations of deep-sea observations, of which 13 were more than 1000 m deep. The maximum depth of measurement was 3800 m. The work at these stations demanded a huge effort, especially during polar nights and intense cold.

The prize was a series of discoveries and achievements. First, the farthest branch of the Gulf Stream was found near the North Pole, more than 10 000 km from its origin. Second, the three-layer structure was determined in the Polar Basin: surface layer (0–200 m) as the genuine Polar Water, intermediate layer (200–700 m) as the "fresh" Gulf Stream water, and the deep layer (more than 700 m) as the "old" Gulf Stream water. The greater part of all water layers in the Polar Basin consists of water having its direct origin in the Gulf Stream. Third,
unmonotonic vertical distributions of temperature were detected with a sub-surface minimum (at about 50–60 m) and intermediate maximum (between 200–700 m). Nansen’s measurements greatly advanced the structural analysis. He discussed in detail the main attributes of the different kinds of water: origin, characteristics, distribution, and transformation. He used the joint analysis of temperature and salinity distributions because the main agents of interaction in the Polar Basin were polar waters with low salinity and low temperature and Atlantic waters with high salinity and relatively high temperature. And the last remark: Nansen used the term "water" in the classification – so only one step (one word) was needed to give birth to the "water mass" idea.

**ICES period**

In a practical sense, ICES activities began before the formal establishment of the organization and were connected with the scientific work of some of its future leaders, such as Otto Pettersson, Fridtjof Nansen, and Martin Knudsen.

In 1890, Pettersson was constructing a new kind of insulating water bottle. In older types, the insulation was affected by the solid walls with poor conductance. In his new bottle, the insulation was obtained by dividing the enclosed water volumes into a number of thin strata by means of coaxial cylinders and lids (Pettersson, 1894).

In 1900, the great Pettersson–Nansen insulating water bottle was constructed. Nansen made several improvements to the previous model, with the deep-sea thermometer fixed in the central chamber and protected against water pressure, the frame with the reversing thermometer, and the instrument triggered by a messenger instead of the propeller mechanism. Thus, the water bottle became more reliable in function and provided more accurate measurements (Knudsen, 1923).

Precisely this kind of insulating water bottle was used during the first stage of the Norwegian investigations in the Norwegian Sea during 1900–1904. Nansen and Helland-Hansen conducted the cruise in 1900 as an experimental one, during which they carried out comparative studies of different methods of determining temperature, salinity, and specific gravity. The results of their work resolved the problem of how to improve the instruments and methods so "that Physical Oceanography could be made a really exact science" (Helland-Hansen and Nansen, 1909).

It is also necessary to mention the Danish "Ingolf" Expedition in 1895–1896 when Martin Knudsen began his career as an oceanographer. The most important result of his participation was the improvement of chlorine determination by Mohr’s method in which he introduced the famous "Knudsen’s pipette and burette" and "standard water" for calibration of the titration procedure.

In 1899, at the international conference in Stockholm, Knudsen put forward his methodological proposals and received full support. He became a member of the committee charged with revising the existing hydrographic tables. The main practical work was entrusted to Knudsen who directed it with great efficiency. During the next two years, a series of samples of seawater (from the Baltic to the Red Sea) was collected and the "constants of seawater" were precisely determined. In 1901, the well-known "Hydrographic Tables" were drawn up, which made it possible to determine chlorinity, salinity, and specific gravity of a sample of seawater with great accuracy from a titration method and to calculate salinity and specific gravity from hydrometric measurements.

The second international conference in Kristiania in 1901 accepted the programme for hydrographic and biological research, with the main task of total modernization and standardization of all methods of observation. For these aims, the International Laboratory was established in 1902 with Fridtjof Nansen as leader and V. Walfrid Ekman and Charles Fox as assistants. The main purposes of the Laboratory were 1) to control apparatus and ensure uniformity of methods, and 2) to improve the apparatus or construct new and better ones. The work was begun very intensively. In 1903, under the initiative of Nansen, the new reversing thermometer (Richter) appeared and was exactly the same instrument that was subsequently used in oceanography for about 50 years. Ekman began the new generation of serial water bottles, together with reversing thermometers. The first model was constructed (weight 7.5 kg) in 1902, the second model (weight 5.5 kg) was developed in 1910, the famous Nansen stop-cock serial water bottle (weight 2.5 kg) appeared in 1912, and later came the famous Knudsen water bottle (weight 3 kg). The last two types of water bottles were the most widely used for many decades.

Ekman (1905) carried out the comparative analysis of different methods of temperature determinations and calculated the necessary corrections. As a result, the precision of temperature measurements was improved to 0.01°C. The same level of precision for the method of salinity determination was achieved by chlorine titration.

The progress in methods promptly stimulated the rise of new concepts in oceanography. After the research of 1900–1904 in the Norwegian Sea (where the new instruments and methods were widely used), the results were published in the book *Norwegian Sea* (Helland-Hansen and Nansen, 1909). The term "water masses" was first found in this publication, but it was more than just the new words – it was a new approach to oceanography. The special chapter "General Description of the Water-Masses of the Norwegian Sea" contained the main principles of water masses analysis and also the first classification of the water masses in the sea. The authors explained why the Norwegian Sea is precisely the place for the realization of these new ideas: "it forms the meeting-place of the waters coming from the North
Atlantic and North Polar Sea" and these water masses have a "very different origin, keep their physical character for a long time and may be traced at a great distance from the place of their entrance".

Accordingly, for the core of water masses idea, the joint analysis of temperature, salinity, and density is necessary. But this task was realized on the old basis: all distributions were first combined on one graph. The effect was not very sensible; entangled isolines were troublesome to analyse. An adequate graphic form for the water masses was proposed in 1916, when Helland-Hansen (1918) first presented the temperature–salinity (TS) diagram. But it was wartime and the presentation was in Norwegian; thus it took several years to distribute the new graphic idea. The main content of the presentation was published in English nine years later (Helland-Hansen and Nansen, 1927). However, the remarkable event happened: water masses found their own space, and oceanography received its own coordinates.

The final events in the process of the birth of the water masses idea were connected to expeditions in the Atlantic Ocean: "Armauer Hansen" (1913–1924), "Dana" (1920–1922), "Meteor" (1925–1927), and others. The newest methods and instruments, developed through ICES activities, were used in the expeditions, the observations carried out were of very high quality, and the stations covered almost all the ocean and gave remarkable results. These results included 1) TS curves of individual stations throughout the Atlantic Ocean as a graphic portrait of the structure of water masses; 2) classification of water masses of the Atlantic Ocean; and 3) theoretical approaches in the analysis of water masses, the appearance of the new function \( S = f(t) \), and investigations of mixing processes in the TS diagram (Defant and Wüst, 1930).

Conferences and publications under the leadership of ICES during this period were of primary importance in ensuring the wide and quick distribution of these new ideas and results among oceanographers. Therefore, water masses are an essential and extensively applied concept in oceanography, and the TS diagram has become one of the most valuable tools, not only in physical, but also in interdisciplinary investigations. The birth of this idea developed over some 30 years.

References


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