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The life and work of Nick Fofonoff

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Early life and education

Nicholas Paul Fofonoff was born August 18, 1929, and raised on a small farm near Queenstown in Alberta, Canada. His parents spoke only Russian at home, so Nick did not learn English until he attended the two-room school that served the first six grades for the town of 200. He was the second born of four, the prince among three sisters. The small school meant he was exposed to several grades at a time and could advance quickly. He also learned many practical skills on the farm from a clever father and the necessity to be self-sufficient. It was a good environment to nurture an interest in science and mathematics. The young Nick was an inveterate tinkerer, forever repairing or inventing machinery at the blacksmith shop and experimenting with chemicals. His sister tells a story of a trick he liked to play in which a carefully layered test tube of alcohol and water was held against the skin and shaken. The resulting contraction on mixing provided enough suction to hold the test tube in place on the victim. This youthful interest in nonlinear mixing effects turned out to be a long recurring theme of Nick's research career. He was able to learn science in a more formal way when he attended a dormitory school for grade 12 in Cluny, Alberta. In 1945 the family moved to an apple orchard at Creston, British Columbia, where Nick finished grades 12 and 13 and won a scholarship to the University of British Columbia. During his time at UBC, Professor George Pickard opened the Institute of Oceanography, which intrigued Nick enough to divert his studies from nuclear physics. He received a Bachelor's Degree in 1950 and a Master's Degree in physics and mathematics in 1951, but

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with his interest now piqued by the idea that science and adventure could be combined in oceanography.

At that time the word 'oceanography' was almost unknown. In 1950 Raymond B. Montgomery was appointed visiting professor in oceanography at Brown University. What was particularly odd about Montgomery's appointment was that it was in the Graduate Division of Applied Mathematics, yet Montgomery was interested primarily in field observations and plotting of data. Even so, the appointment was fortunate because in 1951 Nick Fofonoff, after marrying Mabel Deckard, arrived at Brown specifically to work with Montgomery. Nick's training was in physics and mathematics but he was very interested in learning about oceanographic data and analyses from his mentor. Fortunately, Montgomery also kept up with the important developments in oceanographic theory and often visited the Woods Hole Oceanographic Institution (WHOI). Indeed, some years earlier he had been instrumental in getting Henry Stommel to work on the problem of the westward intensification of the Gulf Stream.

It is unknown whether it was specifically Montgomery's influence or that of George Carrier, who left Brown for Harvard in 1952, but sometime during 1953 Nick took up the problem of free inertial flow in the ocean and published his findings in the *Journal of Marine Research* in 1954. That paper was the forerunner of subsequent studies of inertial boundary layers in ocean circulation by Stommel, Charney and Morgan, all of whom cited Fofonoff's paper. In some respects Nick's work was more complete than the ones that followed because his model was the only self-contained study of inertial flow. Even so, most subsequent references to inertial flows cite the derivative papers of Charney and Morgan.

A career in oceanography

After receiving his doctorate from Brown in 1955, Nick spent a year at the National Institute of Oceanography in England. While he was there, Sir George Deacon sparked his interest in physical properties of seawater by his discussions of the formation of Antarctic bottom water. This interest evolved into a long commitment to examining fundamental properties of seawater. He then joined the Pacific Oceanographic Group of the Fisheries Board of Canada, where he spent the next five years. He was invited to give a series of lectures on energy transformations in the oceans at the Geophysical Fluid Dynamics summer program at WHOI in 1961. That work was based on some earlier work that he had published in the National Academy of Sciences-National Research Council publication in 1958 on the thermodynamics of oceanographic measurements. It was followed in 1962 by two publications in Volume 1 of *The Sea*—one on the physical properties of seawater and the other on dynamics of ocean currents.

In 1962 Nick joined the WHOI scientific staff. He had spent summers at WHOI during his graduate studies at Brown, so he already knew many of the staff. A major factor in his decision to make the move from Canada was his desire to join the WHOI program to measure ocean currents from moored buoys. The WHOI Buoy Group had been set up and

directed by Bill Richardson. It was a disappointment for Nick to learn, soon after his arrival at WHOI, that Richardson was leaving and that the future of the Buoy Group was uncertain. Hank Stommel and Arnold Arons persuaded Nick and Ferris Webster to get involved in the program. Although he had no previous experience in management, Nick agreed to accept the responsibility for leading the group rather than risk its disbandment.

Nick transferred from the Theoretical Oceanography and Meteorology Group to that of Applied Oceanography to take over management of the Buoy Group, while Webster remained in Physical Oceanography to set up the data processing end of the operation. Nick managed a group that included John Garrett and Bob Heinmiller as operation chiefs preparing instruments and buoys for deployment and directing operations at sea.

Nick faced formidable problems leading the Buoy Group. Moorings were often swept away by strong currents and current meters did not always return usable data. Nevertheless, he persisted and successfully guided a team which at one time numbered as many as forty individuals, working on all aspects of instrumentation, engineering, administration, data handling, and scientific analysis. Some of the work he did was a long way from the theoretical studies he had been involved with. For example, he carried out studies of mooring line oscillations, of the watch circles of moored buoys at the surface, and of the response characteristics of a variety of current-sensing elements. He was concerned about the attraction of sharks to synthetic mooring lines. After several years of development, and in spite of a number of discouraging losses, the system began to work. His group developed the ability to put in and recover long-term instrumented moorings in the deep sea, and results began to come in. That soon attracted a number of younger scientists, including Mel Briscoe, Bill Schmitz, Jim Luyten, Raymond Pollard, and Rory Thompson, all of whom joined the group to work on the data.

Nick also helped to foster the development of the Conductivity-Temperature-Depth (CTD) instrument at WHOI by Neil Brown. He recognized the need for accurate high-resolution information on temperature and salinity profiles in the ocean. He was the first to write software that translated the high bit rates from the CTD into data in engineering units and allowed it to be plotted and manipulated at sea. Early on he formulated solutions to the sensor dynamic response problems and was much involved in developing calibration procedures.

Reorganization at WHOI brought Nick additional administrative duties in 1967. The Theoretical Oceanography and Meteorology Group was merged into the Department of Physical Oceanography, and Nick took over the chairmanship of the combined departments. He continued in this job until 1971 and later took it on again from 1981 to 1985. Throughout this period he ran the Buoy Group and continued his work on developing moored deep-sea instrumentation. In 1968 he also began a long association with Harvard University, where he was Professor of the Practice of Oceanography until 1985, then a Distinguished Research Associate until 1991. This was a part-time appointment that for many years required weekly trips to Boston to teach and advise at Harvard. The lecture notes from his Harvard course on “Thermodynamics of a Seawater System” became

required reading for several generations of physical oceanography students. Nick was known as a patient and supportive advisor to his own graduate students, Harry Bryden, Nan Bray and Clark Freise.

Nick's foresight and determination led to the first systematic studies of the eddy motions in the ocean. When the system of moored current meters began to function reliably, the direct measurements of ocean currents produced unexpected results. They showed a rich variety of time-dependent motions extending over all measurable time scales. At the local inertial and the semi-diurnal tidal frequencies, intermittent oscillatory motions with random changes of amplitude and phase were found. At higher frequencies, motions were irregular and nearly isotropic horizontally. The kinetic energy of the time-varying components exceeded that of the mean flow. In a *Deep-Sea Research* paper (Fofonoff, 1969), Nick showed that between the inertial frequency and the Brunt-Väisälä frequency, the motions were governed by inertio-gravitational wave dynamics. In so doing, he derived the concepts of collinear and rotary coherence between vector velocity measurements. He noticed that the velocity measurements in the internal wave band often had an energy level of 1 cm^2/s^2 at a frequency of 1 cycle per hour, an observation that came to be known as "Fofonoff's rule." This body of work had a clear influence on the later development of the internal wave spectrum by Garrett and Munk.

The richness of the time-varying currents revealed by moored current meters and by drifting floats was a major stimulus to the creation of two large research programs, the Mid-Ocean Dynamics Experiment, and the US-Soviet POLYMODE Experiment. Nick played a leading role in both programs. His knowledge of Russian allowed him to maintain strong links with Soviet scientists during a period when US-Soviet collaboration was difficult. He was pleased to have the opportunity to work aboard Soviet research vessels.

Over a period of about 15 years (1962-1977), under Nick's leadership, the WHOI Buoy Group developed a reliable deep-sea mooring technology and associated analytical techniques that today are standard tools of oceanographic research. At the same time, Nick continued to study the properties of seawater and the thermodynamics of the ocean.

Nick's article on the physical properties of seawater, published in 1962 in Volume 1 of *The Sea*, was a watershed article for oceanographers. He applied fundamental thermodynamic concepts to seawater and so provided both chemical and physical oceanographers with a solid foundation for much of the development of algorithms in observational oceanography that was to follow. He related the Gibbs function of seawater to the other quantities of interest to oceanographers, such as enthalpy, internal energy, specific heat, sound speed, adiabatic lapse rate, chemical potential, potential temperature and specific volume. In that article Nick managed to cover the evaluation of salinity and practical expressions for the equation of state in just four pages. His later work would change these topics forever and would become one of his main legacies in oceanography. In a revealing section, Nick considered the mixing of water parcels at constant pressure and showed that the conservation of enthalpy in this process implied that temperature was not conserved

because of the dependence of the specific heat on temperature and salinity as well as the so-called "heat of mixing" when parcels of dissimilar salinity are mixed.

At about this time there was discussion about the best way to evaluate the ocean's salinity, since it could be determined more accurately from measurements of conductivity rather than from chlorinity derived from titration. Nick played an important role in sorting this out and in delivering the International Equation of State for seawater. These issues were under constant debate and review by the Joint Panel on the Equation of State of Seawater which was jointly sponsored by ICES, IAPSO, SCOR and UNESCO. The panel was established in 1962, and it was renamed JPOTS (Joint Panel on Oceanographic Tables and Standards) in 1964. Its work was finally completed in 1981 when the last of its reports was published describing the modern procedures for determining salinity from conductivity measurements and density from the International Equation of State. These internationally accepted algorithms have proved the test of time in that they are still in use today, providing the field of oceanography with a uniformly accepted method for evaluating these quantities with high accuracy. Fofonoff (1985) provides a summary of the results of this panel as well as a history of the twists and turns along the route, particularly in the advances that were required during the life of the panel to justify the adoption of conductivity as the recommended route to salinity and the meaning of "practical salinity" versus "absolute salinity."

In his retirement Nick returned to a fascinating aspect of the work he did at the Fisheries Board of Canada shortly after his doctorate. Nick's article in the 1961 summer Geophysical Fluid Dynamics Program notes contained not only the material on the thermodynamics of seawater that subsequently appeared in *The Sea* in 1962, but also a section on the implications of the nonlinear nature of the equation of state for the gravitational potential energy of oceanic water columns. The idea was that mixing at some depth in the ocean usually results in a contraction of the water volume at that location and hence the whole water column above that location slumps vertically and so loses gravitational potential energy. In a series of articles published between 1995 and 2001, Nick explored the possibility that this process could be self-sustaining in the sense that the change in gravitational potential energy could appear as an increase in the dissipation of kinetic energy at the location of the original mixing and so cause a positive feedback loop. He proposed that this process acted to limit the vertical stratification at several locations in the world's ocean. Nick found this possibility inspiring and was enthusiastically working on the problem shortly before his death.

Nick's personal style

Besides Nick's tours of duty as chair of Physical Oceanography and Buoy Group manager at WHOI, he also undertook duties as chair and directorship for various international projects (such as the JPOTS committee), and after his retirement from WHOI, at the International WOCE project office in England. Anyone who worked under him came to appreciate his gentle style and universal accessibility. One could only be impressed by

his tremendous generosity with time. Nick made no class distinctions— student, technician or senior scientist alike all had equal access to this thoughtful, wise and patient man. This even-handedness, along with his inherent wisdom, made him an excellent manager, supervisor and mentor. He was adept at bridging the gap between theorist and technician. These skills led to his being drafted to serve two terms as department chairman, the only person to be so chosen in PO department history. On one occasion he had to arm-wrestle the program manager from the Office of Naval Research for the last $100,000 of funding. Fortunately, he won.

In his service on the JPOTS, SCOR, POLYMODE and other committees and in heading the International WOCE office he was doing the difficult homework for thousands of oceanographers. Generally, it was Nick who first figured out what an instrument really measured and who showed the rest of us how to use the data. And he did this in his typically low-profile style. He seemed to follow the maxim that there is no limit to what you can accomplish if you don't focus on who gets the credit.

Nick loved technology. He was a ham radio enthusiast and helped set up a communications system for the Falmouth Road Race before the days of cell phones. He often returned from trips with mechanical toys for his daughter and three sons and encouraged them to take an experimental approach to the world around them. He always had several computers. Some called him the "Computer Canuck." In the 60's he talked the Navy into buying a very expensive analog computer so he could make calculations at sea. This was a complex thing and very hard to program. Bob Millard tells the story of taking the analog computer to sea on one of his first cruises, when it was smashed to bits off Gay Head because he had not properly tied it down. Bob was terrified of what Nick would say when he got back from the cruise and was surprised to find him very understanding. He suspects that Nick was ready to move on to the new digital computers coming out, and was secretly relieved to be rid of it. When he went to sea himself Nick spent most of his waking hours at the computer, an inveterate hacker.

The world of science has recognized Nick's tremendous value to the oceanographic community. He is the recipient of the American Geophysical Union's Ocean Science Award in 1990, the American Meteorological Society's Henry Stommel Award in 1998 and an Honorary Doctoral Degree from the University of Victoria in 2002.

Nick kept working hard right up to the end. In the last few years he finally found the time to get back to his early interest in the difficult topic of the nonlinear thermodynamics of seawater in which he produced some intriguing results in recent papers. That he continued to be so creative and productive despite failing health is a testament to his deep involvement in oceanographic research. It was great to see him producing these wonderful scientific nuggets late in his career, the product of a lifetime of careful and disciplined thinking.

Nick's dedication to the field of oceanography is evidenced by his willingness to work on important issues, such as analyzing the components of a mooring system or developing an accurate equation of state for seawater, that would not bring him fame or even visibility.

But they provided the field with essential procedures that are used daily by oceanographers all over the world. Long into the future oceanographers will still have to learn about the "Fofonoff gyre" and still have to understand the exotic thermodynamics of seawater that Nick discovered. He has left us a substantial scientific legacy. He was a generous, patient, wise, and deep-thinking man, and we are all going to miss him.

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