Perspectives of Earth and Space Scientists

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Key Points:

- Let your career path be molded by your interests, but remain flexible to fit opportunity
- Pay attention to the observational data as it rolls in, there might be a hidden discovery
- The global ocean is composed of a network of interactive warm and cold water regions

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How Did I Get From There to Here?

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Abstract In this memoir I trace the trajectory from childhood to a career in physical oceanography. The trajectory was not based on a well thought out plan, but I had a sense of my interest in the ocean and atmosphere. One is faced with many career opportunities in life, choosing the best for you depends on your interest and talents. The better you understand them, the better you recognize "opportunity," but be flexible, opportunity is never likely to be a perfect fit (it might actually be better fit to your "passion"). My research quest, as an observationalist, is to develop a clearer, conceptual, picture of ocean, how it "works," with a tilt toward its role in the climate system. I have worked in the cold southern polar regions to the hot tropics, and in-between; from the top to the bottom of the water column. Here I discuss a few discoveries that led to new insight into interocean exchange and deep ocean ventilation, which are now widely explored: Southern ocean: two modes of convection, along the margins of Antarctica and in the open ocean of the Weddell Sea; Agulhas Leakage: Indian Ocean invades the Atlantic, essential to the Atlantic Meridional Overturning Circulation; The Indonesian Throughflow: tropical Pacific water spreads into Indian Ocean, part of the global interocean thermocline exchange.

Plain Language Summary I followed my interests that led to exploration of the global ocean, from cold to warm regions, from the sea surface to the sea floor. There was a lot of luck, serendipity, in my career trajectory, but knowing my interest and talents helped guide my decisions, and how I got from "There to Here."

1. Introduction

As I say on my webpage (https://lamont.columbia.edu/directory/arnold-l-gordon). "*I am a field-going physical oceanographer, an observationalist. My research is directed at the ocean's stratification, circulation and mixing and its role in Earth's climate system. I study the transfer of heat and freshwater within the ocean and between the ocean, cryosphere and atmosphere, with specific attention to interocean exchange and to ventilation of the deep ocean interior*."

> "Historically much of my research deals with the Southern Ocean and South Atlantic, but research within the warmer waters of the Maritime Continent and Indian Ocean now compose most of my research program."

During my ship-based research I occasionally stumbled on an unexpected feature, that is, not a planned discovery. Perhaps as I was "locked on" the data as it slowly rolled in, I became aware of something strange-bad data or the unexpected? (How many discoveries have I missed?) First, I discuss my early days that led me to oceanography, and then a few of my research adventures in the far corners of the world ocean, leading to discoveries of global significance.

2. College to Upstate New York, Lamont Geological Observatory of Columbia University

I have had a long career, ~60 years on a faculty of Columbia University of New York City and on the research staff at Lamont-Doherty Earth Observatory in Palisades New York, which at the time of my first visit in January 1961, was called Lamont Geological Observatory. My career might be better referred to as a "hobby" for which I got paid, met so many interesting people, from all over the world that my exploratory research brought me to.

For that January 1961 visit my father accompanied me as he let me I drive the family car from Brooklyn to Palisades (other than nearly having an accident as I turned at top speed into Oak Tree Road from 9°W, it went fine, except for the dog incident," see below) for an interview with Professor Jack Nafe at his office in the basement of Lamont Hall, which was the Torrey Cliff residence of the Thomas Lamont family, before they donated it to

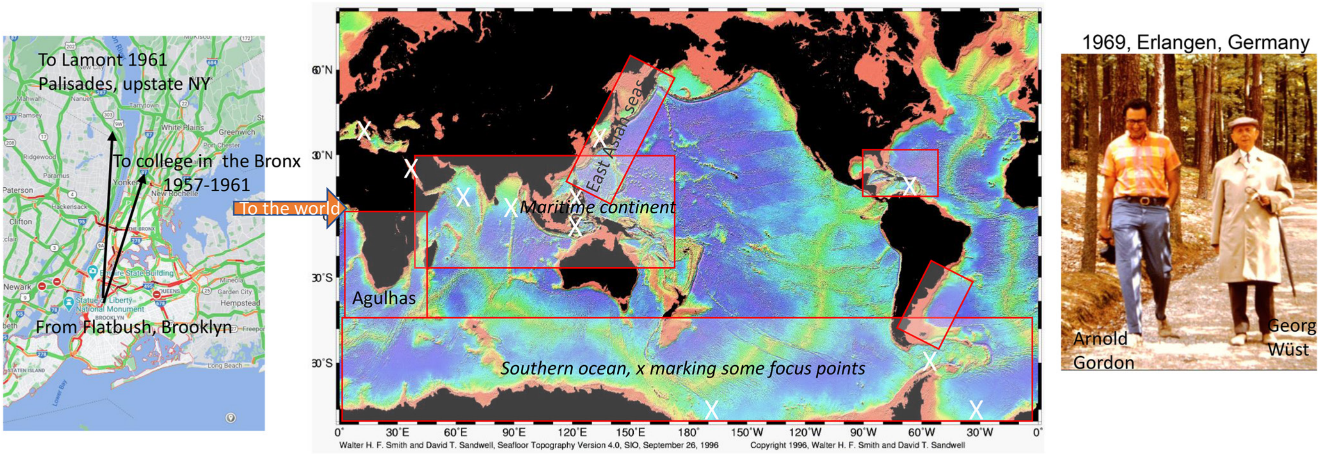

Figure 1. Left panel: From Brooklyn to the Bronx and then to Palisades "upstate" New York. Central panel: The red boxes denote the wide-ranging ocean regions that I have investigated, plus a few more specific areas marked by X. Right panel, walking with Georg Wüst in Erlangen Germany, 1969.

Columbia University in 1948, becoming the home of Lamont Geological Observatory in 1949. I thought of Lamont as "up-state," though it's just ~15 miles north of the George Washington Bridge, on the western side of the Hudson River (Figure 1), that is, the "wild west." I wrote "Palisades, Upstate New York" in my textbooks, for which I took a lot of ribbing from those north and west of the Tappan Zee Bridge.

I asked Jack Nafe if I could study physical oceanography at Lamont, which was a geological institution. I was explicitly interested in physical oceanography of the world ocean. I was already was admitted to MIT graduate school, but in coastal oceanography. Little did I know that Lamont wanted to add physical oceanography to its global spanning program. The story: Maurice (Doc) Ewing, the first Director of Lamont, realized that he could not get rid of the ocean to gain a clearer picture of the sea floor-he needed a physical oceanographer to study the water column and its role in sedimentation. With funding from the Ford Foundation a famous German oceanographer, Georg Wüst, joined Lamont for a 3-year visiting position, with the purpose to train a physical oceanographer, which turned out to be me! I began at Lamont in June 1961. I was awarded a PhD in 1965, with a dissertation on the circulation of the Caribbean Sea.

I knew Lamont was right for me, I accepted, though I wondered if the offer was still valid, because of the "dog incident." During my meeting with Jack Nafe my father walked our dog, Nellie, near the apple trees in front of Lamont Hall. Doc Ewing's dog charged out of Lamont Hall and a dog fight ensued. Doc and with my father separated the dogs (what a memory stuck in my mind!).

What got me to that day at Lamont in January 1961? An important person in my childhood was my cousin, Marvin Gordon, who received his Ph.D. (first in my family) from Columbia University in the Geography Department. I remember going with him to Schermerhorn building on the Columbia Campus in the mid-1950s when he turned in his PhD dissertation. Little did I know that is where I would eventually teach. He suggested around 1950 when I was 10 years old, that I receive daily US weather maps from the weather bureau, which arrived about three days after the weather (i.e., no web site to explore). I saw how weather systems moved across the country, with fronts and low/high pressure systems. The impact of the coastal ocean on weather caught my fancy. In high school (Erasmus Hall, Flatbush and Church Avenues, Brooklyn) I took a course on Earth Science taught by Miss Turner. It included some climate information. Wonderful course. In college, my term paper in a geomorphology course dealt with comparing the weather of coastal cities moving clock-wise around the North Atlantic, from Rio de Janeiro to Dakar. The signature of the ocean sea surface temperature and associated ocean circulation was evident (I still have that report). I was clearly headed for a career in physical oceanography.

I attended Hunter College in the Bronx (now called Herbert Lehman College; part of the New York City University system, CUNY). My major was Geology, but with nearly equal number of courses in Physics, and slightly less in chemistry (multi-discipline science background, well suited for the study of the ocean). There was some issue of having enough credits for a major as needed to graduate, but it worked out: BA in June 1961. The cost of my college education was $44/year, it included textbooks! What a relief to my father. No student loans needed. I

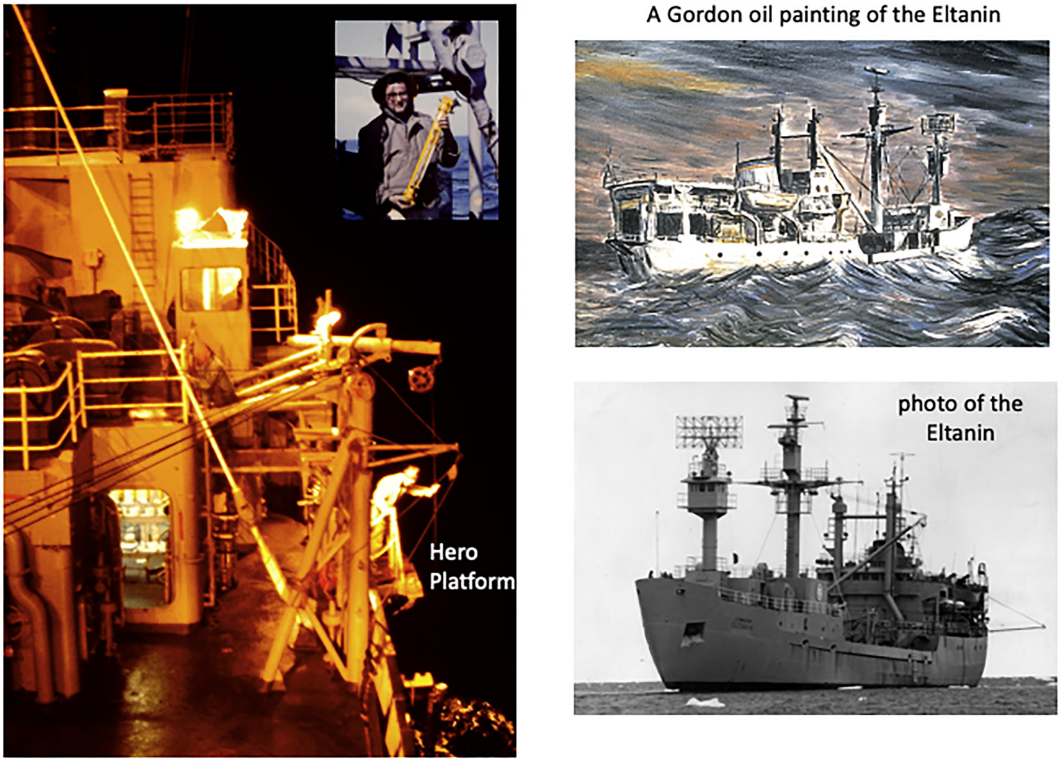

Figure 2. Left Panel, working from the Hero platform on the *Eltanin*, insert A Gordon holding Nansen Bottle, 1965. Right panels: the *USNS Eltanin*, oil painting by A. Gordon and a photo taken by A. Gordon.

communited from Brooklyn to the Bronx by subway, 1 hr + trip, each way, first to last stop on the D train, always got a seat, opportunity to do homework. My first small step into "Upstate New York" (see Figure 1).

During my career the technology of observing the ocean from research ships evolved. Hydrographic stations some 50–100 km apart obtained with Nansen Bottles (Figure 2) equipped with reversing thermometers obtained measurements and water samples for processing on the ship at 23 depths in the entire water column. The Nansen casts were replaced with the CTD lowered into the ocean, gathering temperature, salinity and oxygen data at ~1 m intervals! Now we have vast array of in situ measurements from Argo floats, surface drifters, gliders, arrays of moorings, reporting data via satellites in near real time. About 1,500,000 Argo profiles were collected between January 1999 and October 2015; compared to 500,000 shipboard hydrographic stations collected over the past 100 years (Riser et al., 2016). We also view the ocean from orbiting satellites sensing sea surface properties, as temperature, salinity, chlorophyll, and sea level height. In some ways it is convenient to "grow-up" with the developing technologies and expanding data sets, it helps one absorb the evolving observations "point-by-point"- to spot something strange. Today flooded with re-analysis data, model output, data streams from a wide array of in situ and satellite based sensors, buried in statistical analysis, it's more difficult to separate the "wheat from the chaff" to see a unique feature, to discover some new phenomena. I don't think my conceptual imagination would make it today's oceanography. The flood of data that we now collect daily reveals details of spatial and temporal variability of the global ocean at scales unimaginable 50 years ago. But there is still a place for isolated (random) observations that discover something new, something unexpected, if you can spot it.

3. My Research Path

My career quest is to develop a clearer, conceptual, picture of ocean, how it "works," with a tilt toward its role in governing the climate system. I worked in the cold southern polar regions to the hot tropics, and in-between, in each ocean (though not the Arctic sea, yet; Figure 1). Here I discuss a few discoveries that led to new insight into interocean exchange and deep ocean ventilation, which are now widely explored: (a) Southern ocean: two modes of convection; (b) Agulhas Leakage: Indian Ocean invades the Atlantic, part of the global interocean thermocline exchange; (c) The Indonesian Throughflow: tropical Pacific water spreads into Indian Ocean, more massive and cooler than expected.

1. Southern Ocean.

From Gordon 2012: "Scientific discovery at sea is exhilarating, an adventure that few experience. The long voyage far away from home is rewarded with new views of how the ocean is stratified and circulates, and with insight on the processes that govern its behavior. Collecting data at sea is specially challenging in remote regions of harsh conditions as in the Southern Ocean, where wind, waves and ice conspire to make observations particularly difficult.

Circumpolar survey (Figure 2). My first adventure into the cold Southern Ocean, was the *USNS ELTANIN* circumpolar survey (Gordon, 2012), which may be viewed as the closing phase of an era of broad-based surveys of the Southern Ocean. It consisting of a series of ∼60 day cruises aboard the *USNS ELTANIN*, later run by Argentina as the *ARA Islas Orcadas* 1976 to 1978 (I directly participated in 9 *ELTANIN/ISLAS ORCADAS* cruises); and the Lamont research vessel the *Conrad* in the southwest Indian Ocean in 1977, and in the perennial sea ice fields of the western margin of the Weddell Sea in 1992 by the Ice Station Weddell (see below). These expeditions were built on the circumpolar legacy of Sir George Deacon of the 1930s (Deacon, 1984). I visited Sir George at the National Oceanography Centre in Wormley, Surrey, England (I learned how to drive on the wrong side of the road) during my first sabbatical leave from Columbia in 1973.

I learned a lot from working within the ∼21,000 km Southern Ocean circumpolar belt around Antarctica, which links the major oceans basins. It is not a uniform structure, but varies markedly with longitude. The Southern Ocean is broken into distinct sectors. The Antarctic Circumpolar Current and associated fronts shift from ∼50°S to 65°S, guided by sea floor topography; Antarctic Bottom Water is formed in a few sites along the continental margin of Antarctica, with quite a range of salinity; cyclonic gyres of varied sizes fall between the Antarctic Circumpolar Current and Antarctica's continental margin, affecting the seasonal sea ice cover extent.

Weddell Sea Convection: Aboard the *Isla Orcadas* in the austral summer 1977, in the central region of the Weddell Sea, a chance discovery was made. The pen and ink plotter recorded the temperature and salinity profiles as the CTD was slowly lowered into the ocean. It looked strange: there was no T-max or S-max, characteristic of the Weddell Deep Water (WDW). Rather, I saw a near homogeneous water column to ∼2,500 m, except for the low salinity surface water layer. I thought the pens were stuck, I moved them with my finger to free them up-no change-the WDW maximum were not there! I realized that there had to be deep reaching convection in the previous winter to do this. I had the ship follow a star pattern to get at the horizontal dimension of the anomaly, at ∼10 km Rossby Radius scale. A convective chimney was discovered. It was only after the cruise did I learn of satellite observations that revealed the existence of the Weddell Polynya - a large ice free region in winters of 1974–1976.

Discovery: enhanced deep reaching open ocean convection injected deep ocean "warm" water into the surface layer, prohibiting sea ice formation; representing another mode of Southern Ocean ventilation far from the continental margin (Gordon, 1978, 2014). Why did deep reaching convection occur in the mid-1970s? It is likely associated with a prolonged -SAM that leads to a saltier, denser surface layer (Gordon, 2014; Gordon et al., 2007). Lesson: pay attention to the data stream in near real time, to quickly follow-up with more observations, so that the anomalous point is not throw out later as "bad data." I had a similar experience occurred about 6 years later working off the SW coast of Africa, discussed below.

Ice Station Weddell 1992 (*ISW;* Figure 3). In 1989 I signed an agreement with Nikolai A. Kornilov, of the Arctic/Antarctic Research Institute (AARI) in Leningrad USSR, to establish a field station on an ice floe drifting northward along the western margin of the Weddell Sea. The ISW was carried out in the first half of 1992 (Gordon & Ice Station Weddell Group of Principal Investigators and Chief Scientists, 1993; Gordon et al., 1993; Muench & Gordon, 1995). The USSR to Russia transition after signing of the agreement did not hinder the 1992 implementation. The 25th anniversary was celebrated in St Petersburg in February 2017. The western Weddell Sea is where most of the globally important Antarctic Bottom Water is formed, but has limited observations because of the thick year-round sea ice cover. To gain access to the western Weddell Sea we needed to work from an ice floe drifting northward along the western Weddell Sea margin. Ice floe stations were commonly used for arctic studies, mainly by Russia.

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Figure 3. Upper left panel: signing of the agreement for the USA/USSR Ice Station Weddell in 1989. Lower left panel, the Ice Station Weddell commemorative plaque. Upper right, group picture in early June 1992 ending the USA/Russian Ice Station Weddell ice floe adventure. Lower right panel: group picture at the 25th anniversary in St Petersburg, February 2017.

Water column physical and chemical observations to the sea floor, as well as sea ice, biological and atmospheric measurements, were made as the ice floe drifted northward (~6.6 km/day). They revealed a benthic layer of 200–300 m thick, with swift flow to the north, carrying concentrated Weddell Sea Bottom Water toward the world ocean. Helicopter were used to obtained four east-west temperature/salinity sections from the outer continental shelf to the deep ocean east of the ice floe trajectory. They detailed the nature of the shelf-slope front that coupled the continental margin to the deep ocean, and the ocean processes that provided the first view of the western boundary of the Weddell Sea that ventilated the abyssal world ocean with cold Antarctic Bottom Water.

The ISW expedition in the remote perennial sea ice cover of the western Weddell Sea, with limited access, was risky, dangerous, but it worked! A truly historical expedition. ISW adventure may best be summarized by quoting a section of the closing statement prepared on 9 June 1992: "The difficult environmental conditions of the western Weddell Sea have previously prohibited data collection in this segment of the Southern Ocean. Only now in the closing decade of the 20th century has this region been thoroughly observed through this joint effort. Ice Station Weddell, the 1st drift station of the Southern Ocean, becomes an important part of the history of Antarctic exploration, filling a large gap in our view of this remote part of the global ocean."

2. Agulhas Retroflection and leakage into the Atlantic Ocean.

This work brought me to a collaboration with the great South Africa oceanographer Lutjeharms (2006) (Lutjeharms' comprehensive book "The Agulhas Current," 2006, "in memory of Günther Dietrich, 2011–1972, the first true oceanographer of the Agulhas Current system").

Aboard the *R/V Knorr* in November/December 1983, I was surveying the Agulhas Retroflection, where the Indian Ocean Agulhas Current flows along the southern rim of Africa before curling back to the Indian Ocean. We left Cape Town and took a test CTD station in the Cape Basin of the southeast South Atlantic Ocean, to see if all was working. Having worked in the South Atlantic a few years earlier, and aware of the 1925–1928 R/V Meteor data (one of the primary contributions of my advisor Wüst). I knew what I would find. Wrong. The test CTD did not depict South Atlantic from the eastward flowing southern limb of the South Atlantic subtropical gyre, but rather Indian Ocean subtropical water. *How did it get there?*

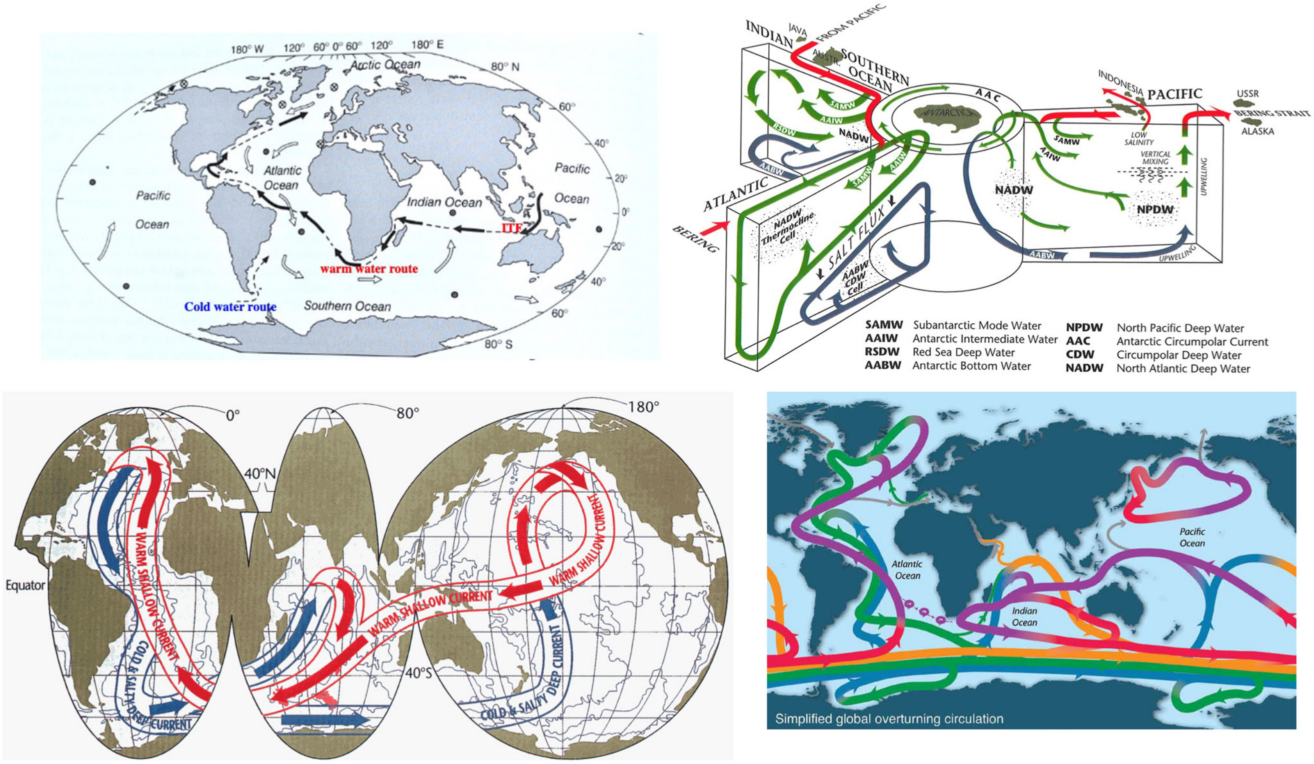

Figure 4. Upper left, interocean exchange of cold and warm thermocline water and Indonesian Throughflow; solid arrows represent thermocline flow; open arrows represent deep water flow (modified from Gordon [1986a]). Lower left: the Great Conveyor Belt (Schmitz, 1995; modified from Broecker [1991]). Upper right: three winged schematic links to the Antarctic Circumpolar Current (Gordon, 1991). Lower right: an example detailed interocean wiring schematic, Talley, 2013 (modified from Schmitz [1995]).

A star pattern survey, of ∼100 km dimensions was implemented to confirm and to define the spatial nature of the unexpected feature. It was clearly an eddy or Ring of southern Indian Ocean water shed from the western edge of the Agulhas Retroflection.

Discovery: the Agulhas Retroflection was leaking into the Atlantic! This observation has important implications that led to key Interocean Thermocline exchange papers (Gordon, 1986a, 1986b, 2003) and the global view of the Atlantic Meridional Overturning Circulation (AMOC), often referred to as the Great Conveyor Belt (Broecker, 1991). Export of NADW into the Southern Ocean is compensated, at least partially by eddies and streams of Indian Ocean water-the so called warm route for the returning upper limb into the Atlantic thermocline. There is also a cold water route via the Drake Passage injecting water into the subthermocline layer (Rintoul, 1991). It's never simply one or the other, but rather a complex blend of each. In 1991, I did a three-wing schematic for a Lamont newsletter. In retrospect I should have published it in a journal. A plethora of complex wiring diagrams ensued (Figure 4, Richardson, 2008; Talley, 2013).

3. Indonesian Throughflow (ITF).

Agulhas Leakage drove me to the ITF within the Maritime Continent, the Indonesians seas. Agulhas Leakage had to be compensated, how? From plotting the salinity within the Indian Ocean (Gordon, 1986a, 1986b), I found a band of low salinity water stretching westward near 12°S, emanating from the Indonesian seas: the ITF. I had to "swim upstream" to the maritime continent. It was a challenge to develop the cooperative programs within Indonesian waters. A valued friend in Indonesian A. Gani Ilahude helped along the way. I so enjoyed getting to know Gani and the Indonesian people and culture.

After a "get-to-know" period 1985–1991, my first cruise was in December 1991, then Arlindo cruises (1993–1996); according to Gani Ilahude Arlindo means Indonesian throughflow. The Arlindo 1993 and 1994 cruises using water masses defined the multi-pathway ITF pattern and we set moorings in the narrow Labani

Channel to measure the ITF within Makassar Strait, the primary pathway. We discovered (Gordon, 2005) that the ITF was much larger than previously thought: 10–15 Sv, not surface intensified, but with a subsurface velocity maximum near 120 m, making for a colder than expected ITF. The throughflow profile was imposed by a freshwater plug, where low salinity surface layer of the Maritime Continent inhibited the surface water from the western tropical Pacific from freely flowing into the Indonesia seas. Arlindo was followed by a multi-national program to measure the transport in the ITF pathways simultaneously. There was the International Nusantara Stratification and Transport (INSTANT) program, 2004–2006, and extended time series of the Makassar Strait throughflow, ~80% of the total ITF (2007–2019), and now onto to the MINTIE (Measurements and Modeling of the Indonesian Throughflow) program, 2023–2025.

4. Conclusion

I did ok, better than I expected. My work has been recognized, awarded various honors, which I appreciate. I started many research "cottage industries": southern ocean circulation and overturning, including open ocean convection in the Weddell Sea; Agulhas Retroflection and Leakage, a central part of global interocean thermocline exchange; the ITF from Pacific to the Indian Oceans weaving its way through the complex geography of the Maritime Continent, spreading across the Indian Ocean.

How did I get from Brooklyn to see the world? Accident or a well thought out plan? You are faced with many opportunities in life, choosing the best for you depends on your interest ("passion" is the word often used now-a-days). The better you understand your interests, the better you recognize "opportunity." Keep your interest flexible, as opportunity may offer expansion or new aspects that has not occurred to you; be ready to accommodate opportunity. To wait for a better, more perfect fit opportunity? Risky. Accept "serendipity."

I had the pleasure of mentoring many graduate students, 21 received PhD and six received Master Degree. They are now following careers (some already retired, or sadly, deceased), not just in academia, but in government and industry. As anthropogenic activities alter the global climate system, stressing the environment, what was once a hobby to me is now essential in building a quantitative understanding and mitigating these adverse pressures affecting civilization. Hopefully I did my part in contributing to this group effort.

Data Availability Statement

No data was used, except what were cited in the varied references.

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References

Broecker, W. S. (1991). The great ocean conveyor. *Oceanography*, *4*(2), 79–89. https://doi.org/10.5670/oceanog.1991.07

Deacon, G. (1984). *The Antarctic circumpolar ocean* (p. 180). Cambridge University Press.

Gordon, A. L. (1978). Deep Antarctic convection west of Maud Rise. *Journal of Physical Oceanography*, *8*(4), 600–612. https://doi.org/10.1175/1520-0485(1978)008<0600:dacwom>2.0.co;2

Gordon, A. L. (1986a). Interocean exchange of thermocline water. *Journal of Geophysical Research*, *91*(C4), 5037–5046. https://doi.org/10.1029/jc091ic04p05037

Gordon, A. L. (1986b). Is there a global scale ocean circulation? *Eos, Transactions American Geophysical Union*, *67*(9), 109–110. https://doi.org/10.1029/eo067i009p00109

Gordon, A. L. (1991). The role of thermohaline circulation in global climate change. In *Lamont-Doherty Geological Observatory Newsletter* (pp. 44–51). Retrieved from https://academiccommons.columbia.edu/doi/10.7916/D8M04G8H

Gordon, A. L. (2003). The brawniest retroflection. *Nature News and Views*, *421*(6926), 904–905. https://doi.org/10.1038/421904a

Gordon, A. L. (2005). Oceanography of the Indonesian seas and their throughflow. *Oceanography*, *18*(4), 14–27. https://doi.org/10.5670/oceanog.2005.01

Gordon, A. L. (2012). Circumpolar view of the Southern Ocean from 1962 to 1992. *Oceanography*, *24*(3), 18–23. https://doi.org/10.5670/oceanog.2012.69

Gordon, A. L. (2014). Oceanography: Southern Ocean polynya. *News and Views for Nature Climate Change*, *4*(4), 249–250. https://doi.org/10.1038/nclimate2179

Gordon, A. L., Huber, B., Hellmer, H., & Ffield, A. (1993). Deep and bottom water of the Weddell Sea's western rim. *Science*, *262*(5130), 95–97. https://doi.org/10.1126/science.262.5130.95

Gordon, A. L., & Ice Station Weddell Group of Principal Investigators and Chief Scientists. (1993). Ice station Weddell 1 explores the western edge of the Weddell Sea. *Eos, Transactions American Geophysical Union*, *74*(121), 124–126. https://doi.org/10.1029/93eo00260

Gordon, A. L., Visbeck, M., & Comiso, J. C. (2007). A possible link between the Weddell Polynya and the Southern Annular Mode. *Journal of Climate*, *20*(11), 2558–2571. https://doi.org/10.1175/JCLI4046.1

Lutjeharms, J. (2006). *The Agulhas Current*. Springer.

Muench, R., & Gordon, A. L. (1995). Circulation and transport of water along the western Weddell Sea margin. *Journal of Geophysical Research*, *100*(C9), 18503–18515. https://doi.org/10.1029/95jc00965

10.1029/2022CN000159

Richardson, P. L. (2008). On the history of meridional overturning circulation schematic diagrams. *Progress in Oceanography*, *76*(4), 466–486. https://doi.org/10.1016/j.pocean.2008.01.005

Rintoul, S. (1991). South Atlantic interbasin exchange. *Journal of Geophysical Research*, *96*(C2), 2675–2692. https://doi.org/10.1029/90jc02422

Riser, S. C., Freeland, H. J., Roemmich, D., Wijffels, S., Troisi, A., Belbéoch, M., et al. (2016). Fifteen years of ocean observations with the global Argo array. *Nature Climate Change*, *6*(2), 145–153. https://doi.org/10.1038/NCLIMATE2872

Schmitz, W. J. (1995). On the interbasin-scale thermohaline circulation. *Reviews of Geophysics*, *33*(2), 151–173. https://doi.org/10.1029/95rg00879

Talley, L. D. (2013). Closure of the global overturning circulation through the Indian, Pacific, and Southern Oceans: Schematics and transports. *Oceanography*, *26*(1), 80–97. https://doi.org/10.5670/oceanog.2013.07