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Graphical Methods and Cold War Scientific Practice: The Stommel Diagram's Intriguing Journey from the Physical to the Biological Environmental Sciences

ABSTRACT

In the last quarter of the twentieth century, an innovative three-dimensional graphical technique was introduced into biological oceanography and ecology, where it spread rapidly. Used to improve scientists' understanding of the importance of scale within oceanic ecosystems, this influential diagram addressed biological scales from phytoplankton to fish, physical scales from diurnal tides to ocean currents, and temporal scales from hours to ice ages. Yet the Stommel Diagram (named for physical oceanographer Henry Stommel, who created it in 1963) had not been devised to aid ecological investigations. Rather, Stommel intended it to help plan large-scale research programs in physical oceanography, particularly as Cold War research funding enabled a dramatic expansion of physical oceanography in the 1960s. Marine ecologists utilized

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The following abbreviations are used: AFSC, Alaska Fisheries Science Center; FLEX, Fladen Ground Experiment; GEOSECS, Geochemical Ocean Sections Study; HMS, Papers of Henry M. Stommel, Data Library and Archives, Woods Hole Oceanographic Institution, Woods Hole, MA; ICES, International Council for the Exploration of the Sea; IDOE, International Decade of Ocean Exploration; IGY, International Geophysical Year; IOC, Intergovernmental Oceanographic Commission; LTER, Long-Term Ecological Research; MSY, Maximum Sustainable Yield; NATO, North Atlantic Treaty Organization; NMFS, National Marine Fisheries Service; NOAA, National Oceanic and Atmospheric Administration; RBM, Papers of Raymond B. Montgomery, Data Library and Archives, Woods Hole Oceanographic Institution, Woods Hole, MA; Scripps or SIO, Scripps Institution of Oceanography, La Jolla, CA; TENOC, Ten Years in Oceanography; UNESCO, United Nations Educational, Scientific, and Cultural Organization; WHM, Walter Munk Papers, Scripps Institution of Oceanography Archives, University of California, San Diego, La Jolla, CA; Woods Hole or WHOI, Woods Hole Oceanographic Institution, Woods Hole, MA; WOCE, World Ocean Climate Experiment.

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the Stommel Diagram to enhance research on biological production in ocean environments, a key concern by the 1970s amid growing alarm about overfishing and ocean pollution. Before the end of the twentieth century, the diagram had become a significant tool within the discipline of ecology. Tracing the path that Stommel's graphical techniques traveled from the physical to the biological environmental sciences reveals a great deal about practices in these distinct research communities and their relative professional and institutional standings in the Cold War era. Crucial to appreciating the course of that path is an understanding of the divergent intellectual and social contexts of the physical versus the biological environmental sciences.

KEY WORDS: scientific diagrams, scientific techniques, knowledge transmission, multidimensional, Henry Stommel, Loren Haury, physical oceanography, marine ecology

INTRODUCTION

In 1978, Loren R. Haury, then a thirty-nine-year-old biological oceanographer at the Woods Hole Oceanographic Institution and John McGowan and Peter Wiebe, published a landmark paper in the field of plankton studies. At the heart of the paper, jointly written with two fellow biological oceanographers, was an innovative graphical interpretation labeled the Stommel Diagram. While geographers, physicists, mathematicians, and astronomers had tried for decades to represent the four dimensions of space and time on a two-dimensional graph, the Stommel Diagram, published in 1963, was perhaps the first effort to use a three-dimensional diagram to graphically capture similar phenomena in the marine sciences.[1] Haury and his colleagues employed the Stommel Diagram to describe the time and space scales of plankton distributions, then a critical challenge for biological oceanographers. Marine scientists had come to realize that plankton was clumped, not uniform, throughout the near-surface oceans, and understanding phytoplankton concentrations in three dimensions, and how it changed over time, was crucial for understanding its role as a food source for marine life. Within a decade after the paper by Haury et al. appeared,

1. These include Minkowski diagrams in physics and topside ionograms in the atmospheric sciences; on these developments see respectively Stanley Goldberg, *Understanding Relativity: Origin and Impact of a Scientific Revolution* (Boston: Birkhauser, 1984), and Edward Jones-Imhotep, "Disciplining Technology: Electronic Reliability, Cold-War Military Culture and the Topside Ionogram," *History and Technology* 17 (2000): 125–75. Oceanographers used two-dimensional temperature-salinity (T-S) diagrams starting in the 1910s with the research of Bjørn Helland-Hansen; for an introduction see Eric Mills, *The Fluid Envelope of Our Planet: How the Study of Ocean Currents Became a Science* (Toronto: University of Toronto Press, 2009): 180.

the Stommel Diagram had become a central tool of ecology, a highly effective means to compare "space and time scales of ecological questions to the capacity of research programs."[2]

Especially interesting is the subject matter of the 1978 Stommel Diagram. What Haury and his colleagues presented was not the same diagram that Stommel had developed nearly a decade and a half earlier. The original was also a three-dimensional graphical depiction of four-dimensional phenomena. But Stommel's 1963 graph addressed the space and time scales of *physical* phenomena in the high seas, the field in which Stommel worked, and was addressed to colleagues in physical oceanography. By 1978 the Stommel Diagram, which had generated only limited enthusiasm in the physical sciences, made a significant cross-disciplinary leap.

Graphical techniques are one of the most important modern developments in science, allowing the representation of relationships not immediately discernible from tables or equations. Absent during the Scientific Revolution, their rapid proliferation in the nineteenth century suggests, as Thomas L. Hankins has noted, "a profound change in the way that scientists go about their business."[3] In 1840 the British astronomer John Herschel, who had pioneered graphical techniques to calculate orbits for double stars, justified graphical methods in science as providing "the intermediate step between observation and theory that enable the theorist in particular, to choose his ground above all individual place and circumstance, and to select his data, not where casualty or convenience shall have led the observer to collect them."[4] Graphs, claimed Herschel's contemporary William Whewell, the philosopher and Cambridge scientist, could help suppress errors and create facts "more true than the individual facts themselves." As both Herschel and Whewell anticipated, graphical techniques would become particularly crucial for the field sciences, where abundant data at various spatial and temporal scales were often unavailable prior to the late twentieth century. Already

2. Loren R. Haury, John A. McGowan, and Peter H. Wiebe, "Patterns and Processes in the Time-Space Scales of Plankton Distribution," in *Spatial Pattern in Plankton Communities*, ed. John H. Steele (New York: Plenum Press, 1978), 277–327. On the significance of the Stommel Diagram for contemporary ecology, see Simon A. Levin, "The Problem of Pattern and Scale in Ecology: The Robert H. MacArthur Award Lecture," *Ecology* 73, no. 6 (1992): 1943–67, esp. 1943–44; for an overview see David C. Schneider, "The Rise of the Concept of Scale in Ecology," *BioScience* 51, no. 7 (2001): 545–53, on 548.

3. Thomas L. Hankins, "Blood, Dirt, and Nomograms: A Particular History of Graphs," *Isis* 90 (1999): 50–80, on 52.

4. John Herschel, quoted in Thomas L. Hankins, "A 'Large and Graceful Sinuosity': John Herschel's Graphical Method," *Isis* 97 (2006): 605–33, on 625.

by the late 1830s Whewell had successfully laid the foundations for a science of tides using this approach.[5] Despite their significance, however, graphical techniques have received relatively limited attention from historians of science, who have primarily studied the origin of particular graphical techniques and their diffusion within individual disciplinary communities, leaving aside how innovations migrated into new multidisciplinary territories.[6]

The Stommel Diagram's leap from the physical to the biological sciences therefore can offer significant insights into how experimental and theoretical techniques, typically embodiments of tacit knowledge, cross disciplinary thresholds and become adopted (and modified) by new research communities. Several immediate questions emerge: What did Stommel intend to achieve with his pioneering graphical technique? And why did physical oceanographers pay comparatively little attention to his graph, even though he was widely regarded as one of the most influential oceanographers of the twentieth century?[7] Did other techniques fill the same niche for the physical oceanographers? How did the diagram take root in biology, and in what ways did it travel? Why did the Stommel Diagram only begin to spread exponentially once it became a tool of biological oceanographers and ecologists, and why did the diagram retain

5. William Whewell, *The Philosophy of the Inductive Sciences, Founded Upon Their History* (London: John W. Parker, 1840), quoted in Michael S. Reidy, *Tides of History: Ocean Science and Her Majesty's Navy* (Chicago: University of Chicago Press, 2008), 191; on Whewell's larger institutional and professional aims, see 6–17 and 122–295. As Reidy notes, "As science expanded geographically and the object became to find the relationship among increasingly complex variables, the visual graph emerged as a means of accurate and useful representation. The graph was ideally suited to represent massive amounts of data at a single synoptic glance; visual trends appeared in the data that were difficult if not impossible to discern through tables." (191)

6. Notable exceptions, in addition to Hankins, "Blood, Dirt" (ref. 3), include two important recent contributions by David Kaiser: *Drawing Theories Apart: The Dispersion of Feynman Diagrams in Postwar Physics* (Chicago: University of Chicago Press, 2005), and David Kaiser, ed., *Pedagogy and the Practice of Science* (Cambridge, MA: MIT Press, 2005); see also Michael Lynch and Steve Woolgar, *Representation in Scientific Practice* (Cambridge, MA: MIT Press, 1990); Martin J. S. Rudwick, "The Emergence of a Visual Language for Geological Science, 1760–1840," *History of Science* 14 (1976): 149–95; and Michael Friendly, "Milestones in the History of Data Visualization: A Case Study in Statistical Historiography," in *Classification: The Ubiquitous Challenge,* ed. C. Weihs and W. Gaul (New York: Springer Verlag, 2005), 1–19.

7. Oceanographer Carl Wunsch described Stommel as "probably the most original and important physical oceanographer of all time"; see Carl Wunsch, "Henry Stommel," *Biographical Memoirs of the National Academy of Sciences* 72 (1997): 350–51, on 350. Naomi Oreskes's comprehensive entry for Stommel in the *New Dictionary of Scientific Biography* does not mention Stommel's graphical work at all; see Oreskes, s.v. "Stommel, Henry Melson," *New Dictionary of Scientific Biography*, vol. 6 (Detroit, MI: Charles Scribners and Sons, 2007), 527–32.

Stommel's name (and priority) even when it was the work of Haury and his colleagues that made the Stommel Diagram accessible to them?

The uses of the Stommel Diagram are also of interest. David Kaiser has rightly emphasized that, from the time of their integration into science, graphical techniques were less related to theory than to calculation: by examining graphs, he writes, "at once we have been drawn into a world of *calculations,* rather than worldviews, paradigms, or theories."[8] Yet the Stommel Diagram was not a means of calculation, either in physics or biology. To this day, a quantitative Stommel Diagram has yet to be produced.[9] Did supporters of the Stommel Diagram value it primarily for its potential to make calculations, or rather as a means to improve experimental design, to reduce bias in experimental data, and to evaluate competing theoretical claims?

It is also worth noting that the Stommel Diagram was transformed as it moved from physics and blossomed in biology, its axes now reflecting factors germane to marine ecology rather than the properties of ocean waters. In "Visualization and Cognition: Drawing Things Together," Bruno Latour argued that the process of scientific communication and the production of knowledge depends on immutable mobiles traveling largely intact to and from centers of calculation, particularly those that are graphical in nature. As Latour notes, "they are *immutable* when they move, or at least everything is done to obtain this result."[10] Kaiser has challenged a strict Latourian interpretation of the spread of perhaps the most iconic and powerful graphical representation in twentieth-century science, the Feynman Diagram in nuclear physics, introduced by the U.S. physicist Richard Feynman in 1949. Certainly the ecological version of the Stommel Diagram *looked* like its physical oceanographic counterpart, and both varieties portrayed similar kinds of phenomena. But once integrated into biology, the Stommel Diagram sometimes appeared in two distinct forms—one of which (a simplified two-dimensional translation) bore only a limited resemblance to Stommel's original 1963 creation. Tools are indeed malleable and multivalent.[11] But Kaiser's study focused on laboratory

8. Kaiser, *Drawing Theories* (ref. 6), 356.

9. Tiffany C. Vance, "If You Build It, Will They Come? Evolution Towards the Application of Multi-Dimensional GIS to Fisheries Oceanography" (PhD dissertation, Oregon State University, 2008), 103.

10. Bruno Latour, "Visualization and Cognition: Drawing Things Together," *Knowledge and Society* 6 (1986): 1–40, on 19.

11. See Kaiser, *Drawing Theories* (ref. 6), 18, where he relies on insights by Claude Lévi-Strauss.

science. Additional insights may emerge by examining how new methods are transmitted within the field sciences, particularly among members of research communities seeking to classify phenomena on various scales, an issue critically important to ecosystems theory in the second half of the twentieth century.[12]

Understanding why Stommel created his original diagram, and its subsequent leap to the biological sciences, we argue, requires a careful examination of the distinct circumstances of physical and biological oceanography in the second half of the twentieth century. In particular, they involve the character of post–World War II science, disputes over patronage and the production of knowledge, the development of technologies able to collect massive amounts of data, the rapid rise of ecology as a distinct research field, geopolitical struggles over marine exclusive zones, the decline of commercial fisheries populations, and the political economy of the environmental sciences within the United States. That is to say, the manner in which Stommel's graphical technique emerged as a key ecological tool reveals much about the practices and standing of a wide range of science disciplines in the Cold War era, in particular the emerging environmental sciences in the United States—and its initially far better-supported physical branches.

HENRY STOMMEL AND THE CREATION OF THE STOMMEL DIAGRAM

Henry (Hank) Stommel (1920–1992) was one of the most prominent and influential U.S. oceanographers of the twentieth century. Intellectually restless, with remarkably broad interests, Stommel entered Yale University in the late 1930s believing himself bound for divinity school. Instead, he graduated in 1942 with a degree in astronomy. He then began wartime service, spending the next two years teaching analytic geometry and celestial navigation in Yale's Navy V-12 program, designed to provide a short but thorough college education to potential officers. Stommel's upbringing as a Methodist pacifist made him reluctant to serve in the military; he later cited his role as a teacher as "not a consistent or logical moral position, but at least I was not personally killing

12. This point is indirectly raised in Robert E. Kohler, "Plants and Pigeonholes: Classification as a Practice in American Ecology," *Historical Studies in the Natural Sciences* 38, no. 1 (2008): 77–108, esp. 80; related arguments appear in Henrika Kuklick and Robert E. Kohler, eds., *Science in the Field*, *Osiris* 11 (1996), and George Malanson, "Considering Complexity," *Annals of the Association of American Geographers* 89 (1999): 746–53.

FIG. 1 Henry Stommel at sea [likely 1960s]. *Source:* Photo from The Cecil H. and Ida M. Green branch of the University of California Systemwide Institute of Geophysics and Planetary Physics (IGPP), http://igpp.ucsd.edu/aboutigpp/doors/2208HenryStommel.jpeg (last accessed 10 Nov 2009). Reprinted with permission of the IGPP.

anybody."[13] A brief enrollment in the Yale Divinity School during the war and graduate work in astronomy did not suit him. In 1944, on the advice of Yale astronomer Lyman Spitzer, Stommel undertook war work at the Woods Hole Oceanographic Institution (WHOI) in Massachusetts, the preeminent

13. Henry Stommel, "The Sea of the Beholder" (drafted in 1984), published in Nelson G. Hogg and Rui Xin Huang, *Collected Works of Henry M. Stommel* (Boston, MA: American Meteorological Society, 1995), I–16. See also Wunsch, "Henry Stommel" (ref. 7), and Oreskes, "Stommel" (ref. 7).

oceanographic research laboratory on the East Coast. There he joined the research team of geophysicist Maurice Ewing, who was engaged in undersea sound research funded by the U.S. Navy. Stommel developed a love for oceanography while hating Ewing's gruff, authoritative style.[14]

After the war ended, Stommel remained at WHOI. The Harvard physiologist Jeffries Wyman, whom Stommel had met upon his arrival at WHOI and who had spent World War II working there on a variety of war-related research programs, including the detection of submarines, the use of smoke screens, and meteorological measurements, sensed that Stommel was floundering without a clear research direction. He suggested a focus on the entrainment of air in clouds, which launched what proved to be Stommel's lifelong interest in convection in the atmosphere and especially in the ocean. A semester spent at the University of Chicago in 1946 exposed him to two leading meteorologists, Carl-Gustav Rossby and Victor Starr.[15] While pursuing theoretical studies, Stommel also became familiar with oceanographic instruments. After gaining further theoretical and instrumental skills in England during the fall of 1947, he traveled to Scotland to meet the noted geophysicist Lewis Fry Richardson, doing experiments with him on eddy diffusion. Their experiments involved the use of carefully weighted slices of parsnips as drifting buoys, a novel approach that demonstrated his experimental versatility.[16] Stommel's reputation in physical oceanography was established very early in his career. His first major study addressed the westward intensification of wind-driven currents, which he published in the *Transactions of the American Geophysical Union* in 1948. Drawing on Rossby's theoretical work on the vorticity equation, Stommel demonstrated that western boundary currents, such as the Gulf Stream and the Kuroshio Current, resulted from the variation of the Coriolis force with latitude. This

14. Stommel, "Sea of the Beholder" (ref. 13), I–17. On Ewing, see "William Maurice Ewing," *Biographical Memoirs of the National Academy of Sciences* 51 (1980): 118–93.

15. Stommel, "Sea of the Beholder" (ref. 13), I–18; on Rossby, and on the disciplines of meteorology and fluid dynamics in this period, see Robert Marc Friedman, *Appropriating the Weather: Vilhelm Bjerknes and the Construction of a Modern Meteorology* (Ithaca, NY: Cornell University Press, 1989), and Kristine C. Harper, *Weather by the Numbers: The Genesis of Modern Meteorology* (Cambridge, MA: MIT Press, 2008).

16. Stommel, "Sea of the Beholder" (ref. 13), I–18; see also Raymond B. Montgomery, "Notes Related to Stommel's Early Years in Woods Hole," n.d. [1979], RBM, Box 16. Their paper (L. F. Richardson and H. M. Stommel, "Note on the Eddy Diffusion in the Sea," *Journal of Meteorology* 5, no. 5 (1948): 238–40) starts with one of the more intriguing first lines ever seen in a scientific journal article: "We have observed the relative motion of two floating pieces of parsnip, and have repeated the observation for many such pairs at different initial separations." (238)

soon-classic paper established Stommel's ability to create simple models of idealized situations that required limited mathematics. By the early 1950s, he began stressing the need for detailed time-series data on pressure, temperature, and currents in the deep oceans for use in theoretical models of ocean circulation. Working with the British oceanographer John Swallow, who had developed the Swallow float to record such data, Stommel began investigating fluctuations of flow in the deep oceans.[17]

In arguing that new forms of measurement were on the horizon, Stommel shared the concerns of many physical oceanographers that modeling efforts might proceed without sufficient observational verification. In 1955 the Woods Hole physical oceanographer William von Arx warned colleagues that "we lack the necessary insight to extend our thinking very far without observations to verify our progress."[18] In his own subsequent writing, Stommel insisted that "too much of the theory of oceanography has depended upon purely hypothetical physical processes. Many of the hypotheses suggested have a peculiar dream-like quality, and it behooves us to submit them to especial scrutiny and to test them by observation."[19]

Well into the second half of the twentieth century, most researchers in oceanography were primarily theorists or experimentalists. Stommel was both: from the late 1940s to his death in 1992, his work touched on almost all branches of physical oceanography. In 1959, noting that oceanography was "one of the last remaining strongholds of the all-embracing naturalist," the eminent geophysicist Jule Charney declared that Stommel (and Walter Munk at Scripps) were its two most versatile practitioners.[20] Munk himself declared in 1960 that "[n]o other living person" besides Stommel "has such a record in the field of oceanography."[21] Stommel's rapid rise in physical oceanography ultimately

17. Arnold Arons, "The Scientific Work of Henry Stommel," in *Evolution of Physical Oceanography: Scientific Surveys in Honor of Henry Stommel*, ed. Bruce Alfred Warren and Carl Wunsch (Cambridge, MA: MIT Press, 1981), xvi; and Russ E. Davis, "Contributions to Global Ocean Circulation," in *Physical Oceanography: Developments Since 1950*, ed. Markus Jachum and Raghu Murtugudde (New York: Springer, 2006), 45–66, on 46–47.

18. W. M. Ewing, handwritten notes on presentation by William S. Von Arx, WHOI, "On the Promise and Limitations of Ocean Model Experiments," undated [circa 1955], W. Maurice Ewing papers, Center for American History, University of Texas at Austin, Box 57.

19. Henry Stommel, *The Gulf Stream: A Physical and Dynamical Description* (Berkeley: University of California Press, 1965), 178.

20. Jules Charney, letter of recommendation for Walter Munk, undated [Mar 1959], Frank Press Collection, MIT Archives, Box 14.

21. Munk to George F. Carrier, 14 Jan 1960, WHM, Box 19.

caused him to forgo further graduate training in the field. In the late 1940s he considered getting a PhD from Brown or Scripps. But after Munk and his senior colleague Roger Revelle argued he already deserved the degree "sight unseen"—and Columbus Iselin advised him that his achievements made it unnecessary—Stommel did not seek the degree. Rare in the earth sciences by that time but not unheard of, Stommel became one of the last of the postwar generation of leading U.S. researchers lacking a PhD, a development that occasionally hindered his relationships with graduate students without affecting his international renown.[22]

In 1958 Paul Fye succeeded Iselin as WHOI director. A heavy-handed administrator, more comfortable than Iselin in working with military agencies on applied projects, Fye sought to steer the direction of research at Woods Hole by appointing a director of research. His controversial plans led several researchers, Stommel included, to resign. In 1959 Stommel accepted an offer to teach at Harvard. Uncomfortable there—likely because he lacked a doctorate—Stommel then accepted a primarily research appointment at the Massachusetts Institute of Technology. Still attracted to the ambience of Cape Cod and to the research community at WHOI, Stommel finally returned there in 1977 after Fye retired as director.

Through the early 1960s, most of Stommel's publications on physical oceanography appeared in focused research journals. At the same time, he gave thought to the larger questions raised by the tools used to collect the data for these publications. The flood of new data, the development of new instruments, and the challenges of understanding phenomena at varying spatial and temporal scales in the oceans over long periods of time—all were on Stommel's mind. Indeed, they had begun to coalesce in his thoughts nearly ten years before, and were captured in a question that became the title of one of his most influential privately circulated papers, "Why Do Our Ideas about the Ocean Circulation Have Such a Peculiarly Dream-Like Quality?"[23] In many respects,

22. See Ray Montgomery to Stommel, 23 Mar 1950, RBM, Box 263; Munk to Stommel, 18 Apr 1950, WHM, Box 19; and Iselin to Stommel, 30 Apr 1950, HMS, Box 2, Folder 3. Other leading earth scientists in Stommel's generation lacking a PhD included Sydney Paige, John Ewing, Lloyd V. Berkner, and Vincent Schaffer; on Berkner and Schaffer respectively see Allan A. Needell, *Science, the Cold War, and the American State: Lloyd V. Berkner and the Balance of Professional Ideals* (London: Harwood Academic Press, 2000), and Kristine C. Harper, "Climate Control: U.S. Weather Modification in the Cold War and Beyond," *Endeavour* 32, no. 1 (2008): 20–26.

23. Henry Stommel, "Why Do Our Ideas about the Ocean Circulation Have Such a Peculiarly Dream-Like Quality?" (written in 1954), reprinted in Hogg and Huang, *The Collected Works of Henry M. Stommel* (ref. 13), I–124, I–135.

Stommel's self-published "Dream-Like" pamphlet—written in 1954, a time when numerous papers in rapidly growing physical science fields circulated outside of formal journals—pointed the way toward what later became known as the Stommel Diagram.[24] Forwarding the paper to colleagues in physical oceanography, Stommel called it "a little memo about types of observations needed in oceanography," adding that it was a "polemical pamphlet."[25] The polemical label was apt. It was a creative approach Stommel employed to deal with his mounting frustration over the lack of widespread systematic data collection that he believed necessary to gain "an accurate idea of the mean distribution of properties in the ocean."[26]

Not until 1963 did Stommel write a second, similarly forceful statement on experimental practices in physical oceanography, this time for publication. "Varieties of Oceanographic Experience"—his "valedictory to Harvard," as he later put it—appeared in the journal *Science*.[27] In contrast to his "Dream-Like" paper of nine years before, "Varieties" was largely qualitative. But it contained his strongest assertion yet of what he considered one of the key challenges of physical oceanography: the design of expeditionary programs needed to take into account the "whole spectrum of phenomena" on both periodic and geometric scales. This paper marked the first appearance of what was later termed the Stommel Diagram.

This now-classic Stommel Diagram (Fig. 2a) was a "schematic diagram of the spectral distribution of sea level."[28] As Stommel devised it, the diagram was a three-dimensional plot with time versus space as the axes of the horizontal (X-Y) surface, and the power of the spectrum as the vertical (Z) axis. Short time period and short wavelength phenomena (such as gravity waves and tsunamis) were represented near the X-Y origin.[29] Very long-term variations—for example, ice age changes in sea level—appeared at the extremes of X and Y.

24. Arons, "Scientific Work" (ref. 17), xvi. On the widespread circulation of mimeographed notes and lectures after World War II, see Kaiser, *Drawing Theories* (ref. 6), 257.

25. Stommel to Drs. Munk, Arthur, Knauss, and Montgomery, 1 Jun 1954; and Stommel to Munk, 10 May 1954, both in WHM, Box 19, Folder Stommel 1954.

26. Stommel, "What Do We Know about the Deep Ocean Circulation?" text for talk at Deep-Sea Research Symposium, undated [circa 1955], W. Maurice Ewing papers, Center for American History, University of Texas at Austin, Box 57.

27. Stommel, "Sea of the Beholder" (ref. 13), I–47.

28. Henry Stommel, "Varieties of Oceanographic Experience," *Science* 139, no. 3555 (1963): 572–76.

29. Gravity waves in the earth and atmospheric sciences are distinct from gravitational waves or gravitational radiation, which are perturbations in space-time as treated in general relativity;

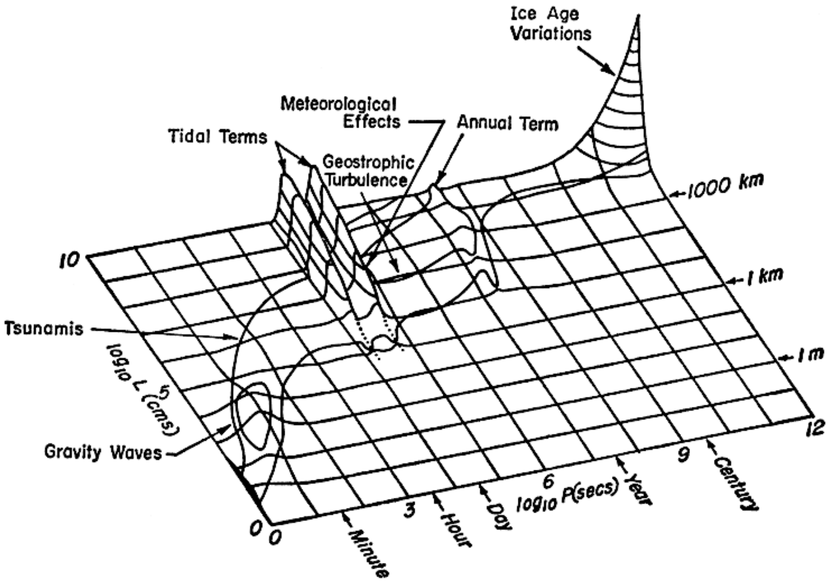

FIG. 2A The original Stommel Diagram, "Schematic Diagram of the Spectral Distribution of Sea Level." A three-dimensional graphical depiction of four-dimensional phenomena, it portrays space and time scales of physical phenomena in the high seas, from tsunamis to ice ages. *Source:* Stommel, "Varieties" (ref. 28), 573. Reprinted with permission from AAAS.

Tidal terms were depicted as two peaks, with long wavelengths and high power at a 12- and 24-hour timing. While intending to illustrate a general point, Stommel went on to provide a practical example. He used the plot to evaluate the results of the *Argo* research cruise in the Indian Ocean, undertaken by Scripps in 1960 as part of the Indian Ocean Expedition. (Fig. 2b) On this plot he indicated the spectra researchers expected to see (B) and the spectra actually observed on the cruise (C). In so doing, he showed how a cruise designed to measure one set of spectra could not correctly map another set of spectra due to the mismatch in the timing and spacing of the samples researchers had taken. What made the diagram particularly significant and potentially useful was that it portrayed all of these relationships simultaneously.

At the time, researchers in physical oceanography were quite familiar with a wide range of techniques to visually display data and theoretical relationships. Throughout the 1950s and early 1960s one of the prime periodicals in the field,

on attempts to detect the latter see Harry Collins, *Gravity's Shadow: The Search for Gravitational Waves* (Chicago: University of Chicago Press, 2004).

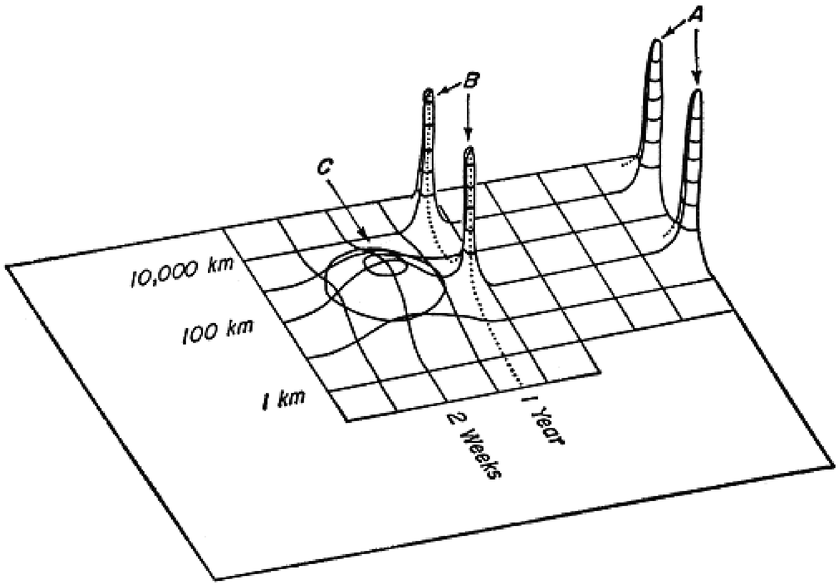

FIG. 2B Stommel's application of his diagram to sampling strategies involving a research cruise in the Indian Ocean. His original caption read: "Schematic diagram of velocity spectra, showing (A) the two peaks associated with the Pacific equatorial undercurrent; (B) the two annual peaks which the Argo expedition expected to find for the Indian Ocean at the equator and which it planned to map; and (C) the probable actual peak for velocity that was revealed to be present but that could not be mapped by the procedures, appropriate for mapping B, that were employed in the expedition." Stommel used the same coordinates as in his first graph. *Source:* Stommel, "Varieties" (ref. 28), 573. Reprinted with permission from AAAS.

the *Journal of Marine Research*, routinely published hemispherical and regional maps depicting data collection points as well as diagrams showing atmospheric-oceanic interactions, sea-level changes, temperature-salinity relationships, energy spectra, and even electronic circuit diagrams (their preparation aided by the Sears Foundation for Marine Research, which supported the journal following its creation in 1937).[30] Physical oceanographers at this time were also familiar with new physiographic maps of the ocean floor prepared by the Columbia University researchers Bruce Heezen and Marie Tharp beginning in the late 1950s, which portrayed the topography of undersea mountains and landforms from a landscape perspective. While the Stommel Diagram's layout and orientation superficially resembled the Heezen-Tharp physiographic diagrams, a more immediate visual context for the diagram may have been a set of major

30. Yngve H. Olsen, "Note to Subscribers, Authors and Associate Editors," *Journal of Marine Research* 19, no. 1 (1960): 1–5.

articles that Walter Munk, together with his Scripps colleagues Gaylord R. Miller and Frank E. Snodgrass, published in the *Journal of Marine Research* in 1962. Their work addressed in part the spectra of waves generated from a Pacific Ocean tsunami, and included diagrams of energy density versus wavelength—a relationship that later fit perfectly into one axis of the Stommel Diagram.[31]

Despite creating a technique later heralded as a breakthrough, Stommel seemed to have limited interest in the approach. The only other time he published a Stommel Diagram was in a 1965 article on planning a major research program on the Kuroshio Current, the fast-flowing warm river analogous to the Gulf Stream that runs from the Philippines past the east coast of Japan. In it he returned to his strategy from two years earlier, using this diagram to drive home the point that oceanographers needed to carefully consider the varieties of phenomena they wished to measure. Fellow oceanographers, he warned, needed to plan their experiments far more carefully than they often were normally inclined.[32]

STOMMEL'S AMBITIONS: DEFINING RESEARCH STRATEGIES IN COLD WAR OCEANOGRAPHY

Key questions remain: what did Stommel hope to achieve with his diagram, and why did he put it forward? It was not for the purpose of calculation, the fundamental use for almost all graphs in science. Indeed, it was only vaguely quantitative, and no evidence suggests that he ever sought to use the diagram for producing quantitative information.

> What, then, did it mean for Stommel and for his colleagues in physical oceanography?

31. On the creation of the Heezen-Tharp map series, see Ronald E. Doel, Tanya J. Levin, and Mason K. Marker, "Extending Modern Cartography to the Ocean Depths: Military Patronage, Cold War Priorities, and the Heezen-Tharp Mapping Project, 1952–1959," *Journal of Historical Geography* 33, no. 5 (2006): 605–26. Stommel almost certainly saw the tsunami article diagrams soon after their publication, as one of his own research papers immediately followed it in the same journal volume; see Gaylord R. Miller, Walter H. Munk, and Frank E. Snodgrass, "Long-Period Waves over California's Continental Borderland. Part II. Tsunamis," *Journal of Marine Research* 20, no. 1 (1962): 31–41.

32. Henry Stommel, "Some Thoughts about Planning the Kuroshio Survey," *Proceedings of Symposium on the Kuroshio, Tokyo, October 29, 1963*, Oceanographical Society of Japan and UNESCO (1965), 22–33, on 30.

The most persuasive answers come from considering the Cold War environment in which it was created, emerging tensions over competing institutional styles of oceanography in the United States, and perceived challenges to the autonomy of physical oceanographers as state funding spiked in the 1960s. An immediate stimulus for the graph was a visit that Stommel made to the Soviet Union in 1962. The occasion of the visit—partly a result of his interaction with Soviet oceanographers during a meeting of the International Union of Geodesy and Geophysics in Toronto in 1957—was to discuss a new Soviet proposal to begin large-scale repeated hydrographic studies of the world oceans. Submitted by members of the Soviet Academy of Sciences and the Soviet State Hydro-Meteorological Agency to the new Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific, and Cultural Organization (UNESCO)— a commission created to pressure governments to provide significant resources and national participation in major international cooperative programs—the Soviet plan sought "all-round knowledge of the physical, chemical, geological, and biological phenomena and processes developing in the water mass of the oceans, the atmosphere above it, in the earth crust beneath it; all these aspects should be viewed in their interrelations and mutual interdependence." While several nations had submitted ideas for internationally cooperative projects, and the IOC was already a co-sponsor of the Western-dominated International Indian Ocean Expedition, the Soviet proposal was unusually comprehensive, and the West German oceanographer Günther Böhnecke had recommended that U.S. and British experts (including Stommel) weigh in on it before final decisions were made.[33]

Joining his close colleague John Swallow and other U.S. researchers, Stommel used the opportunity to reiterate now-familiar arguments about proper sampling patterns in space and time. Many Western scientists, he argued, were convinced that ships should not be used for extensive and repetitive surveys of the kind the Soviet Union had proposed, since they were unlikely to yield insight into fundamental physical processes. Rather, surveys should be carefully designed to measure at scales appropriate to capture the phenomena being studied. For Stommel and Swallow, turbulence played such a major role in ocean properties that repeated ocean sections—linear slices of data collection

33. Soviet plan quoted in Jacob Darwin Hamblin, *Oceanographers and the Cold War: Disciplines of Marine Science* (Seattle: University of Washington Press, 2005), 171. On the IOC, see Helen Rozwadowski, *The Sea Knows No Boundaries: A Century of Marine Science Under ICES* (Seattle: University of Washington Press, 2002), 131; Stommel's perspective is well captured in Stommel, "Sea of the Beholder" (ref. 13), I–46.

made through particular regions—would be hopelessly distorted, aliased (sampled at too small or large a frequency to detect the sought-after phenomenon), and unproductive. Instead, Stommel and fellow American colleagues advocated using ships to study the role of eddies rather than for conducting standard ocean sections, believing this could help measure the seasonal variation of transport within the large current systems in the Atlantic and Pacific oceans.[34]

Indeed, Stommel seemed determined to use his 1963 *Science* article (which included the first Stommel Diagram) to thwart what he regarded as ill-conceived international research proposals intended to gain UNESCO sanction and funding. "[I]nadequate design of the expedition on the whole" had now become the principal limitation for physical oceanography, rather than finding funding for large-scale voyages in physical oceanography, he argued. "If we regard an expedition as a scientific experiment, then we must propose to answer certain specific questions, and the strategy of exploration, the disposition of ships and buoys, and so on, must be designed with a view to obtaining quantitative, statistically significant answers to these questions." A simple net "does not catch fish of all sizes," just as "the existing net of tide-gauge stations does not suffice for a study of geostrophic turbulence." No harm came from thinking about the ocean "in various simple ways, to see how satisfactory a model one can devise." Stommel nevertheless argued that even the massive research efforts undertaken during the International Geophysical Year (IGY) of 1957–58 often amounted to little more than unsophisticated surveys, concluding that the time had come "when consideration of the next stage in complexity can no longer be postponed. Happily, we have the technological means to begin oceanographic observation of the new type, and we can look forward to a time when theory and observation will at last advance together in a more intimately related way."[35] Stommel's *Science* article thus was an exhortation to fellow physical oceanographers to devise research strategies at the intersection of experimental and theoretical practice, borders he had straddled throughout his career.

34. Stommel's claims notwithstanding, repeated global surveys of ocean properties to consider the role of the oceans in climate became the centerpiece of the World Ocean Climate Experiment (WOCE) conducted from 1990–98 as well as the Geochemical Ocean Sections Study (GEOSECS), beginning in the 1970s; on GEOSECS, see Deborah Day, "Resources for the Study of Oceanography at the Archives of the Scripps Institution of Oceanography," in *Oceanographic History: The Pacific and Beyond*, ed. Keith Rodney Benson and Philip F. Rehbock (Seattle: University of Washington Press, 2002), 526–31.

35. Stommel, "Varieties" (ref. 28), 572, 574, 575.

Why Stommel chose to publish his review in *Science* is uncertain. But in choosing the organ of the American Association for the Advancement of Science, rather than a specialized marine sciences journal, Stommel clearly wished to reach a wide range of professional researchers and planners. It marked a significant departure for Stommel, who previously had found little use for generalized scientific periodicals. In 1947, upon realizing he had missed a significant paper published in the *Proceedings of the National Academy of Sciences* by the physical oceanographer and former Scripps leader Harald Sverdrup, Stommel had sniffed that the *Proceedings* was a journal read only by "its aging members."[36] Now he had second thoughts. Stommel may also have sensed that *Science*'s new editor, the physicist Philip H. Abelson, would find his concerns had merit. Anxious about the direction of science policy in the United States, and wary of the government's increasing role in setting research goals, Abelson had opened the journal to articles on science policy, and was about to publish the geophysicist M. King Hubbert's indictment of the coziness of U.S. research universities with federal patrons, "Are We Retrogressing in Science?"[37] That Stommel had a wide audience in mind for his argument—and for his graphical technique—seems clear.

Stommel's desire to address planning in oceanography also reflected his own experiences, both joyful and frustrating, at the interface of experimental and theoretical research. In 1954 Stommel started a series of hydrographic measurements, later termed the *Panulirus* series, in deep water off Bermuda (where Woods Hole maintained a research station).[38] As he reported in a characteristically folksy and detailed round-robin letter to oceanography colleagues in 1955, he had gotten thermistor cables installed after two tries, and could now see patterns caused by internal waves generated by distant storms.[39] From 1952 to 1955, employing these devices, he obtained measurements of subtle voltage differences in the undersea communication cable linking Halifax, Bermuda, and the Turks Islands, which allowed him to compute tidal velocities and transports.[40] As a time

36. Stommel, "Sea of the Beholder" (ref. 13), I–18.

37. M. King Hubbert, "Are We Retrogressing in Science?" *Science* 139, no. 3558 (1963): 884–90. On Abelson, see David Dickson, *The New Politics of Science* (Chicago: University of Chicago Press, 1988), 29; and Daniel S. Greenberg, *The Politics of Pure Science*, 2nd ed. (Chicago: University of Chicago Press, 1999), 35.

38. George Veronis, "A Theoretical Model of Henry Stommel," in Warren and Wunsch, *Evolution* (ref. 17), xx–xxi.

39. Stommel to Dale Leipper, 1 May 1955, Leipper papers, SIO, Box 1.

40. Stommel, "Sea of the Beholder" (ref. 13), I–29.

series, these data provided a view of variability in the ocean. This work later contributed to his soon-classic 1958 book-length study, *The Gulf Stream*.[41] His labors also filled him with a rare calm. Proud of the sturdy, seaworthy buoys he had devised, Stommel also found his physical labor in the warm and then isolated environment of Bermuda to be energizing, writing his closest associates that installing the wireless telemetering buoys "was by far the happiest most pleasant bit of field work that I ever did. It was unhurried, comfortable, and lasted long enough for one to begin to get the feel of the sea." From this experience he drew institutional lessons: "I am positive that deep-sea research institutions should be (1) small (2) on ocean islands. Our big institutions get to be like factories after awhile—and they are too far from the deep-sea itself. . . . The freshness, easy associations, simple arrangements, informality of a little laboratory really makes one happy."[42]

However, in carrying out this ambitious project, Stommel also faced the practical question of where to place moored buoys to measure currents. Researchers needed buoys to record major and fundamental patterns and physical properties, rather than local eddies—a crucial challenge in experimental design that informed his later thinking. His Bermuda work also reflected his growing interest in gathering time-series observations of pressure, temperature, and currents in deep ocean regions after he had initiated the *Panulirus* series. He devised an approach that involved strings of moored instruments and recoverable instrument packages containing automatic recorders, particularly after becoming aware of John Swallow's neutrally buoyant float system for tracking deep currents. During a 1957 cruise of the new WHOI research ship *Aries*, Stommel further tested his ideas about deep-water circulation, discovering that it displayed a wide spectrum of motions.[43] From 1958 to 1960, Stommel and a Woods Hole collaborator, Arnold Arons, intensively studied deep currents in the vicinity of Bermuda. Their investigations dovetailed with Stommel's efforts to install thermistors and other deep-sea instruments off the islands, making use of new forms of electronic instruments that until then had not been applied

41. Stommel, *Gulf Stream* (ref. 19).

42. Stommel to W. Munk, 14 Jan 1954, WHM, Box 19; Stommel, Letters from Oceanographers Series (1954), p. 149, Dale Leipper Papers, SIO Archives, Folder 8. Studies of science in the field remain infrequent, despite their importance; for entries to the literature see Henrika Kuklick and Robert E. Kohler, *Science in the Field*, *Osiris*, 2nd ser., 11 (1996); and Sverker Sörlin, "Science, Empire, and Enlightenment: Geographies of Northern Field Science," *European Review of History* 13, no. 3 (2006): 455–72.

43. G. E. R. Deacon, "Henry Stommel," in Warren and Wunsch, *Evolution* (ref. 17), xxv.

to physical oceanography.[44] Ultimately these new time series provided additional data for the Z-axis of what would later become the Stommel Diagram.

Yet another factor that shaped Stommel's 1963 arguments in *Science* was his increased appreciation that relevant data sets were rapidly expanding, together with new means to analyze them. A particularly crucial development was Stommel's early exposure to computers and computing and his interest both in the modeling of oceanographic phenomena and the visual display of large oceanographic data sets. Stommel's interest in the use of computers for the analysis and display of oceanographic data had begun in the immediate aftermath of World War II when, in 1946, he and Munk visited the eminent mathematician John von Neumann at Princeton's Institute for Advanced Study, then working to develop new computing machines.[45] Stommel, Munk, and von Neumann discussed how high-speed electronic computers could be used to tackle previously unsolvable problems of oceanography, including understanding diffusion and calculating eddy viscosity.[46] Later, Stommel became particularly interested in the possibility of using computers to display and machine-plot oceanographic data. In 1963—the same year he was drafting the paper that came to include his influential diagram—Stommel wrote an article with Malcolm Pivar and Edward Fredkin, both at Maynard, Massachusetts–based Information International (an early computer technology company), on the machine display of oceanographic data. Their collaborative article (accomplished in part by Stommel making late-night forays to Maynard, situated west of Boston, so that he could gain additional computing time on the Digital Equipment Corporation machines located there) described a program to create a computer-compiled oceanographic atlas. They argued that the increasingly huge amounts of data being gathered by oceanographers could only be plotted by a computer, since individual scientists would want specific displays based upon what questions each was addressing. Stommel and his colleagues demonstrated that a cathode ray tube, light pen, input-output typewriter, and control switches could produce a display of data stored on magnetic tape. The output was a two-dimensional plot showing the location of data points; points could be interrogated for more information by pointing at them with the light pen.[47] While only a

44. Arons, "Scientific Work" (ref. 17), xvi.

45. Harry Wexler to Francis Reichelderfer, 15 Nov 1946, Wexler Papers, Library of Congress (Washington, DC).

46. Munk to Stommel, 1 Mar 1949, WHM, Box 13.

47. Dennis Moore, personal communication to Tiffany C. Vance, 8 Sep 2008; Stommel, "Sea of the Beholder" (ref. 13), I–48; Malcolm Pivar, Edward Fredkin, and Henry Stommel,

FIG. 3 Henry Stommel working at a computer [circa 1970]. *Source:* Photo courtesy of WHOI Archives, http://dlaweb.whoi.edu/DIG_RES/archive_photo.html (last accessed 10 Nov 2009).

preliminary step toward visualizing oceanographic data, the publication revealed Stommel's strong and growing interest in arranging complex data in visual ways, another issue embodied in the Stommel Diagram.

The most significant motivation behind Stommel's inclusion of the diagram, however, was the role he saw for it in maintaining the autonomy of individual scientists in setting the research agenda for physical oceanography—precisely as the field, buoyed by federal patronage, began expanding at an unprecedented rate. It was this theme more than any other that Stommel used in stitching together his 1963 *Science* essay. Early on, Stommel critiqued recent expedition

"Computer-Compiled Oceanographic Atlas: An Experiment in Man-Machine Interaction," *Proceedings of the National Academy of Sciences* 50, no. 2 (1963): 396–98.

planning, arguing that "[m]ore often than not the design characteristics of oceanographic experiments are such that few statistically significant answers are obtained" to address critical research questions. While individual researchers were sometimes at fault, thereby missing precious opportunities to make measurements that would enhance physical theory, he reserved his strongest criticisms for large-scale international scientific programs where state interests could compromise research designs and strategies. It was in this context that he took aim at the recently concluded IGY of 1957–58, arguing that "there is a need for more sophisticated and more physically oriented observational programs than the geographical surveys" he believed were the IGY's sole gains in many fields.[48]

Why this concern had become central to Stommel in the early 1960s owed to major, indeed unprecedented, changes under way in the funding and organization of physical oceanography in the United States and Europe. Like his colleagues in physical oceanography at Woods Hole and similar research institutes in the United States, Stommel had perceived an extraordinary shift in the oversight of research in his field beginning in the late 1950s. Funding for physical oceanography had grown massively since World War II and the early Cold War years because of oceanographic research's application to the Navy's operational needs, including weather prediction and anti-submarine warfare. Navy contracts had been the engine that drove the dramatic expansion of Woods Hole from a nucleus of twenty-five individuals in the 1930s to nearly three hundred by 1945; like Scripps, it remained an active center for defense-related research through the 1950s.[49] What changed in the late 1950s was the intensity of U.S. Navy and federal interest in physical oceanography. Advances in Soviet submarine technology had made anti-submarine warfare the Navy's top priority, requiring it to have "as great an intimacy as possible with the unforgiving ocean environment." In 1958 the U.S. government had announced a dramatic expansion in support of oceanographic research, approving a major Next Ten Years in Oceanography (TENOC) program. By 1960, seventy percent of WHOI's research budget came from Navy contracts.[50] It was this ramp-up in

48. Stommel, "Varieties" (ref. 28), 575; on the scientific and political contexts of the IGY, see Needell, *Science* (ref. 22).

49. Columbus Iselin, untitled notes on WHOI in the war years, circa 1950, Columbus Iselin papers, WHOI Archive, Box 31, Folder Draft (Folder B) WHOI History During the War Years; and Eric L. Mills, *Biological Oceanography: An Early History, 1870–1960* (Ithaca, NY: Cornell University Press, 1989), 285.

50. Gary Weir, *An Ocean in Common: American Naval Officers, Scientists, and the Ocean Environment* (College Station: Texas A&M University Press, 2001), 336; see also 335 and 390; see also

military expenditures for physical oceanography that had inspired Iselin's successor at Woods Hole, Paul Fye, to seek greater emphasis on applied military research—the move that had perturbed Stommel and other senior WHOI researchers, who were concerned that heightened secrecy requirements and related restrictions would affect their international reputations as scientists.[51]

What Stommel found particularly troubling was not the volume of military funding available to physical oceanography. Despite his pacifist views, he recognized that Navy contracts had been his primary source of patronage throughout his research career. Rather, he objected to new *procedures* for funding research initiatives in his field. Through the mid-1950s, scientific expeditions from WHOI, SIO, and similar U.S. research centers had been primarily initiated and managed by research scientists at these institutions. As new funds burgeoned, and post-Sputnik pressures grew to utilize oceanographic research as an element of international diplomacy, planning for large-scale international oceanographic expeditions (such as the Soviet-initiated proposal for hydrographical studies of the world's oceans and the later-sanctioned International Decade of Ocean Exploration, or IDOE) came instead from international scientific commissions such as UNESCO's Intergovernmental Oceanographic Commission (IOC). Stommel found this worrisome. Already in 1962, a year before his article appeared in *Science*, Stommel had written Jerome Wiesner, President John F. Kennedy's science advisor, warning that oceanwide survey projects of the kind that Soviet oceanographers favored would likely be unproductive. He instead argued in favor of transforming the national effort in oceanography by allowing physical oceanographers to administer "a strong dose of mathematical physics."[52] This was hardly a new theme for Stommel. Already in 1954, in a private note to close colleagues, including Walter Munk, Stommel had belittled large-scale surveys, declaring that "the exploration stage was finished in the North Atlantic, for all intents and purposes, a few years ago, and I think it is fair to say that somehow we have lacked the necessary vision and imagination to face this situation squarely and to embark on the new phase of oceanographic research which seems to be required."[53] Now, however, the issue

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Hamblin, *Oceanographers* (ref. 33), 150–51; and Richard C. Vetter, "Growth and Support of Oceanography in the United States, 1958–1968," report of the National Academy of Sciences/National Research Council, 1970.

51. See Oreskes, "Stommel" (ref. 7), 530–31; see also J. B. Hersey to director [Fye], 15 Feb 1961, J. B. Hersey papers, Woods Hole Oceanographic Institution archives, Box 1, Folder Correspondence 1948–64, as well as Hamblin, *Oceanographers* (ref. 33), xxvii.

52. Stommel quoted in Hamblin, *Oceanographers* (ref. 33), 235.

53. Stommel, introduction to "Dream-Like" (ref. 23).

had mounting urgency. Burgeoning funding for physical oceanography and its heightened appeal to policymakers, in his view, threatened to undercut the best-science approach of its researchers.

Indeed, for Stommel—and for many of his American colleagues in physical oceanography who had come of professional age in the early Cold War era—an emerging anxiety in the early 1960s was that oceanography was becoming a branch of "marine affairs," justified not only for fundamental research that contributed to national defense but also for its applicability to the disposal of nuclear wastes, predicting climate change, and exploiting the oceans as a food resource. As historian Jacob Darwin Hamblin has argued, senior physical oceanographers in this period felt this shift potentially "politicized science, threatened scientists' autonomy, and took the initiative for shaping the international scientific community out of the hands of scientists themselves."[54] By the mid-1960s a clearly conflicted Stommel—who favored the small-scale research programs of the sort he had led in Bermuda even while recognizing they belonged to a bygone era—sought to shape research policy in his field. In an unpublished draft statement, Stommel made this point most forcefully: "There is a growing consensus among physical oceanographers to find ways to shift the emphasis in oceanography from exclusive preoccupation with the methodology of geographical exploration, to a new methodology centered on revealing the physics of the processes at work in the ocean."[55] That Stommel wrote this statement when his 1965 article "Some Thoughts about Planning the Kuroshio Survey" appeared in print—the only other time in his career that he utilized a Stommel Diagram in his own publications, here also to argue the need for careful experimental design in a major research program—suggests the primary utility that Stommel perceived for his graphical technique.[56]

54. Hamblin, *Oceanographers* (ref. 33), 264. On changing perceptions of the oceans as a food source see Rozwadowski, *Sea Knows* (ref. 33); and Helen Rozwadowski and David K. van Keuren, eds., *The Machine in Neptune's Garden: Historical Perspectives on Technology and the Marine Environment* (Sagamore Beach, MA: Science History Publications, 2004); see also Philip E. Steinberg, *The Social Construction of the Ocean* (New York: Cambridge University Press, 2001). Members of other U.S. science disciplines at this time similarly worried about federal patronage robbing them of autonomy; see David H. DeVorkin, "Who Speaks for Astronomy? How Astronomers Responded to Government Funding after World War II," *Historical Studies in the Physical and Biological Sciences* 31, no. 1 (1999): 55–92.

55. Stommel, "A Zero Order Look at Physical Oceanographic Measurement for the Next Seven Years," draft msc, 18 Jul 1965, HMS, Box 19; on Stommel's internal conflicts over the management of research in oceanography, see Carl Wunsch, "Henry Melson Stommel, 27 September 1920–17 January 1992," *Biographical Memoirs of Fellows of the Royal Society* 43 (1997): 492–502, on 493.

56. Stommel, "Some Thoughts," (ref. 32), 22–33. One reason that Stommel may not have made more use of the diagram is that his interest in any particular technique or experiment tended to

Despite Stommel's efforts to promote his visual innovation to his colleagues and to the wider scientific community, his diagram did not fundamentally influence scientific practice in physical oceanography. Few physical oceanographers cited it, and it did not become a core interpretive tool within textbooks—a marked departure from the fate of its near-contemporary in particle physics, the Feynman Diagram, which quickly spread within research communities, mutated to new forms, and became a key tool of calculation prominently featured in physics textbooks and at academic conferences.[57] Nor did any of Stommel's graduate students or close colleagues become enthusiastic advocates of the method.[58] While the Stommel Diagram was familiar to physical oceanographers at Woods Hole and Scripps, most seemed to regard it primarily as an auxiliary aid in planning research expeditions.[59] It would take several more years before Stommel's space-time diagram gained a new and much larger utility in the field of biological oceanography—and, subsequently, in the burgeoning discipline of ecology.

THE DIAGRAM JUMPS: ADOPTION BY BIOLOGICAL OCEANOGRAPHERS AND THE ECOLOGICAL COMMUNITY

In 1978, fifteen years after Stommel's pioneering three-dimensional graphical representation appeared in *Science*, the Stommel Diagram made a dramatic leap to a new scientific field. It appeared in a chapter called "Patterns and Processes in the Time-Space Scales of Plankton Distributions," written by the marine

be short-lived. As he put it in his autobiography: "The truth is that I usually get tired and mired down in any one line of research after it has produced a few new results. Others with more highly developed techniques generally outrun me, so I leave the decorations of an idea to them." Stommel, "Sea of the Beholder," in Hogg and Huang, *Collected Works* (ref. 13), I–9.

57. Kaiser, *Drawing Theories* (ref. 6).

58. Physical oceanographers may also have remained aloof from the Stommel Diagram by seeing Soviet mathematician Andrey Kolmogorov's mathematically rigorous work on turbulent cascades—a central issue in scaling—as more relevant and useful. See his classic 1941 paper, A. N. Kolmogorov, "Local Structure of Turbulence in an Incompressible Fluid for Very Large Reynolds Numbers," *Comptes rendus (Doklady) de l'Academie des Sciences de l'U.R.S.S.* 31 (1941): 301–05, well known to North American physical scientists by the 1950s. See also J. C. R. Hunt, O. M. Phillips, and D. Williams, eds., *Turbulence and Stochastic Processes: Kolmogorov's Ideas 50 Years On, Proceedings of the Royal Society, London, A* 434 (1991): 1–240; and David Schneider to Tiffany C. Vance, personal communication, 2 Jan 2007.

59. D. James Baker, "Ocean Instruments and Experimental Design," in Warren and Wunsch, ed., *Evolution* (ref. 17), 396–433.

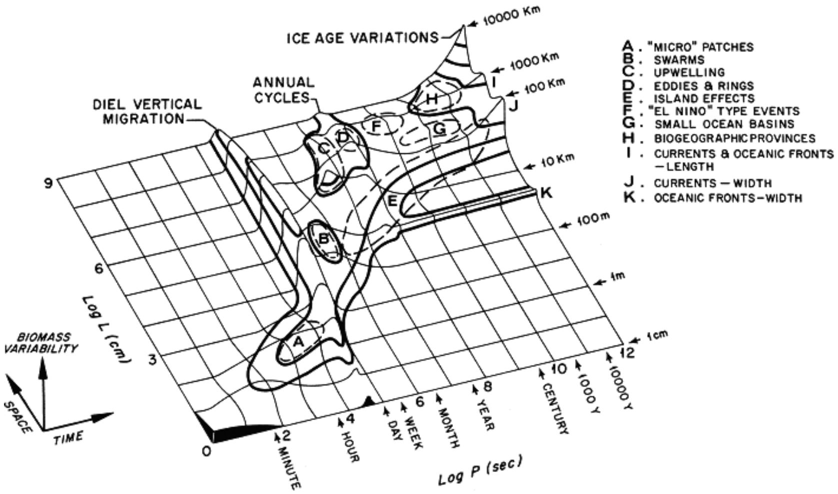

FIG. 4 The first appearance of the Stommel Diagram in a new discipline: The marine biology version of 1978, by Loren Haury, John McGowan, and Peter Wiebe. The graph retains the same form as the original, but now emphasizes factors in marine biology, with an emphasis [Z axis] on biological productivity, here labeled "biomass variability." *Source:* Haury et al., "Patterns and Processes" (ref. 2), 279. With kind permission of Springer Science and Business Media.

ecologists Loren Haury, John McGowan, and Peter Wiebe. Rather than depicting scales of oceanic circulation, they used the diagram to illuminate zooplankton biomass variability over various spatial scales—how it was distributed across the top layers of the ocean—together with the physical factors contributing to this variation. (Fig. 4) The article's main contribution was in emphasizing the importance of understanding scale as a key factor in assessing the relationships among phytoplankton, zooplankton, and fish populations.[60] Their use of a Stommel Diagram to explore these relationships soon became its most famous feature.

Within a decade, the biological version of the Stommel Diagram became a widely utilized graphical tool for addressing ecological relationships within the world oceans.[61] Throughout the last quarter of the twentieth century, this graphical technique propagated exponentially within the biological community, as the number of publications presenting the concept of scale that it embodied grew at nearly twenty percent per year.[62] In 1992 Northwestern University

60. Haury et al., "Patterns and Processes" (ref. 2).

61. See esp. Alex Herman and Trevor Platt, "Meso-Scale Spatial Distribution of Plankton: Co-Evolution of Concepts and Instrumentation," in *Oceanography: The Past*, ed. Mary Sears and Daniel Merriman (New York: Springer-Verlag, 1980), 204–25, on 204; see also Schneider, "Rise of the Concept" (ref. 2), 547.

62. Schneider, "Rise of the Concept" (ref. 2), 532, 546.

ecologist Simon A. Levin highlighted the Stommel Diagram while emphasizing that "[t]he problem of pattern and scale is the central problem in ecology, unifying population biology and ecosystem science."[63] The diagram also entered a range of new fields, including terrestrial biogeography. By 2005 a new biological version of the Stommel Diagram appeared within a marine ecology textbook, attaining a pedagogical status it had never enjoyed within physical oceanography.[64]

In their 1978 article, Haury et al. modified the 1963 Stommel Diagram in several distinct ways. Like the original, their diagram featured peaks due to factors on a wide range of time scales such as ice ages, annual cycles, and daily changes (although now related to biomass variability). It retained the overall conventions of the original graphical representation, with short-term time and space scales in the foreground, and those of long duration and eras in the far background; the Z-axis continued to represent intensity. But in their version, Haury et al. reworked the diagram to address biomass variability rather than oceanic circulation. In addition to associating peaks for daily vertical migrations and annual population cycles with physical oceanographic factors such as eddies and currents, Haury et al. addressed changes in biogeographic provinces, island effects, El Niño events, oceanic fronts, and other ecological parameters. They used their paper to argue that zooplankton abundance was not only considerably influenced by hydrographic processes but also by zooplankton behavior, which caused micropatterns on scales from one meter (lasting for a few hours) to swarms bordering on a thousand kilometers (persisting for several days).[65] The paper also employed a thought experiment involving an infinite number of sensors that could be placed to measure variations in

63. Malanson, "Considering Complexity" (ref. 12), 748; Levin, "Problem of Pattern" (ref. 2), 1943.

64. For biogeography and related fields in geography, see Hazel R. Delcourt, Paul A. Delcourt, and Thompson Webb III, "Dynamic Plant Ecology: The Spectrum of Vegetation Change in Space and Time," *Quaternary Science Reviews* 1 (1983): 153–75; and Malanson, "Considering Complexity" (ref. 12), 748. The first textbook use of the Stommel Diagram of which we are aware occurs in M. J. Kaiser, M. J. Attrill, S. Jennings, D. N. Thomas, D. Barnes, A. Brierley, N. Polunin, D. Raffaelli, and P. J. le B. Williams, *Marine Ecology Processes, Systems and Impacts* (Oxford: Oxford University Press, 2005), 221. This version of the diagram also employed color shadings to superimpose a two-dimensional variant of the Stommel Diagram within the original three-dimensional graphic published by John Steele in 1978, discussed later in this article.

65. Haury et al., "Patterns and Processes" (ref. 2); Alan R. Johnson, "Spatiotemporal Hierarchies in Ecological Theory and Modeling," in *GIS and Environmental Modeling: Progress and Research Issues*, ed. Michael F. Goodchild (New York: John Wiley & Sons, 1996), 451–56, on 452.

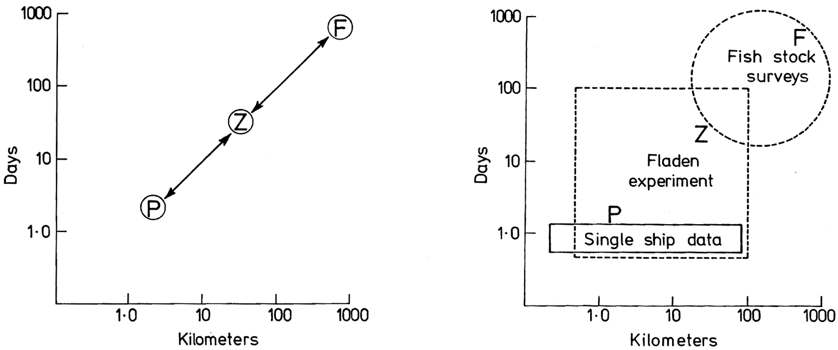

FIG. 5 Simplified two-dimensional versions of the biological Stommel Diagram prepared by John H. Steele, showing (*left*) time and space scales for plants, zooplankton and pelagic fish, and (*right*) space and time scales for sampling strategies (including the pioneering Fladen Ground Experiment [FLEX] of 1976). *Source:* Steele, "Comments" (ref. 67), 5 and 6 resp. With kind permission of Springer Science and Business Media.

biological productivity over many spatial and temporal scales all at the same time. It was their focused, sustained attention to the problem of scale in studying plankton communities that helped establish their paper as a classic among marine ecologists.[66]

A second biology-oriented version of the Stommel Diagram appeared in print simultaneously. It was created by the marine biologist John Steele, editor of the volume *Spatial Pattern in Plankton Communities* that contained the soon well-known chapter by Haury et al. Steele did more than underscore the importance of their graphical innovation. For his introduction, he prepared additional versions of the Stommel Diagram to illustrate what he regarded as its most fundamental contribution: the straightforward link it provided between addressing phytoplankton concentrations and marine populations by focusing on the general problem of variability and its measurement. In contrast to Stommel's three-dimensional graphical representation, Steele employed a simplified pair of two-dimensional diagrams. (Fig. 5) In the first diagram he used axes of time and space to illustrate the typical space-time scales associated with plants, herbivorous zooplankton, and pelagic fish (those that spend much of their lives swimming in the water column, in contrast to benthic or bottom-dwellers).

66. See Schneider, "Rise of the Concept" (ref. 2); and International Council for the Exploration of the Sea (ICES), *Report on the Working Group on Recruitment Processes* (Barcelona: ICES CM 2005/C12, 2005).

Plants had the shortest space and time scales; fish—measured in years and thousands of kilometers—the longest. In the second diagram, using identical scales, Steele plotted the space and time scales utilized by various kinds of sampling programs used by researchers, from single ship data (limited times and distances) to fish stock surveys, covering hundreds of kilometers over several years. Steele used these diagrams to buttress his argument that while horizontal variations at small scales were dominated by physical changes, at larger scales "biological interactions were more likely to occur." Both diagrams made it clear that sampling methods then in use were likely inadequate to provide data at sufficient resolution to address the "general problem of variability in the marine ecosystem."[67] For many ecologists, Steele's compelling restatement of the scaling issues that Haury et al. had raised was equally influential and memorable.[68]

By the time that Steele's publication appeared, with its biological versions of the Stommel Diagram, marine biologists had become increasingly familiar with visual representations of this kind. For many decades, researchers reading *Marine Biology*, the *Journal of Marine Research*, and the *Journal Du Conseil* (produced by the International Council for the Exploration of the Seas [ICES]) had encountered two-dimensional temperature-salinity diagrams, and by the 1960s, diagrams of linear relationships between these variables in combination with nutrient fluxes and illumination levels were common. In the mid-1970s, however, visual representations began to deal with ever more complex relationships, including three-dimensional habitat characteristics over periods of several years. Both Haury and Steele themselves had experimented with visual methods to relate three or more variables simultaneously, and the new *Journal of Plankton Research,* launched just one year after Steele's edited volume, stressing ecological and model studies, requested contributors to provide "figures that tell their story at a glance."[69]

67. John Steele, "Some Comments on Plankton Patches," in Steele, *Spatial Pattern* (ref. 2), 1–20, on 2–3.

68. See esp. Schneider, "Rise of the Concept" (ref. 2), and David Schneider, communication with Tiffany C. Vance, 2 Jan 2007.

69. D. M. Dauer and J. L. Simon, "Habitat Expansion among Polychaetous Annelids Repopulating a Defaunated Marine Habitat," *Marine Biology* 37 (1976): 169–77; J. H. Steele, "A Study of Production in the Gulf of Mexico," *Journal of Marine Research* 22, no. 3 (1964): 211–21; and L. Haury, "Small-Scale Pattern of California Current Zooplankton," *Marine Biology* 37 (1976): 137–57. For the *Journal of Plankton Research*, see D. H. Cushing, editorial, *Journal of Plankton Research* 1 (1979): 1.

But just how the Stommel Diagram jumped from the physical oceanographers to the biological community—a potentially important clue for understanding the transmission and production of knowledge—remains uncertain. Because the utility of graphical methods to new problems is rarely intuitively clear, personal exchanges are often required for them to spread. "The best way to send information," physicist J. Robert Oppenheimer had once remarked, "is to wrap it up in a person."[70] It is tempting to imagine that Stommel might have had direct contact with either Haury or Wiebe. Indeed, Stommel had just returned to Woods Hole when the Haury et al. publication had appeared, and Haury and Wiebe both held research scientist posts there. But WHOI was by then a sprawling institution employing hundreds of individuals, and despite close physical proximity, interactions between physical and biological oceanographers were limited.[71] No evidence suggests this occurred.

One might also suspect a link involving Gordon A. Riley, an influential Yale-trained marine ecologist who had been an early Stommel collaborator. In the early 1940s Riley had grown interested in physical factors, including light and temperature, that affected the growth of phytoplankton. After reading the pioneering 1942 *Oceans: Their Physics, Chemistry, and General Biology* by Harald Sverdrup, Martin Johnson, and Richard Fleming, the first comprehensive textbook in the discipline, Riley became convinced that physical approaches to biological ecology were crucial analytical tools necessary to advance the field. Recruited to wartime research at Woods Hole, Riley had worked with Stommel in geophysicist Maurice Ewing's underwater sound research group, finding Stommel a kindred spirit who further sparked his interest in the fundamental physical properties in the oceans. In 1949 Riley, Stommel, and instrument-designer and biologist Dale Bumpus had collaborated in writing an important paper, which predicted the distribution of stable populations of phytoplankton and zooplankton that came about from changes in their physical environment. Oceanographer and historian Eric Mills later declared that Riley's models "set

70. Quoted in Kaiser, *Drawing Theories* (ref. 6), 357.

71. Eric L. Mills, *Biological Oceanography* (ref. 49), 307; John Dunlap to Tiffany C. Vance, personal communication, 2 Jul 2008; Drew Vastano to Tiffany C. Vance, personal communication, 3 Jul 2008. The division between physical and biological oceanography is explored in Warren S. Wooster, "Immiscible Investigators: Oceanographers, Meteorologists, and Fishery Scientists," *BioScience* 37, no. 10 (1987): 728–30; and Ronald Rainger, "Adaptation and the Importance of Local Culture: Creating a Research School at the Scripps Institution of Oceanography," *Journal of the History of Biology* 36, no. 3 (2003): 461–500; see also David Livingstone, *Putting Science in its Place: Geographies of Scientific Knowledge* (Chicago: University of Chicago Press, 2003).

the standard for a new generation of biological oceanographers through their use of physical techniques," a radically new development that successfully united "the physics of the sea with its biology."[72] Significant as this paper was in providing a quantitative model for the impact of turbulence on phytoplankton production, Riley's 1949 contribution nevertheless did not directly connect marine ecologists with Stommel's graphical innovations. In part this owed to Riley's temperament and personality: a reclusive figure who sought the company of individualists rather than the forceful, entrepreneurial leaders of the biological oceanographic community, Riley was ill-suited to actively promote conceptual innovations. Moreover, Riley's contacts preceded Stommel's experimentation with scale diagrams by a decade, and Riley's work contained no direct references to graphical techniques.[73]

A more likely point of contact for the diagram was someone within Haury's own team of authors: the marine biologist John McGowan, who in 1978 was not at WHOI but instead across the continent at SIO. During the 1960s, soon after receiving his PhD from University of California at San Diego (UCSD), McGowan became concerned with the quality of plankton measurements. Working with E. W. (Bill) Fager, a fellow ecologist and applied statistician at Scripps, he sought to better estimate likely errors. Through their interactions McGowan became increasingly concerned with sampling methods and the design of research programs.[74] Learning about Stommel's *Science* article, McGowan decided to use it pedagogically, employing it in lectures he offered as a professor of oceanography at UCSD. As McGowan later recalled, he employed a Stommel Diagram for three lectures he presented: one on the original Stommel Diagram, a second on

72. Extensive analysis of Riley's work appears in Mills, *Biological Oceanography* (ref. 49); quoted on 289, 309. This monograph, G. A. Riley, H. M. Stommel, and D. Bumpus, "Quantitative Ecology of the Plankton of the Western North Atlantic," *Bulletin of the Bingham Oceanographic Collection* 12, no. 3 (1949): 1–169, came to the attention of Walter Munk but few other physical oceanographers; see Munk to George F. Carrier, 14 Jan 1960, Box 19, WHM. On the significance of *Oceans*, see Robert Marc Friedman, *The Expeditions of Harald Ulrik Sverdrup: Contexts for Shaping an Ocean Science* (San Diego, CA: SIO, University of California, 1994), and Deborah Day, A History of "The Oceans: Their Physics, Chemistry, and General Biology," (2003); available online at http://repositories.cdlib.org/cgi/viewcontent.cgi?article=1190&context=sio/arch (last accessed on 8 Nov 2009).

73. Mills, *Biological Oceanography* (ref. 49), 309, and Eric Mills, editorial, "History of Oceanography and History of Science," *History of Oceanography Newsletter* 8 (1996): 1–2.

74. "Oral History of John A. McGowan," interview by Laura Harkewicz, recorded 17 Jan 2006, SIO Archives, 20; Francis T. Haxo, Michael M. Mullin, and Fred B. Phleger, "Edward William Fager, Marine Biology: San Diego," *In Memoriam, September 1978* (Berkeley: University of California, Berkeley, Academic Senate), 63–65.

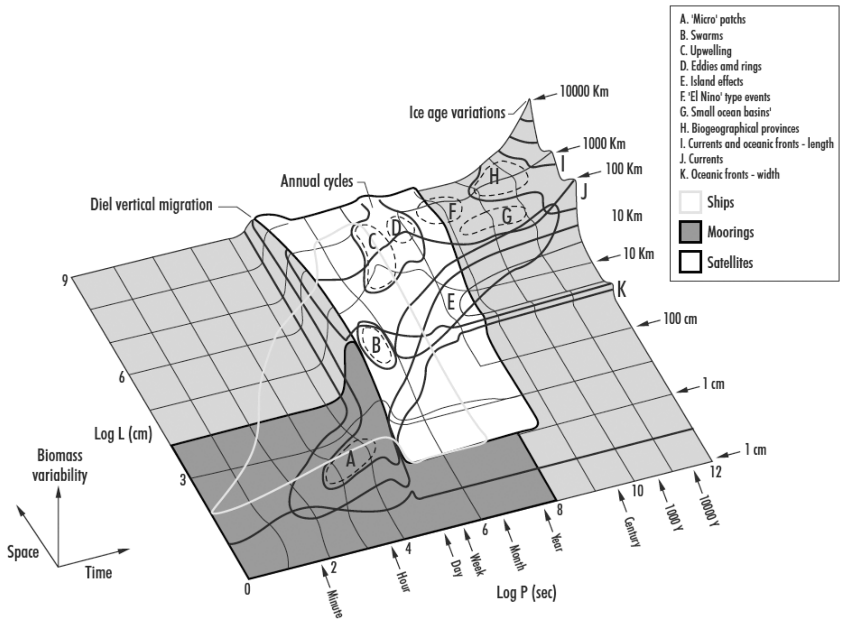

FIG. 6 The biological version of the Stommel Diagram used in teaching: The first known textbook version, produced in 2005, and one of the first originally done in color. In this version, the authors added relevant scales for the main sources of data (ships, moored stations, and satellites). *Source:* Kaiser et al., *Marine Ecology* (ref. 64), 221. By permission of Oxford University Press.

spatial scales in the oceans, and a third on temporal scales. His then-student, the future oceanographer Patricio Bernal, asked: why wasn't it possible to create a biological version of the Stommel Diagram?[75] It is certainly plausible that the diagram came into biology in this way: Stommel's research was known within Scripps through Walter Munk and other senior physical oceanographers, and McGowan's interest in sampling was equally evident.

What is not in question is the rapid spread and diffusion of the biological version of the Stommel Diagram. (Fig. 6) Citations to Stommel's original *Science* publication, as reported in *Science Citation Index*, reveal that the Stommel Diagram gained little traction among researchers in general until the late 1970s, when Haury, McGowan, and Wiebe (as well as Steele) published their own versions. Thereafter, its growth rate was remarkably rapid. (Fig. 7) Already in 1980, a review article on plankton spatial distributions credited Stommel with having "crystallized" a concept that was rapidly becoming axiomatic among researchers in this

75. John McGowan, personal communication to Tiffany C. Vance, 11 Jan 2007.

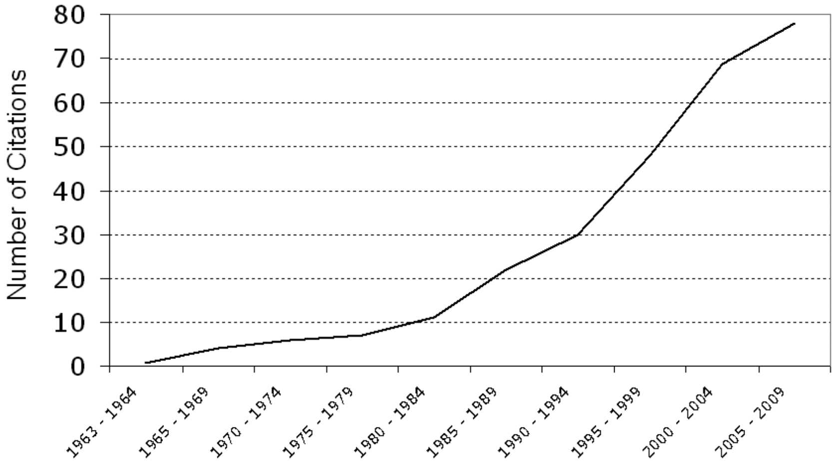

FIG. 7 Growth in the number of articles citing Stommel's *Science* article, sampled in four-year intervals. The dramatic upturn begins in 1980–84, following the publication of the biological version of the Stommel Diagram by Haury et al. and Steele in 1978. *Source:* The counts used in creating the graph come from a search using papers that Vance encountered in her research along with information from the ISI Web of Knowledge Cited Reference Search http://apps.isiknowledge.com/WOS_CitedReferenceSearch_input.do?product=WOS&SID=2DjakdllEnKbnn1LAAD&search_mode=CitedReferenceSearch (last accessed 30 Nov 2009).

field: for any process to be studied, "the sampling grid has to be *at least as fine-scaled as the scale of the process of interest*."[76] Biological oceanographers and marine ecologists widely regarded Stommel as having priority in creating the first three-dimensional graph to address scale as a fundamental issue: in only one instance did an author subsequently refer to a "Haury" Diagram.[77] It is thus noteworthy that the Stommel Diagram's leap into biology did not result in it losing its original identity: although modified, it was malleable.

WHAT MADE THE JUMP POSSIBLE: THE "MARINE REVOLUTION," THE MANAGEMENT CRISIS IN FISHERIES, AND THE EMERGENCE OF ECOSYSTEM ECOLOGY

It is relatively easy to answer *why* the Stommel Diagram spread into biology: it helped marine ecologists (and soon thereafter ecologists more generally) to

76. Herman and Platt, "Meso-Scale" (ref. 61), 204 (emphasis added).

77. International Council for the Exploration of the Sea (ICES), *Report of the Working Group on Recruitment Processes* (ref. 66), 6.

comprehend space and time scales for ecological phenomena against the capacity of observational research programs to address them.[78] Already by the 1960s biological oceanographers had recognized that understanding the spatial and temporal variability of marine organisms, particularly phytoplankton, was a crucial challenge.[79] Unanswered questions at the time had included the relationship between chlorophyll and carbon in phytoplankton cells, how phytoplankton cells responded to light, and the importance of environmental variables such as mixing and upwelling, which the influential ecologist Ramón Margalef had suggested could play a significant role in phytoplankton populations.[80] By the 1970s a significant perceptual shift occurred among biological oceanographers: most became convinced that the apparent uniformity of the oceans, as Steele later declared, was simply "an illusion generated by the original need for widely spaced sampling both horizontally and vertically."[81] That is to say, measurement went from a significant to a fundamental concern within the marine ecology community, underscoring the importance of assessing physical and biological phenomena over a wide range of scales and times.

Precisely *how* biological oceanographers seized on the Stommel Diagram—and why these developments occurred more than a decade after physical oceanographers had reached similar conclusions about the fundamental nature of scale—is a distinct question, which, like the motivations behind Stommel's creating the diagram itself, was tied to larger professional, disciplinary, institutional, and governmental issues in the Cold War era. One answer comes from

78. A more comprehensive discussion of the diffusion of the Stommel Diagram is found in Vance, "If You Build It" (ref. 9).

79. Indeed, the chief of the Fisheries Biology branch of the U.S. Fish and Wildlife Service, Lionel A. Walford, had declared that careful observations of particular characteristics of the marine environment (as Riley, Stommel, and Bumpus had urged in their 1949 paper) had predictive value that could be employed to increase fish harvests; see Lionel A. Walford, *Living Resources of the Sea: Opportunities for Research and Expansion* (New York: Ronald Press, 1958), 84, 87.

80. Mills, *Biological Oceanography* (ref. 49), 314; Herman and Platt, "Meso-Scale" (ref. 61); see also Sharon Kingsland, *The Evolution of American Ecology* (Baltimore: Johns Hopkins University Press, 2005).

81. Steele, "Some Varieties of Oceanographic Experience," in *Evolution* (ref. 17), 376–83, on 376. Terrestrial ecologists such as Paul Ehrlich were slower in appreciating the environmental diversity of the oceans; see G. Carleton Ray, "Man and the Sea—the Ecological Challenge," *American Zoologist* 25 (1985): 451–68, on 454. The closely linked relationship between observational methods and theoretical assumptions in biological oceanography is reminiscent of a key earth sciences issue, when U.S. geophysicists (favoring the Pratt model of isostatic compensation in the mid-twentieth century) strongly objected to the possibility of continental drift; see Naomi Oreskes, *The Rejection of Continental Drift* (New York: Oxford University Press, 1999).

examining the genesis of Steele's contribution as well as those of Haury et al. In 1977 Steele, who left his native Scotland to become the newly appointed director of Woods Hole, convened a NATO School conference, sponsored by NATO's Marine Sciences Panel, at the Ettore Majorana Centre for Scientific Culture in Erice, Sicily. For decades Steele had argued the importance of understanding the physical properties of the sea in order to prevent errors in interpretation due to selecting inappropriate regions or improper time and space scales for sampling; he proposed the workshop to reassess critical biophysical parameters affecting plankton communities.[82] He was increasingly aware—from his own research at the Aberdeen Marine Laboratory and that of colleagues in marine ecology into turbulent diffusion and its effect on plankton distribution on scales of tens and hundreds of kilometers—that the issue of scale now loomed large for a variety of reasons. The improved precision of sampling instruments such as fluorometers, new insights into mixing on small scales, and the surprising variability of chlorophyll and nitrate concentrations highlighted these scale issues. Proper sampling, Steele argued, was the key to improving knowledge of marine ecosystems.

Steele made this point by advancing an argument similar in form to what Stommel had used in physical oceanography. "The classical survey used for fish stock assessment would sample at stations with a 50–100 km grid and repeat the program, if possible, 3–6 times per year over several years to give a 50–100 day spacing," he noted. But such sampling, "with minimum frequencies corresponding to expected herbivore variability, is almost perfectly designed to miss [annual migration cycles] producing apparently random data."[83] Steele invited some sixty participants from a dozen maritime nations to this workshop. It was at this conference that the seminal contribution from Haury and his colleagues, as well as Steele's own graphical representations, emerged.[84]

Given this development, the larger questions may be: what in particular allowed the Stommel Diagram to gain such traction when it did, and to spread so rapidly? Why did biological oceanographers and particularly marine ecologists so avidly seek to utilize and adapt the Stommel Diagram to plankton research? Why did the question of scale suddenly seem open to solution by biological oceanographers in the mid- and late 1970s?

82. Mills, *Biological Oceanography* (ref. 49), 314; Rozwadowski, *Sea Knows* (ref. 33), 247.

83. Steele, "Comments" (ref. 67), 5.

84. Bruno Battaglia and John H. Steele, "Foreword" in Steele, *Spatial Pattern* (ref. 2), v–vi.

Answers to these questions emerge by considering the larger political economy of the marine sciences community in the last quarter of the twentieth century. Researchers in this field experienced a very different realm of opportunities and challenges than physical oceanographers (their wealthier, better-supported cousins) had enjoyed a decade before. A number of factors—all mutually reinforcing—help explain the rapid but delayed rise of Stommel's graphical techniques within biology. Several paralleled those in physical oceanography. One critical development, as Steele noted, was the emergence of new instrumental techniques, particularly in the 1960s and early 1970s. Already by the 1920s the British researcher Alister Hardy had developed the Continuous Plankton Recorder, which he used in making regional surveys before and after World War II, as a way to sample near-surface plankton in space and time. But it was not until the 1950s and especially the 1960s, with the advent of new mechanical high-speed samplers, that plankton data increased dramatically.[85] In the 1970s sampling was achieved at finer scales and over large oceanographic regions, including wide swaths of the North Atlantic Ocean, by use of new instruments, particularly in vivo fluorometry, which provided readouts of chlorophyll concentrations.[86] The growing availability of computers also allowed marine ecologists to better log data, control collection nets, and analyze data—mirroring the circumstances that had encouraged physical oceanographers like Stommel to employ graphical techniques in the 1950s.[87]

An even more important factor was that by the early 1970s biological oceanographers were for the first time able to mount observational programs involving several ships simultaneously, seeking ever finer resolution of phytoplankton and zooplankton populations. In 1976 the Fladen Ground Experiment (FLEX)—involving twenty ships to survey a hundred-kilometer cube of the North Sea for a hundred days—made the first intensive study of the spring plankton bloom in time and space, examining chemical and physical processes

85. Peter H. Wiebe and Mark C. Benfield, "From the Hensen Net Toward Four-Dimensional Biological Oceanography," *Progress in Oceanography* 56 (2003): 7–136, on 7.

86. K. M. Brander, R. R. Dickson, and M. Edwards, "Use of Continuous Plankton Recorder Information in Support of Marine Management: Applications in Fisheries, Environmental Protection, and in the Study of Ecosystem Response to Environmental Change," *Progress in Oceanography* 58 (2003): 175–91, on 175; P. C. Reid, J. M. Colebrook, J. B. L. Matthews, and J. Aitken, "The Continuous Plankton Recorder: Concepts and History, From Plankton Indicator to Undulating Recorders," *Progress in Oceanography* 58 (2003): 117–73, on 117; Steele, "Comments" (ref. 67), 6; and Herman and Platt, "Meso-Scale" (ref. 61), 207–08.

87. Wiebe and Benfield, "Hensen Net" (ref. 85), 7; Reid, Colebrook, Matthews, and Aitken, "Continuous Plankton" (ref. 86), 117; Herman and Platt, "Meso-Scale" (ref. 61), 222.

as well as biological ones. FLEX was soon regarded as a classic experiment, demonstrating the importance of scale for understanding the dynamics of phytoplankton production.[88] This increased the level of attention directed toward the problem of scale in biological oceanography, particularly since new data showed plankton patchiness was more widespread than marine ecologists had previously anticipated. As one marine ecologist noted in the late 1970s, "technology has advanced to the point that it is ahead of our capacity to interpret the data it can give us."[89]

How did the biological ocean sciences gain these additional resources by the 1970s? As with physical oceanography, they did so through the increased involvement of the state. In this instance, however, rising state interest in this field was not primarily because of its military implications. Rather, the field benefited from heightened public and governmental concern over the health and stability of the ocean as a food source. In the United States, President John F. Kennedy in 1961 endorsed a national oceanic program, strengthening the already ambitious "Ten Years" plan for oceanography (TENOC) that the National Academy of Sciences had promoted in 1959. While military funds continued to flow to physical oceanography, it was during the 1960s that for the first time support for biological oceanography and marine ecology also expanded dramatically. In part this resulted from optimism that the world's oceans would provide a nearly limitless supply of protein.[90] It also arose from concerns about the dumping of nuclear wastes and their potential impact on marine life; in part, it followed major incidents of maritime pollution, including the *Torrey Canyon* disaster of 1967, where 117,000 tons of crude oil gushed into the English Channel.[91] But it also stemmed from increased recognition that the widespread use of massive factory trawlers by Japan, the Soviet Union,

88. Steele, *Spatial Pattern* (ref. 2); Rozwadowski, *Sea Knows* (ref. 33), 136, 231.

89. Herman and Platt, "Meso-Scale" (ref. 61), 222.

90. J. W. Chanslor, "Treasure from the Sea," in *Science and the Sea* (Washington, DC: U.S. Naval Oceanographic Office, 1967), 9–16; for perspectives on the Kennedy Administration's larger interests in studying natural resources in all domains, see Lynton Caldwell's essay on the origins of the National Environmental Policy Act, "Implementing NEPA: A Non-Technical Political Task," in *Environmental Policy and NEPA: Past, Present, and Future*, ed. Ray Clark and Larry Canter (London: CRC Press, 1997), 25–50.

91. F. S. Russell, "Marine Biology and Human Affairs," *Advances in Marine Biology* 15 (1978): 233–48, on 244; Timothy Parsons and Humitake Seki, "A Historical Perspective of Biological Studies in the Ocean," *Aquatic Living Resources* 8 (1995): 113–22, on 117; and Jacob Darwin Hamblin, *Poison in the Well: Radioactive Waste in the Oceans at the Dawn of the Nuclear Age* (New Brunswick, NJ: Rutgers University Press, 2008).

Canada, the United States, and other maritime nations—equipped to harvest cod and other commercially viable species on unprecedented industrial scales—threatened postwar hopes that the oceans could be maintained as an unlimited food source.[92] By the mid-1960s the United States began strengthening its commitment to biological oceanography through such undertakings as the formation in 1965 of the Environmental Science Services Administration (which became the National Oceanic and Atmospheric Administration [NOAA] in 1970), created by combining smaller agencies such as the Weather Bureau, the Bureau of Commercial Fisheries, and the Coast & Geodetic Survey, the 1966 Marine Resources and Development Act, and the International Decade of Oceanic Exploration in 1968.[93] Interest in the oceans shifted from a predominant concern over defense and mineral resources to fisheries and coastal management, particularly as ongoing negotiations over the United Nations Law of the Sea Treaty ultimately convinced the United States to extend its exclusive economic zone to 200 miles offshore, joining dozens of other maritime nations that had abandoned their former three-mile limits as insufficient.[94]

The expansion of biological oceanography and marine fisheries in the 1960s and 1970s paralleled the growth of terrestrial ecosystem science in this same period. While historians have noted that comparatively little intellectual exchange took place between terrestrial and marine ecosystem researchers at the time, members of both communities were concerned with finding improved ways to quantitatively examine changes in ecosystems over time.[95] Following the limited success of the International Biological Programme (1962–66), modeled after the IGY, terrestrial ecosystem ecologists focused increasingly on questions involving scale.[96] The Long-Term Ecological Research (LTER) stations funded by the

92. Mary Carmel Finley, "The Tragedy of Enclosure: Fish, Fisheries Science, and U.S. Foreign Policy, 1920–1960" (PhD dissertation, University of California, San Diego, 2007), 2.

93. William J. Merrell, Mary Hope Katsouros, and Jacqueline Bienskiu, "The Stratton Commission: The Model for a Sea Change in National Marine Policy," *Oceanography* 14, no. 2 (2001): 11–16; and Edward Wenk, Jr., *The Politics of the Ocean* (Seattle: University of Washington Press, 1972).

94. Finley, "Tragedy of Enclosure" (ref. 92), 565. By 1976 the U.S. Magnuson Fishery and Conservation Act established a 200-mile Fishery Conservation Zone, expanded to an Exclusive Economic Zone in 1983; see Edward R. Wenk, Jr., "Global Principles for National Marine Policies: A Challenge for the Future," in *Comparative Marine Policy: Perspectives from Europe, Scandinavia, Canada, and the United States*, Center for Ocean Management Studies, University of Rhode Island (New York: Praeger, 1981): 3–16.

95. See Mills, Editorial (ref. 73).

96. Eugene Odum, "The Emergence of Ecology as a New Integrative Discipline," *Science* 195, no. 4284 (1977): 1289–93. Odum commented here that the "somewhat disappointing performance" of this undertaking "can, in hindsight, perhaps, be attributed to the fact that unifying

National Science Foundation as key research centers for ecosystem studies in the late 1970s and early 1980s, like the FLEX experiments in marine ecology, were fundamentally shaped by concern over measuring crucial variables at a wide range of scales, in which sampling and data collection were central concerns.[97]

Terrestrial and marine ecologists in the late 1960s and 1970s were connected in yet another way: through a widely shared conviction that industrial and technological factors were ravaging the planet, causing great harm to ecosystems and planetary balance. In 1968 the editor of the new research journal *Biological Conservation* justified its appearance by proclaiming that "[t]he insidious degradation of the biosphere, the 'world ecosystem,' must be generally halted, but this cannot be expected without far wider and more effective dissemination of the need for, and means of, biological conservation, than has hitherto been accomplished."[98] Marine ecologists voiced similar sentiments. In a widely quoted 1970 article, Carleton Ray proclaimed that a "Marine Revolution" similar to the Agricultural and Industrial revolutions had begun in the late 1960s, when marine ecologists realized the inadequacy of isolated expeditions doing "descriptive ecology." When Ray called on marine researchers to focus on the practical problems of fisheries, pollution, and undersea mining, particularly as nations began claiming 200-mile economic zones, he found widespread support for his ideas.[99] By the mid-1970s biological oceanographers had grown increasingly aware that the principle of Maximum Sustainable Yield (MSY) adopted by international agreement in 1955—allowing commercially viable fish stocks to be harvested up to the point that no surplus was allowed to remain—was a deeply flawed concept, made evident by the late 1960s collapse of the North

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theories or concepts were not set up for testing on the outset," p. 1290; for an overview see Joel B. Hagen, *An Entangled Bank: The Origins of Ecosystem Ecology* (New Brunswick, NJ: Rutgers University Press, 1992), 173–96.

97. Toby A. Appel, *Shaping Biology: The National Science Foundation and American Biological Research, 1945–1975* (Baltimore: Johns Hopkins University Press, 2000), 226–32; Kingsland, *Evolution* (ref. 80), 160; Tulley A. Long, "The Forest and the Mainframe: The Dynamics of Modeling and Field Study in the Coniferous Forest Biome, 1969–1980" (masters thesis, Oregon State University, 2005).

98. Nicholas Polunin, "Some Warnings," *Biological Conservation* 1, no. 1 (1968): 5.

99. Carleton Ray, "Ecology, Law, and the 'Marine Revolution,'" *Biological Conservation* 3 (1970): 8–17. Later researchers accepted a similar periodization: "The history of biological studies of the ocean can be divided into two periods: the first was characterized by many expeditions of discovery; the second by attempts to solve practical problems. Progress in biological studies has been achieved through developments in methodology, physiological investigations, ecosystem modeling, pollution monitoring, aquaculture and global networking of scientific effort," Parsons and Seki, "Historical Perspective" (ref. 91), 120. See also John H. Steele, "Oceanography as a Career," *Oceanography* 10, no. 3 (1997): 145.

Atlantic herring stocks.[100] Arguing that a key weakness of MSY was that it assessed species in isolation and did not allow for environmental fluctuations, many marine ecologists agreed with Eugene Odum's 1977 assertion that ecology was "an anti-reductionist, holistic science" whose practitioners recognized that humans were "abysmally ignorant of the ecosystems of which we are dependent parts," a situation that contributed "to the current dissatisfaction with the scientist who has become so specialized that he is unable to respond to the large-scale problems that now require attention."[101]

A further significant factor was a shift of favored research styles at this same time within the professional organization most concerned with fisheries science, the International Council for the Exploration of the Sea (ICES). Through the 1950s and 1960s, key ICES researchers remained primarily concerned with boosting fish catches, and favored the development of mathematical models to understand fluctuations in particular stocks. Few then saw the need for coordinated ecological studies of marine environments, agreeing with ecologist David Livingston's 1964 assertion that "there were very few biological problems that require the simultaneous collection of data over a wide area."[102] But by the mid-1970s, growing numbers of ICES scientists, increasingly wary of seeking general laws for fisheries comparable to those in the physical sciences, began embracing ecological approaches, a trend that accelerated after the United States joined ICES in 1973. Researchers pressed for oceanographic investigations that emphasized large marine ecosystems—among them John Steele, a vigorous proponent of the FLEX experiment and long-term advocate of following paths through foodwebs. "By 1977," as historian Helen Rozwadowski has noted, "environmental science had become an integral part of ICES," helping integrate fisheries research within the biological sciences as well.[103]

100. Finley, "Tragedy of Enclosure" (ref. 92), 13; see also Tim Smith, *Scaling Fisheries: The Science of Measuring the Effects of Fishing, 1855–1955* (New York: Cambridge University Press, 1994). Not all fish stocks crashed in this period, as certain cod family catch rates briefly spiked in the early 1960s, complicating assessments; see Rozwadowski, *Sea Knows* (ref. 33), 143, 177.

101. Quoted in Odum, "Emergence" (ref. 96), 1289; see also Parsons and Seki, "Historical Perspective" (ref. 91), 120.

102. D. A. Livingston to Frank Campbell, 14 Feb 1964, IBP papers, series 1, USNC/IBM, Folder Membership: D. C. Frey, Survey of Biologists re. Interest in IBP; we thank Elena Aranova for providing us an advance draft of a forthcoming study containing this citation. See also Rozwadowski, *Sea Knows* (ref. 33), 261.

103. Rozwadowski, *Sea Knows* (ref. 33), 234; see also 6, 106, 136, 139, 177, and 226; and Eugene George Kovach oral history interview by Ronald E. Doel, 28 Jun 2001, Niels Bohr Library, American Institute of Physics, College Park, MD, 67.

Indeed, it seems likely that this particular confluence of events in marine science in 1977—the publication of zoologist Peter L. Larkin's stinging critique "Epitaph for MSY," the U.S. decision to adopt the 200-mile limit, the increasingly urgent need to assess the state of marine fisheries stocks, expanded funding for marine science, and renewed interest in oceanographic and ecological approaches—together helped create a particularly receptive environment for utilizing the Stommel Diagram in this community.[104] By the mid-1970s many biological oceanographers had become convinced that the best way to address crucial research issues in their field (as well as problems of fisheries management) was to gain detailed knowledge of the larger ecosystem of the oceans, including the fundamental issue of plankton patchiness and its significance for productivity. To the extent that the response of phytoplankton cells to light, the magnitude of turbulence and upwelling in the upper ocean, and the importance of grazing remained poorly understood, quantitative ecosystem models would remain elusive.[105] Assessing these factors required more than occasional opportunistic expeditions available to biological oceanography through the 1960s: as Ray later noted, the size of the world oceans meant that station data gathered from ships made short-term events "extremely difficult to detect" and synoptic views were "not possible at all."[106] Increased resources available to marine ecologists as states sought comprehensive assessments of fisheries populations, and marine ecosystems required them to think about ways to design adequate experiments to address fundamental conditions. These were precisely the same kind of issues that had first stimulated Stommel to publish his three-dimensional graphing techniques for physical oceanography in *Science* some fifteen years before.

Seen in that light, Steele's edited 1978 *Spatial Pattern in Plankton Communities*—which offered the modified Stommel Diagram among other methods to address these key challenges—appeared at a particularly auspicious moment. While Haury was a junior researcher compared to Steele as well as to his co-authors McGowan and Wiebe (Haury had completed his dissertation just two years before), all had worked on research questions where experimental design and issues of scale were crucial. Their combined efforts to apply Stommel's method to biological oceanography thus were intellectually novel and a catalyst

104. Another influential work from this time is P. R. Ehrlich, A. H. Ehrlich, and J. P. Holdren, *Ecoscience: Population, Resources, Environment* (San Francisco: W. H. Freeman & Co., 1977).

105. Mills, *Biological Oceanography* (ref. 49), 314.

106. Ray, "Man and the Sea" (ref. 81), 463.

within the community of marine ecologists. It is not surprising that Steele's mimeographed conference volume quickly gained the kind of audience that Stommel had not achieved even through *Science*.[107]

Ultimately, then, the Stommel Diagram gained adherents among biological oceanographers for several distinct reasons, beyond its ability to portray scale factors necessary to understand marine environments. It did not matter to them that the Stommel Diagram was neither strictly quantitative nor a tool for calculation. For marine ecologists suspicious of reductionist approaches, seeking to examine ecosystems at the broadest possible scales, the diagram suggested a new approach to marine science. Prior work had attempted to make predictions about the forcing effects of critical components in isolation—for instance, Sverdrup's 1953 effort to create a mathematical model involving critical depths for determining when spring phytoplankton blooms would occur in temperate latitudes, or estimating the biological significance of oceanic frontal zones.[108] But by the 1980s and 1990s, as biological versions of the Stommel Diagram diffused to terrestrial ecology, the challenge of analyzing biological phenomena at appropriate spatial and temporal scales—particularly those at regional and global scales lasting decades or longer—had become the central consideration.[109] When the ecologist Simon A. Levin delivered the Robert H. MacArthur Lecture in 1992, setting as his topic "The Problem of Pattern and Scale in Ecology," he credited Stommel with recognizing that "the observed variability of the system will be conditional on the scale of description." For Levin—who had spent time with Steele, Haury, McGowan, and Wiebe in Sicily in 1978 as a fellow invited participant in Steele's NATO conference—the value of Stommel's Diagram ultimately lay in management and prediction. "Understanding patterns in terms of the processes that produce them," Levin declared, "is the essence of science, and is the key to the development of principles for management."[110] In this way, the Stommel Diagram achieved a deeper status within biology than it had gained within physical oceanography.

107. For a measure of the impact of the Stommel article, see Vance, "If You Build It" (ref. 9), 105.

108. H. Sverdrup, "On Conditions for the Vernal Blooming of Phytoplankton," *Journal du Conseil International pour l'Exploration de la Mer* 18 (1953): 287–95; see also Parsons and Seki, "Historical Perspective" (ref. 91), 117; and D. A. Siegel, S. C. Doney, and J. A. Yoder, "The North Atlantic Spring Phytoplankton Bloom and Sverdrup's Critical Depth Hypothesis," *Science* 296 (2002): 730–33.

109. Johnson, "Spatiotemporal Hierarchies" (ref. 65), 451.

110. Levin, "Problem of Pattern" (ref. 2), 1943.

The rapid proliferation of the Stommel Diagram in the last quarter of the twentieth century thus reflected the political ecology of oceanography in Western nations, particularly the United States. For marine ecologists, the Stommel Diagram was not just a tool for designing observational programs to understand fundamental biological processes (important as this was), but a means of addressing core issues in biological oceanography, with further benefits for fisheries management. In contrast to Stommel—intent on planning experiments to understand the physical ("lifeless") oceans as a central problem in physical science—the burgeoning community of marine ecologists saw the oceans in terms of understanding the necessary conditions for biological productivity.[111] Both groups of researchers were studying the ocean environment, but as the veteran oceanographer Warren Wooster pointed out, important professional and cultural distinctions divided them.[112] Stommel and his colleagues, long accustomed to stable, abundant, military-leavened funding, were hoping by the 1960s for reduced interference from state planners, anxious to do what they defined as "best science." By contrast, many marine ecologists welcomed state research goals that included applied aims, seeing little moral value in science divorced from practical concerns. It is true that the Stommel Diagram's leap from physics to biology took place within the realm of the environmental sciences—in particular at places such as Woods Hole and Scripps, where members of both disciplines worked in close physical proximity. But the professional gulf between them was profound, and the diagram's slow shift within the broad environmental sciences reflected not only the asymmetrical research opportunities and instrumental base but also their distinct disciplinary cultures.

CONCLUSION

Herschel's defense of double star diagrams helped convince dubious nineteenth-century colleagues that graphical methods held great promise for science; Whewell's support of spatial and graphical approaches for studying tides helped persuade governments to fund observing networks; and Feynman's squiggly diagrams of subatomic particle interactions were a crucial innovation in twentieth-century physics as well as a widely recognized icon. But the Stommel

111. Ray, "Man and the Sea" (ref. 81); Rozwadowski, *Sea Knows* (ref. 33), 226.
112. Wooster, "Immiscible Investigators" (ref. 71), 728–29.

Diagram is particularly revealing because it spread further than most graphical methods in modern science, leaping from the physical to the biological sciences.

The Stommel Diagram's remarkable journey across the environmental sciences illuminates significant transformations in science after World War II. Disciplinary issues were crucial. Its use as a tool in both the physical and biological sciences was a direct consequence of instrumental advances and increased opportunities to distribute them across the oceans. No less was it a response to the growing density of observational networks at sea (resulting in an avalanche of data), and the expanding availability of digital computers in the decades following World War II. The Stommel Diagram offered researchers a way to conceive of the oceans as a three-dimensional space to understand the complex interplay between physical and biological processes over a wide range of spatial and temporal scales. In this sense, it was uniquely a product of the second half of the twentieth century: just as the emergence of scale as a unifying concept of ecology depended on the rapid accumulation of ecosystem data in the mid- and late 1970s, the opportunity to develop large new observational programs in physical oceanography in the early Cold War led Stommel to advocate the importance of scale in his privately circulated 1950s papers and in his *Science* article.[113]

At the same time, the Stommel Diagram's delayed leap from physical to biological oceanography reflected very distinct institutional, professional, and cultural practices and concerns within these two research communities, despite being adjoining branches of the environmental sciences.[114] Each was affected by the Cold War, but in remarkably different ways. The military's concern with understanding the undersea environment—as the Navy struggled to address applied problems involving undersea warfare and related defense needs—released a floodgate of resources for physical oceanography as the Cold War began. Physical oceanographers such as Stommel working at WHOI and related research facilities benefited from these greatly enhanced resources (even if Stommel personally opposed the increasing militarization of Woods Hole after 1960). Stommel's ability to pursue instrumented buoy research near

113. Schneider, "Rise of the Concept" (ref. 2), 532.

114. While perhaps tempting to see this as an instance of a trading zone outside physics, related to those which Peter Galison addressed in *Image and Logic: A Material Culture of Microphysics* (Chicago: University of Chicago Press, 1997), the very limited contacts between members of these research communities, and the long time lag between initial developments and subsequent applications, suggests a different dynamic here.

Bermuda in the 1950s was a direct consequence of military funding for his research field, and the major expeditions whose research plans he argued were not adequately addressed—including the Indian Ocean Expedition—primarily emphasized physical oceanography.[115] Not until the 1970s, when oceanic pollution and rapidly declining commercial fish stocks led many nations to adopt protective 200-mile fishery and natural resource conservation zones, did biological oceanographers begin to gain comparable access to resources. When marine ecologists finally gained sufficient funds to begin planning the pioneering Fladen Ground Experiment of 1976, they faced for the first time the kinds of questions concerning observational design that Stommel and his colleagues had already faced decades before.

Moreover, by the 1970s the political ecology of the environmental sciences was divided in even more fundamental ways. As Jacob Darwin Hamblin has noted, physical oceanographers in the 1960s worried about maintaining control over the planning of oceanographic research, which they saw as increasingly subject to state efforts to craft science suited for applied policy aims.[116] They defended a "best science" tradition intended to address fundamental unsolved problems; Stommel's intent to use his graphical method as a means to maintain control of expedition planning in the hands of research scientists fits this framework. But marine biologists embraced, often enthusiastically, the direct application of their work to reverse the decline of critical ecosystems and ocean fish stocks, proclaimed the failure of the politically brokered Maximum Sustainable Yield concept for fisheries management, and advocated that the oceans be viewed as a fragile ecological environment. When Eugene Odum argued in 1977 that science "should not only be reductionist in the sense of seeking to understand phenomena by detailed study of smaller and smaller components, but also synthetic and holistic in the sense of seeking to understand large components as functional wholes," many marine ecologists agreed both with his critique and its implicit embrace of applied aims.[117] These epistemological and

115. Oreskes, "Stommel" (ref. 7), 530; Ronald Rainger, "Patronage and Science: Roger Revelle, the U.S. Navy, and Oceanography at the Scripps Institution," *Earth Sciences History* 19, no. 1 (2000): 58–89.

116. Hamblin, *Oceanographers* (ref. 33), 260–63.

117. Odum, "Emergence of Ecology" (ref. 96), 1289. These criticisms echoed earlier debates over the proper scope of the proposed U.S. National Science Foundation, which pitted adherence to basic research against applied aims; see particularly Daniel J. Kevles, "The National Science Foundation and the Debate over Postwar Research Policy, 1942ñ1945: A Political Interpretation of *Science—The Endless Frontier,*" *Isis* 68 (1977): 5ñ26; and Jessica Wang, "Liberals, the Progressive Left, and the Political Economy of Postwar American Science: The National Science Foundation

cultural distinctions persisted even as biological oceanographers gained access to resources increasingly comparable to those in physical oceanography. The "marine revolution" that G. Carleton Ray perceived occurring in marine ecology and biological oceanography in the 1970s had no counterpart in physical oceanography, and widely voiced hopes of creating a new science of "oceanology" uniting physical, chemical, and biological oceanography remained largely elusive in U.S. oceanographic facilities.[118]

The delayed migration of the Stommel Diagram from the physical to the biological sciences also underscores important constraints on the spread of innovative techniques within science. Certainly the Stommel Diagram represents a kind of immutable mobile: a graphical representation that retained its general structure and iconic form even after marine ecologists modified it to address key research questions in biological oceanography. Latour himself noted immutable mobiles are often somewhat mutable when they pass into distinct research communities and are adapted to particular new approaches.[119] But the larger significance of the Stommel Diagram's journey is in underscoring the importance not of publications, but rather people, in its diffusion and utility.[120] Despite the initial appearance of the Stommel Diagram in *Science*, one of the most widely read leading research journals, its jump to biology occurred primarily through individual contacts, including within the tight network of marine biologists that Steele brought together for his landmark 1977 workshop on plankton variability. That the diagram spread primarily between two interdisciplinary marine sciences institutions, WHOI and SIO—rather than among researchers working within traditional university departments—is a further reminder of the importance of these and related institutions for the production

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Debate Revisited," *Historical Studies in the Physical and Biological Sciences* 26, no. 1 (1995): 139–66.

118. Ray, "Ecology" (ref. 99), 466; on recent developments see for instance Jane Lubchenco, "Entering the Century of the Environment: A New Social Contract for Science," *Science* 279 (1998): 491–97. Ray did not mention in his writing Soviet efforts to create a unified discipline of oceanology, an important instance of national styles in science; see Hamblin, *Oceanographers* (ref. 33), xxiii–xxiv.

119. Bruno Latour, "Drawing Things Together," in *Representation in Scientific Activity*, ed. Michael Lynch and Steve Woolgar (Cambridge, MA: MIT Press 1990): 19–61, and Susan Leigh Starr, "The Politics of Formal Representations: Wizards, Gurus, and Organizational Complexity," in *Ecologies of Knowledge: Work and Politics in Science and Technology*, ed. Susan Leigh Starr (Albany: SUNY Press, 1995): 88–118, on 91–92.

120. Kaiser, *Drawing Theories* (ref. 6), K. Knorr-Cetina, *Epismetic Cultures: How the Sciences Make Knowledge* (Cambridge, MA: Harvard University Press, 1999).

of knowledge in post–World War II U.S. science.[121] Finally, the fact that the Stommel Diagram was never an instrument of calculation, but rather one of research planning and design, also makes clear that scientists do not value graphical techniques solely for their potential to achieve quantitative results.

In the end, the Stommel Diagram served the purpose that Herschel had hoped his graphical methods (and those developed after him) would achieve: to show connections that the "most subtle mind" would find "difficult to perceive without such aid," enabling researchers "at once to detect and often to rectify errors." Graphical methods indeed gave shape to the regularities hidden in nature, and encouraged individual scientists and entire research communities to formulate better data-gathering strategies at the start of new research programs.[122] Stommel himself, in 1963, echoed Herschel more than a century before, declaring that technological advances now made possible "a time when theory and observation will at last advance together in a more intimately related way."[123] While Stommel had his own research community in mind, it was the ecologists, more than the physical oceanographers, who best grasped how to utilize his diagram to illuminate the importance of scale as a unifying concept for their discipline.

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121. On this issue see A. Hunter Dupree, "Commentary: The Smithsonian Astrophysical Observatory—from Washington to Cambridge," *Journal for the History of Astronomy* 21, no. 1 (1990): 107–10; Roger L. Geiger, *Research and Relevant Knowledge: American Research Universities Since World War II* (Edison, NJ: Transaction Publishers, 2004); and Ronald E. Doel, "Quelle place pour les sciences de l'environnement physique dans l'histoire de l'environnement?" *Revue d'histoire modern et contemporaine* 56, no. 4 (2009), forthcoming.

122. Herschel quoted in Hankins, "Large and Graceful" (ref. 4), 605; see also 625.

123. Stommel, "Varieties" (ref. 28), 575.

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