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Key Points:
- New technologies have enabled unprecedented interdisciplinary high-resolution, long-term measurements at depth in the ocean
- There remain major challenges to adequately sample the full three-dimensional and temporal variability of the interior ocean
- These observations have advanced understanding of upper ocean physical, biogeochemical, and bio-optical responses to hurricanes, mesoscale eddies, monsoons, and equatorial longwaves

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New Discoveries Enabled by the Emergence of High-Resolution, Long-Term Interdisciplinary Ocean Observations

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Abstract This review describes the author's path leading toward a career in science and four decades of experiences. Some of the important people influencing my intellectual development are mentioned. Crossings of disciplinary boundaries were keys to novel research efforts. In particular, new areas of research such as geophysical fluid dynamics and bio-optics were embraced and used to advantage. Likewise, identifying and utilizing relevant new technologies enabled unprecedented interdisciplinary high-resolution, long-term measurements at depth in the ocean. Early on, my group utilized satellite-based as well as in situ data sets to advantage. In addition, with colleagues, we conducted modeling as well as observational studies. A few examples of resulting scientific breakthroughs involving interdisciplinary observations are presented. In addition, our time-space diagrams for ocean processes and platforms have been utilized for ocean experimental design and modeling. Finally, some career advice for future generations and my unconventional teaching methods using therapy dogs are discussed.

Plain Language Summary The vastness and inhospitable nature of our oceans has limited our ability to understand oceanic phenomena and to make ocean predictions Great progress in sampling the vertical and temporal variability of the ocean was made with new sensors and moorings in the period of 1980-2000; however, there remain major challenges to adequately sample the full three-dimensional and temporal variability of the interior ocean. In particular, new technologies have enabled unprecedented interdisciplinary high-resolution, long-term measurements at depth in the ocean observations of physical, biological, biogeochemical, and bio-optical processes have now been made over time and space scales spanning ten orders of magnitude and oceanic phenomena such as upper ocean physical, biogeochemical, and bio-optical responses to hurricanes, mesoscale eddies, monsoons, and equatorial longwaves.

1. Introduction

This article describes my path leading toward a career in science and four decades of experiences. Some of the important people influencing my intellectual development are mentioned. Crossings of disciplinary boundaries were keys to novel research efforts. In particular, new areas of research such as geophysical fluid dynamics and bio-optics were embraced and used to advantage. Likewise, identifying and utilizing relevant new technologies enabled unprecedented interdisciplinary high-resolution, long-term measurements at depth in the ocean. Early on, my group utilized satellite-based as well as in situ data sets to advantage. In addition, with colleagues, we conducted modeling as well as observational studies. A few examples of resulting scientific breakthroughs involving interdisciplinary observations are presented. In addition, our time-space diagrams for ocean processes and platforms have been utilized for ocean experimental design and modeling. Finally, some career advice for future generations and my unconventional teaching methods using therapy dogs are discussed.

2. Early Years

I grew up in a very small farm town in Indiana and dreamed of being a farmer until my family moved to a larger but still quite small town. There, my fourth-grade teacher took great interest in me and felt that I had some academic potential. In addition, my father, who worked in a factory and wrote sports for a local newspaper, asked me to write an article about a high school basketball game. The article and my picture were published, launching my writing career at the age of 10. From that point forward, I strived to make

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straight A's. I had a couple of dedicated high school teachers, who also encouraged and nurtured my academic development. As a high school senior, I decided I would study physics at the next level.

I then received scholarships and majored in Physics and Math at Ohio University. It was not an easy path coming from a rural, small-town high school. Fortunately, I was befriended by an Ohio University physics graduate student, Dr. Phil Chute, who helped me through the rough spots. Before my final year of undergraduate studies, I was selected for a summer honors research program at Argonne National Laboratory, then under the U.S. Atomic Energy Commission. My project concerned plasma discharges in particle accelerators. Under the guidance of Dr. Albert Hatch, I wrote a student research paper describing the experiments.

After graduation from Ohio University, I enlisted in the U.S. Coast Guard where I spent about 3 years teaching electronics and 1 year as a human relations instructor and counselor during racial strife on our Governors Island, New York base. In addition, I was able to attend night courses at Stevens Institute of Technology and earned an MS in Physics. Eventually, I taught some night course in Physics and Math for the New York Institute of Technology. During the final year of my enlistment, I met Coast Guard marine science technician students and became interested in the physics of the atmosphere and the ocean.

3. Graduate School and Postdoctoral Research

I was then accepted into the nascent Princeton University graduate Geophysical Fluid Dynamics (GFD) Program, which is now known as the Atmospheric and Ocean Program. GFD was still a relatively new field of study with goals concerning the prediction of weather, climate, and ocean circulation using state-of-the-art computers, first at the Princeton Institute for Advanced Study (where Albert Einstein spent some of his later years) and later at the newly formed NOAA Geophysical Fluid Dynamics Laboratory (GFDL; see Day, 2019). There, Professor George Mellor, a co-founder of the Princeton GFD Program with Dr. Joseph Smagorinsky, mentored me in the fundamental fluid dynamics study of internal gravity waves and turbulence. Although my PhD thesis was on this topic (Dickey & Mellor, 1980), Professor George Philander guided my modeling study of equatorial long waves; this latter research resulted in a JGR paper (Dickey, 1978). Upon completion of my PhD, I was selected to be the 1977 Rosenstiel School of Marine and Atmospheric Sciences (RSMAS) Fellow at the University of Miami. This fellowship enabled me to pursue my emerging interests in going to sea and conducting field observations. It also defined my future career path in interdisciplinary ocean research through discussions with Professors Rana Fine, Claes Rooth, and Michael Roman. I also utilized the RSMAS fellowship to write a seminal paper on observations and modeling of ocean bottom boundary Ekman layers with Professor John Van Leer (Dickey & Van Leer, 1984).

4. University Research and Teaching

I was then hired as an assistant professor by Dr. Don Walsh of the Institute for Marine and Coastal Studies (IMCS) and the Department of Geological Sciences (now the Department of Earth Sciences) at the University of Southern California (USC). Dr. Walsh is well known for his record deepest oceanic dive with Jacques Piccard in 1960 aboard the bathyscaphe *Trieste* in the Marianas Trench. My research at USC and later at the University of California Santa Barbara (UCSB) focused on a variety of interdisciplinary problems. Interestingly, oceanographic research in the early 1900s through roughly the 1950s was largely done from a limited number of ships, necessitating physical, chemical, and biological oceanographers to share ship time and often write collaborative papers. However, disciplinary ocean research was more the norm until roughly 1980 when I began my interdisciplinary field research. A few other oceanographers, such as Professor Raymond Smith and collaborators, were also initiating interdisciplinary multiplatform ocean sampling (Smith et al., 1984, 1987). Like Smith et al., I was interested in attacking problems that clearly crossed disciplinary boundaries. Consequently, my group, along with Smith's, developed and utilized instruments for contemporaneous in situ physical, optical, biological, and chemical ocean measurements.

My fellow Navy Chair, Professor Walter Munk, articulated another major historical oceanographic problem in 2000: "… the era starting with the Challenger expedition in 1870 can be viewed as a near-century of undersampling." He outlined the need for ocean measurements at temporal and spatial scales commensurate with ocean phenomena. Ships have served us well; however, they simply cannot

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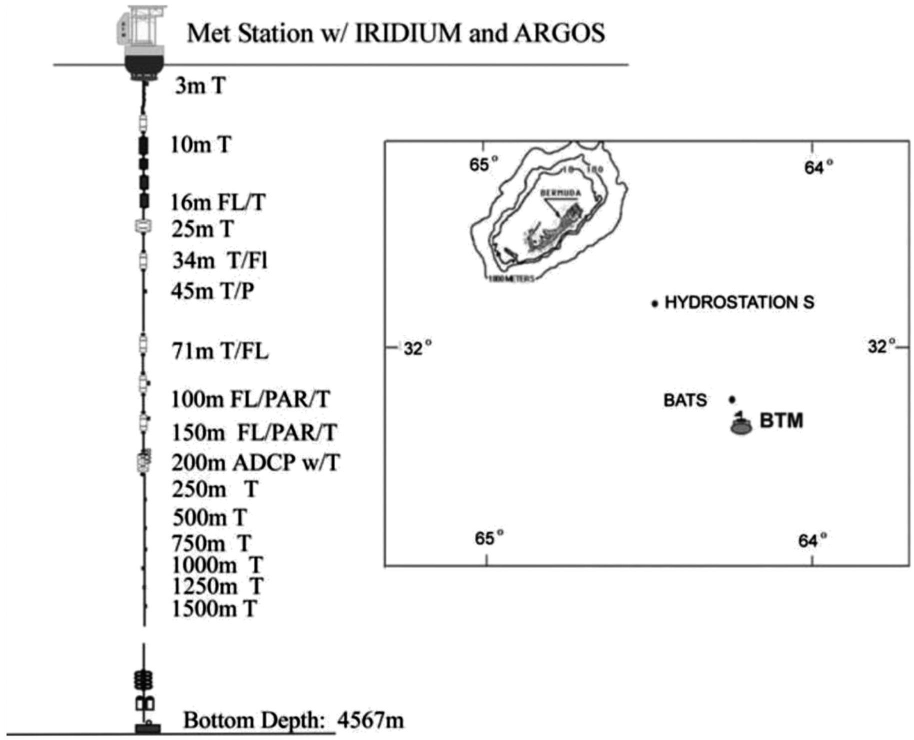

Figure 1. Bermuda Testbed Mooring (BTM) instrumentation diagram used for deployments during a decade off the island of Bermuda. Several major storms and hurricanes passed near the BTM. Representative depths of temperatures sensors (T), fluorometers (Fl), PAR sensors, and an ADCP are shown. Data collected during Hurricane Fabian and the passage of a major mesoscale eddy are shown in the following figures. From Black and Dickey (2008).

sample extreme events like hurricanes and are far too costly for needed long-term data collection. Taking this message to heart, we developed a multivariable profiler (MVP; Dickey, 1991) using one of John Van Leer's cyclesondes interfaced with bio-optical sensors and later a multivariable moored system (MVMS; Dickey, 1991) based on a vector measuring current meter (VMCM; Weller & Davis, 1980) interfaced with bio-optical and chemical sensors. Smith et al. (1991) also developed a moored spectroradiometer and bio-optical system. Several of our group's research results were obtained with MVMSs, which collected in situ data at intervals of seconds to a few minutes for physical, biological, biogeochemical, and bio-optical variables for months to years. The MVMSs with their experimental bio-optical and chemical sensors and satellite data telemetry systems were tested at the Bermuda Testbed Mooring (BTM) for about a decade (Dickey & Bidigare, 2005). The BTM's spectroradiometers were also developed to ground truth NASA ocean color satellite data sets. Several of these new sensors plus others were later deployed from a host of other autonomous ocean sampling platforms as exemplified in a special volume of Limnology and Oceanography (see introduction by Dickey et al., 2008).

The BTM, equipped with meteorological instruments and MVMSs, made high-frequency observations over a decade (e.g., Dickey, Frye, et al., 1998; Dickey et al., 2001; Black & Dickey, 2008) off Bermuda (Figure 1). During that decade, Hurricane Felix (1995), Hurricane Fabian (2003), Tropical Storm Harvey (2005), and Hurricane Nate (2005) all passed near the BTM. One of the most impressive upper ocean responses was produced by Hurricane Fabian. In Figure 2, the path of Hurricane Fabian and the location of the BTM along with a satellite sea surface temperature (SST) map overlaid with wind vectors are shown for 5 September 2003. SST cooling is apparent in the wake of Fabian with the peak response occurring very near the BTM. The satellite data revealed the horizontal response; however, high temporal resolution BTM data obtained from multiple depths were needed to reveal the subsurface response to Fabian. BTM data show that near-surface cooling exceeded 3.5 °C, vertical mixing occurred to a depth of greater than 130 m, and upper ocean near-inertial currents reached 100 cm/s as shown in Figure 3 (from Black & Dickey, 2008).

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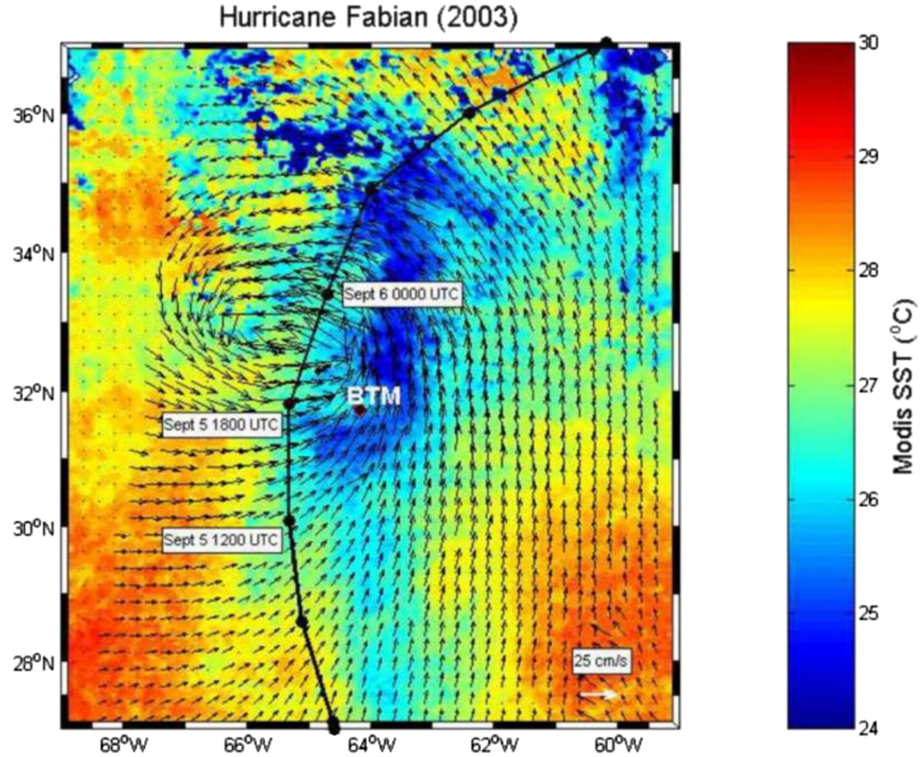

Figure 2. Track of Hurricane Fabian near the BTM (black curve, black dots every 6 hr). Color shading is MODIS 8-d composite SST beginning on Day 249 of 2003. Vectors show QuikSCAT 10-m wind velocity from 2200 UTC 5 September. The position of the BTM is shown in the center of the image. From Black and Dickey (2008).

Remarkably, the current data revealed a rarely observed upper ocean Ekman spiral rotating near the local inertial period. The BTM Hurricane Felix data sets (Dickey, Frye, et al., 1998) were used to test four commonly used mixed layer models (Zedler et al., 2002). In addition, BTM data indicated that Fabian triggered a phytoplankton bloom also evident in SeaWiFS ocean color satellite images. This phenomenon was later described for other hurricanes using ocean color satellite data by Babin et al. (2004).

Another important BTM data set (Figure 4) was used to document the injection of nutrients into the euphotic later and an accompanying major phytoplankton feature as a cold core eddy (est. 150 km in diameter) passed very near the BTM (McNeil et al., 1999). Peak nitrate plus nitrite and chlorophyll *a* concentrations were observed at depth as well as a 25- to 30-m shoaling of the 1% light level depth. A Doppler shift in currents from the local inertial period of 22.8 to 25.2 hr was observed in our time series records due to the advection of the eddy past the mooring site. Inertial pumping brought cold, nutrient-rich waters farther into the euphotic zone than would occur solely by isothermal lifting. The chlorophyll *a* values associated with the eddy were the largest recorded during the 8 years of the U.S. JGOFS Bermuda Atlantic Time Series Study (BATS) program up to that time. McGillicuddy et al. (1998) utilized these BTM mesoscale eddy data in asserting that "Further synthesis of *in situ* observations with remote sensing in the context of data-assimilative dynamical models offers an opportunity to better understand the role of intermittent processes in biogeochemical cycling in the ocean." These same BTM mesoscale eddy data were influential in stimulating two major biogeochemical eddy field studies (E-Flux off Hawaii and EDDIES in the Sargasso Sea, Benitez-Nelson & McGillicuddy, 2008; also, see Benitez-Nelson et al., 2007; Dickey et al., 2008; McGillicuddy et al., 2007).

High temporal resolution mooring data sets collected by our group and colleagues at multiple depths have also been used to document biological responses to tropical instability waves in the equatorial Pacific (Foley et al., 1997) and monsoons in the Arabian Sea (Dickey, Marra, et al., 1998). Using similarly instrumented moorings and bottom tripods, bottom boundary layers as well as transient, episodic sediment

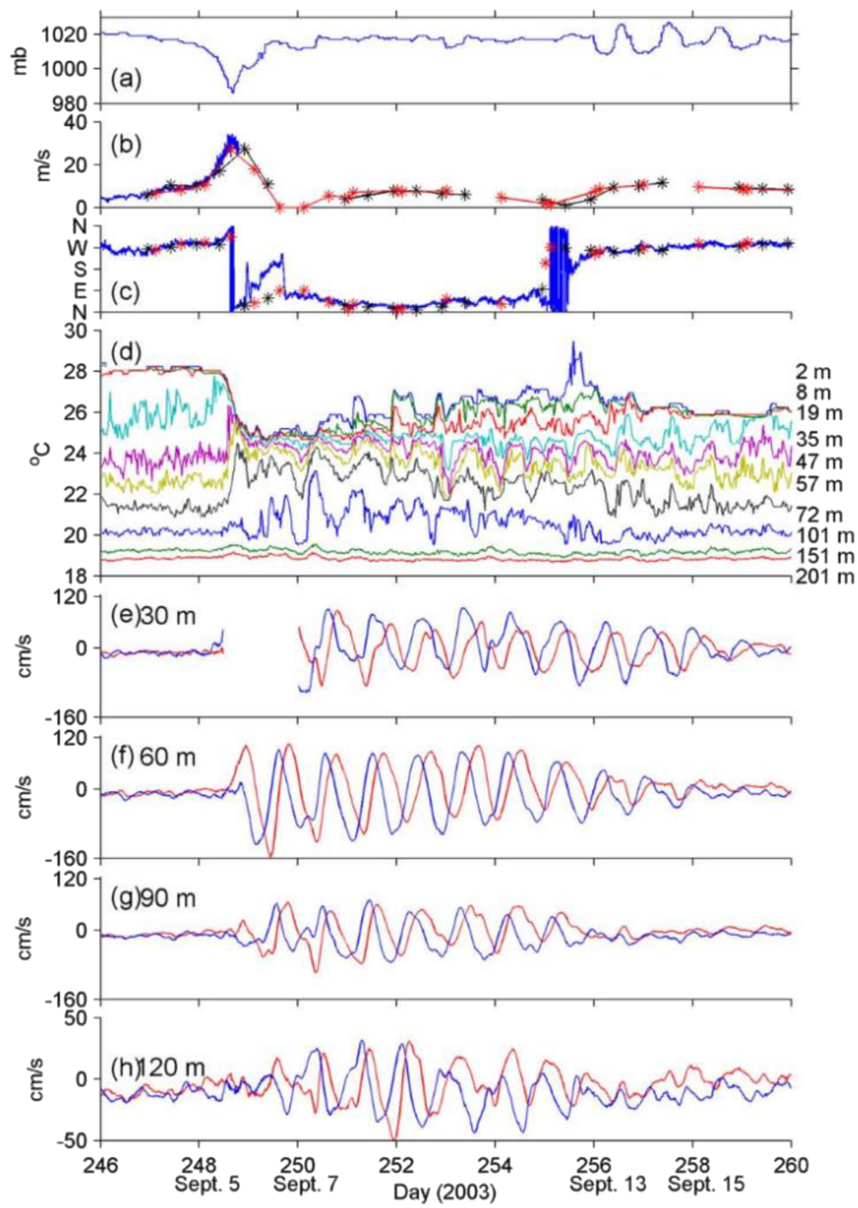

Figure 3. Atmospheric and oceanographic observations during Hurricane Fabian. (a) BTM barometric pressure, (b) SeaWinds on ADEOS II (black) and QuikSCAT (red) and BTM surface buoy measured wind speed (blue), (c) SeaWinds and BTM in situ wind speed and direction, (d) BTM temperature time series (sensors depth: 2, 8, 19, 35, 47, 57, 72, 101, and 151 m), and (e–h) currents at the BTM site for selected depths, zonal component in red, and meridional component in blue. Note the change in scale in panel h of figure. Figure 8h. From Black and Dickey (2008).

resuspension events driven by internal solitary waves (Bogucki et al., 1997) and hurricanes have also been observed (Dickey, Chang, et al., 1998) Several of our experiments have thusly revealed a variety of interactions of biological, biogeochemical, optical, geological, and physical phenomena.

We developed time-space diagrams for a host of interdisciplinary ocean phenomena spanning time and space scales covering 10 orders of magnitude (upper panel in Figure 5 from Dickey & Bidigare, 2005). Shown in the lower panel of Figure 5 is a diagram roughly indicating the time and space scales, which could be observed in 2005 from a host of emerging ocean sampling platforms, each with its own advantages and deficiencies. Each of the sampling domain capabilities has expanded significantly over the past 15 years.

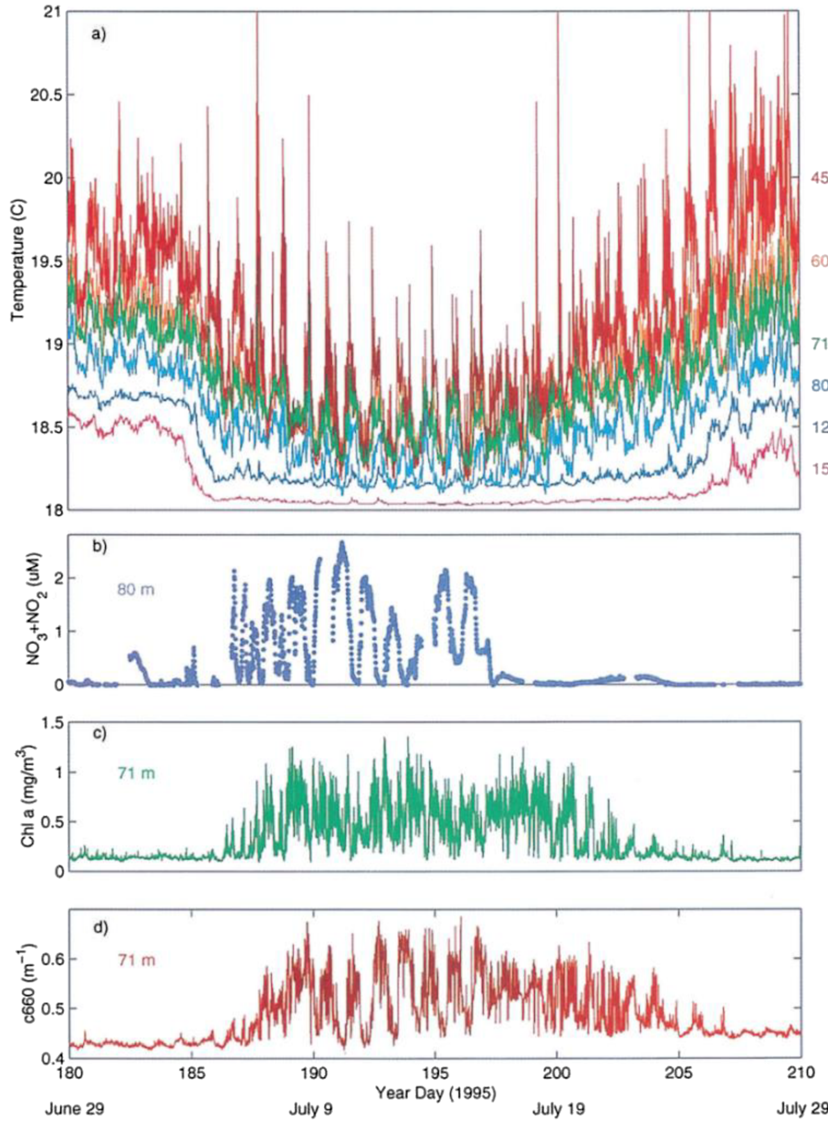

Figure 4. Passage of a mesoscale cold core eddy past the Bermuda Testbed Mooring. Time series of the third deployment of the BTM showing (a) temperature at depths of 45–150 m, (b) nitrate plus nitrite concentrations at 80 m, (c) chlorophyll *a* (indicative of phytoplankton concentrations) at 71 m, and (d) beam attenuation coefficient *c* at 660 nm (indicative of particle concentrations) at 71 m. From McNeil et al. (1999).

These platforms include ships, moorings, drifters, profiling floats, and autonomous underwater vehicles (AUVs) including gliders, airplanes, and satellites (Figure 6 from Dickey & Bidigare, 2005). Our time-space diagrams have been widely used for planning and executing interdisciplinary field experiments and predictive data assimilation models (Dickey, 2003).

During my career, I typically taught introductory oceanography to over 300 students each year. A highlight was teaching from a textbook co-authored with my friend and former student Dr. Sean Chamberlin. While at UCSB, we developed several hands-on laboratory experiments and a campus meteorological observing system. During my final decade of teaching at UCSB, I brought my Great Pyrenees therapy dogs to my classes (Figure 7). The popularity of their visits was appreciated by UCSB's students, faculty, and administration. In particular, my therapy dogs and I were asked to be involved in the campus community's vaccination program for a rare disease and to join in campus vigils for student victims of mass murders.

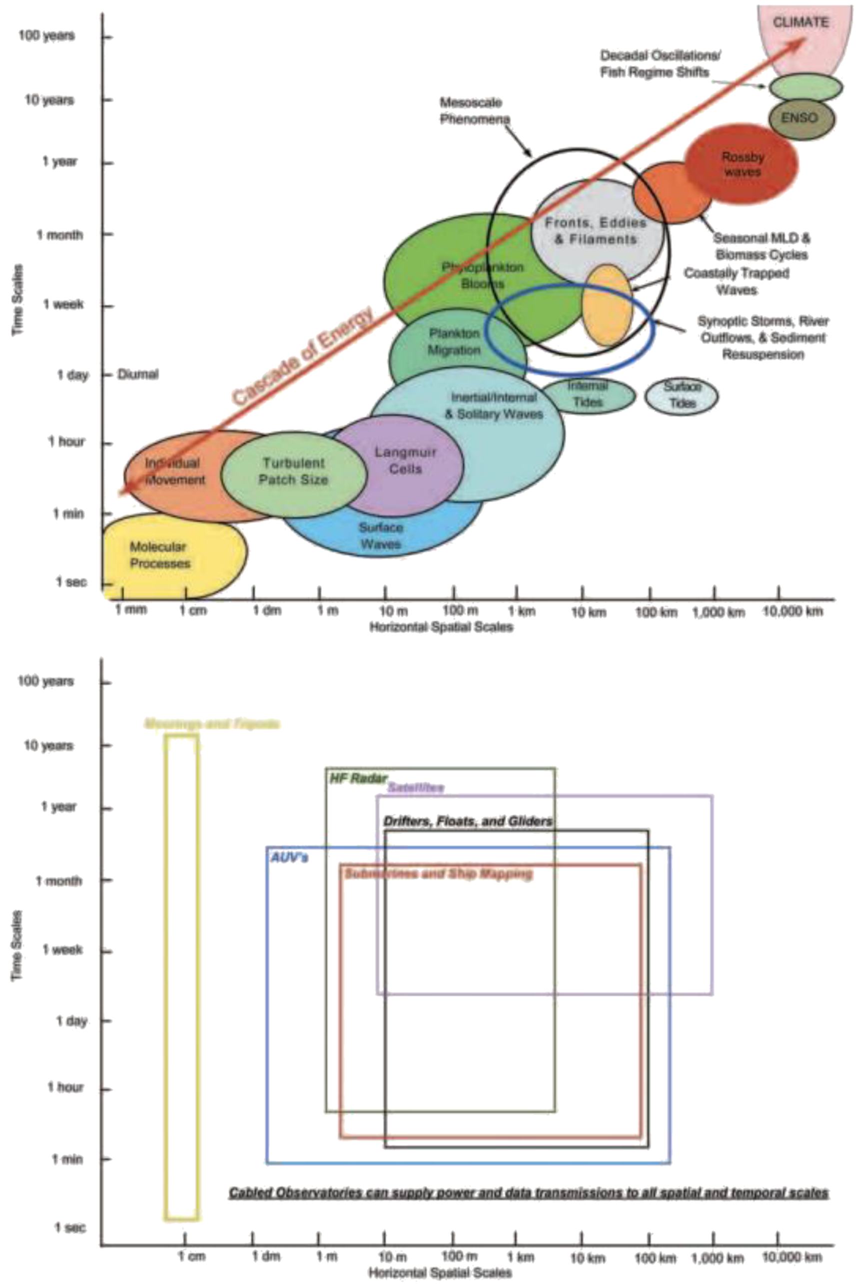

Figure 5. Time and horizontal space plot indicating a variety of ocean processes (top) along with rough coverage domains of various oceanographic platforms in 2005 (bottom). Each of the sampling domain capabilities has expanded significantly over the past 15 years. The arrows on the figure draw attention to the cascade of energy and information from large to small scales as well as small to large scales. From Dickey and Bidigare (2005).

5. Reflections

On reflection, there are a few general words of advice, which I would like to share. Be flexible in setting goals. In my case, visions of being a farmer were dashed early on, and through great mentors and a lot of hard work, I was able to eventually graduate with degrees in Physics and Geophysical Fluid Dynamics. The hallmark of the Princeton GFD Program was modeling of atmospheric and oceanic processes. However, I chose to focus my thesis research on laboratory experiments. From there, I moved into observational ocean research. However, the fundamental theoretical and modeling skills I learned as a PhD student

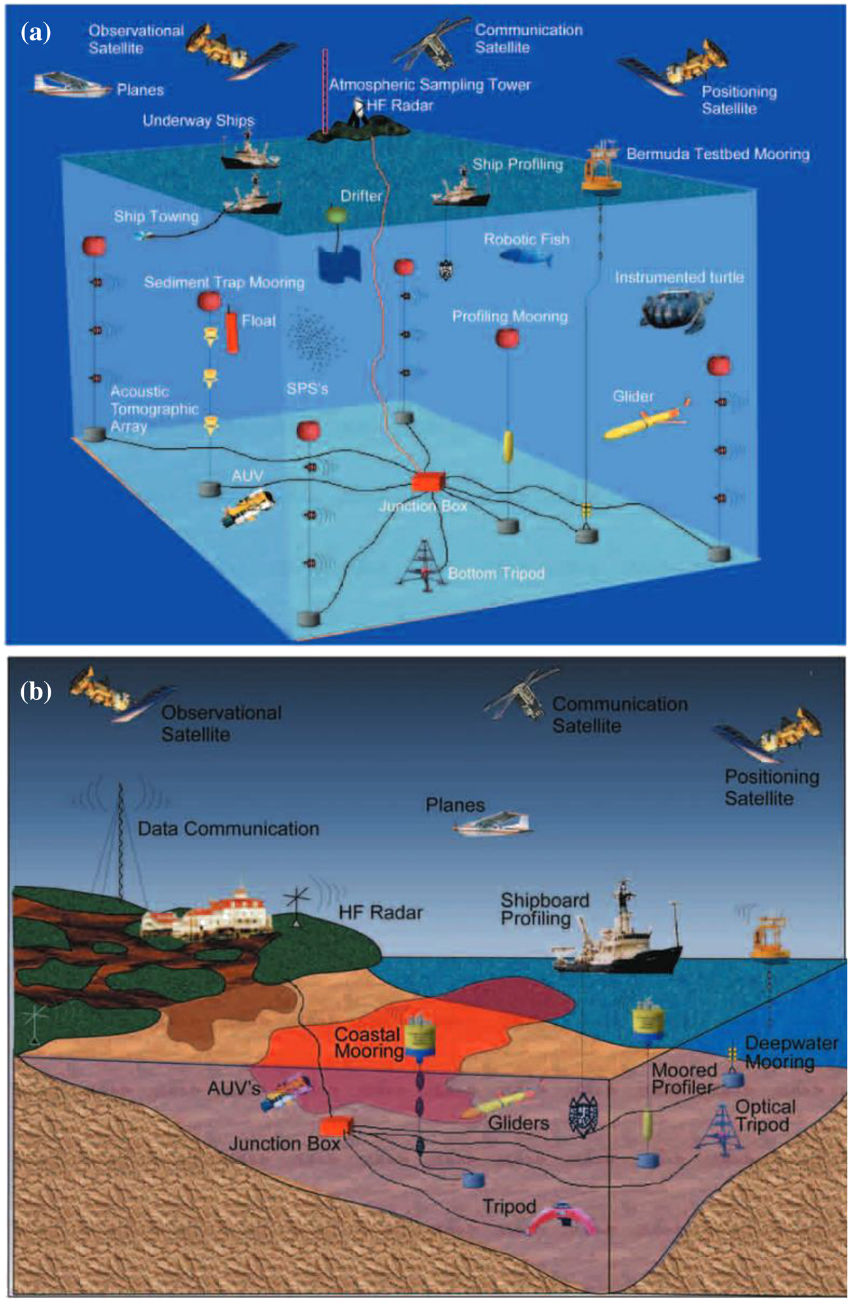

Figure 6. Schematics depicting platforms that can be used in studies of the open (a) and coastal (b) ocean. From Dickey and Bidigare (2005).

served me well as I utilized our field measurements to test and improve ocean models. To amplify this point, I offer a couple of examples that demonstrate the dynamic interplay of theory and observations. In particular, we collected unique ocean data during the passages of hurricanes that were intercompared with three different upper ocean mixed layer models. These intercomparisons allowed for examination of the detailed parameterizations and physics of these models. An important missing element of the models was the explicit inclusion of internal gravity waves. Similarly, our observations of sediment resuspension during passages of internal solitary waves argued for modifications of bottom boundary layer models. Models in turn have also preceded observations. In particular, the classical Ekman layer theory eluded observations for many decades until new technologies enabled the theory's verification as discussed earlier.

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Figure 7. The author with his Great Pyrenees dogs: Teddy, Linkin, and Summer. They have done 3,000 therapy dog visits.

My formal education was centered upon physical processes. However, as I met and collaborated with biological, optical, and chemical oceanographers, I learned from them and eventually led teams to observe and study several important interdisciplinary problems involving ocean ecosystems, biogeochemistry, and bio-optics. One of the resulting important discoveries was the role of phytoplankton in modifying upper ocean heating and vertical distributions of temperature and density. Again, there was an important interplay of interdisciplinary observations and ocean models. Clearly, my informal education was equally important as my traditional formal education. I found that learning takes many forms and every personal interaction with ship crew members, students, and colleagues can be turned into an educational experience. As mentioned earlier, studying earlier work and ideas (e.g., Walter Munk's influence) is important for setting your own research course. Finally, love of writing is a wonderful asset for a career in science and eventually for a retirement career as explained in the final section.

6. Retirement

After almost 40 years of university teaching and research, I was diagnosed with cancer and had to retire. The cancer is in remission and the next stage of my life actually builds on my last decade of therapy dog work at UCSB. My Great Pyrenees therapy dogs and I (Figure 7) continue to visit college and university campuses on a regular basis during final exams. In addition, we teach dog safety and therapy dog classes at schools and libraries. We do children's library therapy dog reading programs, visit schools and colleges following tragedies, help with Special Olympics events, and visit patients in hospitals and retirement communities and centers. We have also done a series of educational demonstrations about therapy dogs at the Los Angeles California Science Center. My therapy dogs have now done 3,000 visits. Finally, I have published a children's book entitled, “The Therapy Dog Adventures of the Great Pyrenees Ted E. Bear and Friends,” and recently published a second children's book entitled, “Rocky and Splash's Lighthouse Dog Adventures.”

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References

Babin, S. M., Carton, J. A., Dickey, T. D., & Wiggert, J. D. (2004). Satellite evidence of hurricane-induced phytoplankton blooms in the oceanic desert. *Journal of Geophysical Research*, *109*(C3), C03043. https://doi.org/10.1029/2003JC001938

Benitez-Nelson, C. R., Bidigare, R. R., Dickey, T. D., Landry, M. R., Leonard, C. L., Brown, S. L., et al. (2007). Mesoscale eddies drive increased silica export in the subtropical Pacific ocean. *Science*, *316*, 1017–1021.

Benitez-Nelson, C. R., & McGillicuddy, D. J. (2008). Mesoscale physical-biological-biogeochemical linkages in the open ocean: An introduction to the results of the E-Flux and EDDIES programs. *Deep Sea Research, Part II*, *55*(10–13), 1133–1138.

Black, W. J., & Dickey, T. D. (2008). Observations and analyses of upper ocean responses to tropical storms and hurricanes in the vicinity of Bermuda. *Journal of Geophysical Research*, *113*. https://doi.org/10.1029/2007JC004358

Bogucki, D., Dickey, T., & Redekopp, L. (1997). Sediment resuspension and mixing through resonantly-generated internal solitary waves. *Journal of Physical Oceanography*, *27*, 1181–1196.

Day, C. (December 2019). *Climate and weather*, (pp. 52–55). New York: Physics Today.

Dickey, T. (1991). The emergence of concurrent high resolution physical and bio-optical measurements in the upper ocean and their applications. *Reviews of Geophysics*, *29*, 383–413.

Dickey, T. (2003). Emerging ocean observations for interdisciplinary data assimilation systems. *Journal of Marine Systems*, *40–41*, 5–48.

Dickey, T., Frye, D., McNeil, J., Manov, D., Nelson, N., Sigurdson, D., et al. (1998). Upper-ocean temperature response to Hurricane Felix as measured by the Bermuda Testbed Mooring. *Monthly Weather Review*, *126*(5), 1195–1201. https://doi.org/10.1175/1520-0493(1998)126<1195:UOTRTH>2.0.CO;2

Dickey, T., Marra, J., Sigurdson, D. E., Weller, R. A., Kinkade, C. S., Zedler, S. E., et al. (1998). Seasonal variability of bio-optical and physical properties in the Arabian Sea: October 1994–October 1995. *Deep-Sea Research Part II*, *45*(10-11), 2001–2025. https://doi.org/10.1016/S0967-0645(98)00061-7

Dickey, T., Zedler, S., Yu, X., Doney, S. C., Frye, D., Jannasch, H., et al. (2001). Physical and biogeochemical variability from hours to years at the Bermuda Testbed Mooring site: June 1994–March 1998. *Deep-Sea Research Part II*, *48*, 2105–2131.

Dickey, T. D. (1978). A note on the effect of zonal boundaries on equatorial waves. *Journal of Geophysical Research*, *73*, 3675–3678.

Dickey, T. D., & Bidigare, R. R. (2005). Interdisciplinary oceanographic observations: The wave of the future. *Scientia Marina*, *69*(Suppl. 1), 23–42.

Dickey, T. D., Chang, G. C., Agrawal, Y. C., Williams, A. J. 3rd, & Hill, P. S. (1998). Sediment resuspension in the wakes of Hurricanes Edouard and Hortense. *Geophysical Research Letters*, *25*(18), 3533–3536. https://doi.org/10.1029/98GL02635

Dickey, T. D., Itsweire, E. C., Moline, M., & Perry, M. J. (2008). Introduction to the *Limnology and Oceanography* special issue on autonomous and Lagrangian platforms and sensors (ALPS). *Limnology and Oceanography*, *53*(5part2), 2057–2061. https://doi.org/10.4319/lo.2008.53.5_part_2.2057

Dickey, T. D., & Mellor, G. L. (1980). Decaying turbulence in neutral and stratified fluids. *Journal of Fluid Mechanics*, *99*, 13–31.

Dickey, T. D., & Van Leer, J. C. (1984). Observations and simulation of a bottom Ekman layer. *Journal of Geophysical Research*, *89*, 1983–1988.

Foley, D.G., T.D. Dickey, M.J. McPhaden, R.R. Bidigare, M.R. Lewis, R. T Barber, S.T. Lindley, et al., 1997, Longwaves and primary production in the central equatorial Pacific at 0°, 140°W, *Deep-Sea Research Part II*, *44*, 1801–1826, 9-10, DOI: https://doi.org/10.1016/S0967-0645(97)00080-5.

McGillicuddy, D. J., Anderson, L. A., Bates, N. R., Bibby, T., Buesseler, K. O., Carlson, C. A., et al. (2007). Eddy/wind interactions stimulate extraordinary mid-ocean plankton blooms. *Science*, *316*(5827), 1021–1026. https://doi.org/10.1126/science.1136256

McGillicuddy, D. J., Robinson, A. R., Siegel, D. A., Jannasch, H. W., Johnson, R., Dickey, T. D., et al. (1998). Influence of mesoscale eddies on new production in the Sargasso Sea. *Nature*, *394*(6690), 263–266. https://doi.org/10.1038/28367

McNeil, J. D., Jannasch, H. W., Dickey, T., McGillicuddy, D., Brzezinski, M., & Sakamoto, C. M. (1999). New chemical, bio-optical, and physical observations of upper ocean response to the passage of a mesoscale eddy off Bermuda. *Journal of Geophysical Research*, *104*(C7), 15537–15548. https://doi.org/10.1029/1999JC900137

Smith, R. C., Booth, C. R., & Star, J. L. (1984). Oceanographic biooptical profiling system. *Applied Optics*, *23*, 2191–2197.

Smith, R.C., O.B. Brown, F.K. Hoge, K.S. Baker, R.H., Evans, R.N. Swift, and W.E. Esaias, 1987, Muliti-platform sampling (ship, aircraft, and satellite) of a Gulf Stream warm-core ring, *Applied Optics*, *26*, 2068–2081, 11, DOI: https://doi.org/10.1364/AO.26.002068.

Smith, R. C., Waters, K. J., & Baker, K. S. (1991). Optical variability and pigment biomass in the Sargasso Sea as determined using deep sea optical mooring data. *Journal of Geophysical Research*, *96*(C5), 8665–8686. https://doi.org/10.1029/91JC00080

Weller, R. A., & Davis, R. E. (1980). A vector measuring current meter. *Deep Sea Research*, *27A*, 565–582.

Zedler, S. E., Dickey, T. D., Doney, S. C., Price, J. F., Yu, X., & Mellor, G. L. (2002). Analyses and simulations of the upper ocean's response to Hurricane Felix at the Bermuda Testbed Mooring site: 13–23 August 1995. *Journal of Geophysical Research*, *107*(12), 25–21. https://doi.org/10.1029/2001JC00969