Venice and I: How a City Can Determine the Fate of a Career

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Abstract

Quoting the ancient Romans: *Audentes Fortuna iuvat*. Being in the right place at the right time is useless if you do not grasp your Fortuna and build upon it. In this article, I expound on the milestones of my multiform research career, which over more than 40 years brought me from Venice to California to MIT; from the Venice problem to highly nonlinear, coherent structures in the ocean and atmosphere; and from the mare nostrum (the Mediterranean Sea), a laboratory for global processes, to the tropical ocean-atmosphere systems and regional coupled climate models of the Maritime Continent. The climate system, with its daunting complexity, is arguably the greatest challenge for, and the future of, the entirety of the earth sciences. Finally, living in and working for Venice has been the privilege and Fortuna of my life.

> If every museum in the New World were emptied, if every famous building in the Old World were destroyed and only Venice saved, there would be enough there to fill a whole lifetime with delight. Venice, with all its complexity and variety, is in itself the greatest surviving work of art in the world.
>
> —Evelyn Waugh

1. INTRODUCTION

When I was asked to write an autobiographical article for the *Annual Review of Marine Science*, I felt honored and proud. Then the vastness of the challenge hit me. Apart from sections obviously focused on the scientific milestones of my career, what else should I write about myself? Should I focus on being a female scientist in the late 1960s in a fully male-dominated world? Should I focus on comparing the academic and research environments in the United States and Italy and what they would offer to a woman at the beginning of her career? To illustrate that the Italian scientific community—at least in physics, where I come from—already showed in the 1960s quite a definite enlightenment compared with the American one in its treatment of women, suffice it to say that the head of the Department of Physics at the University of Padua in that decade was a woman!

Then a simple fact struck me: The reason I moved from theoretical physics to physical oceanography at the beginning of my career was simply the city in which I grew up—Venice. Venice was the cornerstone of my career at the beginning and has again become a major cornerstone in recent years. In fact, from 1995 to 2013 I consulted for Consorzio Venezia Nuova (CVN), the consortium of industries responsible for constructing the Modulo Sperimentale Elettromeccanico (MOSE) system of movable barriers to protect the city from extreme flood events. So the circle closed: I started with Venice in the beginning, and to Venice I returned in the latest stages of my scientific career.

I was born after the end of World War II in the north of Italy. My mother's family was from the northern Veneto region, while my father's was from the central region of Umbria, which was in the line of fire between Americans marching northward and the retreating Germans. My father's family was hosted in my maternal ancestral home for a number of years, in a small city near Verona, where I was born. Both of my parents were distinguished professional violinists. My father, in particular, was one of the top Italian violinists of his time, and he spent a good part of the year on tour, which, before the war, was limited to Italy because of the isolationist policy of fascism. After my birth, my family began an itinerant period, with my mother playing second fiddle to my father as we traveled. We lived for two years in Rome and almost one year in Naples, and finally settled in Perugia, where my brother was born. Every summer we went to either Siena or Venice, where prestigious musical summer schools were held in which my father taught and played. Because of this wandering, I spent a lot of time with my beloved paternal grandmother in Terni, Umbria, where we finally went to live. Until then, I was home schooled with private tutors, including one in French, and I started attending public school in fourth grade. I also attended the local conservatory, studying violin as my first instrument and piano as a complementary instrument, and even gave public performances at the end of each school year. My musical talents were average, however, whereas in school I was truly outstanding: At the end of the school year, when the grades were made public (as is the practice in Italy), I had the top grades not only in my class but in the entire school, and in all the subjects. In 1956, my father won the national competition for conservatory chairs in violin. He was able to choose among Naples, Rome, Milan, and Venice, which had the most prestigious conservatories in Italy. We held a family council. My father valued my opinion, even though I was not yet in my teens—and I wanted to go to Venice! So in 1959 we moved to Venice. My father died one year later. Our life changed dramatically: My mother went back to work, becoming one of the first violins of the Venice orchestra La Fenice, and my brother and I learned to take care of ourselves for the first time.

In 1963, I entered the nearby prestigious University of Padua. I chose physics as my major, physics being one of the research fields for which the university had been renowned for centuries—suffice it to say that Galileo had been a teacher there! I continued my graduate studies there, and for my doctoral thesis, I applied molecular orbital theory to numerically evaluate the electron positions in a molecule's complex system. The theory builds on the electron wave functions of quantum mechanics to describe chemical bonding. I defended my thesis in November 1968, then spent the next year with a postdoctoral fellowship at the university's Institute of Biophysics, studying ion migration through mitochondrial membranes. It was a year of utter frustration: The research was purely biological, and the head of the group was a medical doctor who found the concept of an integral to be unintuitive!

That year, I attended a social event where I met the world-renowned elementary particle physicist Professor Giampietro Puppi (who had discovered the famous Puppi triangle of weak interactions). He had just founded the Institute for the Study of Great Masses (a somewhat meaningless name) of the Italian National Research Council in Venice. The institute had the mandate to investigate the causes of the so-called high waters (*acqua alta*) that recurrently flooded and paralyzed the entire city, and to predict their occurrence. I never found out what the "great masses" were, but Professor Puppi strongly encouraged me to apply for a job, as they were looking for young graduates in geology and physics. At that time, expertise in the *acqua alta* problem, an oceanographic issue, could not be required, as no curriculum in physical oceanography existed in Italian universities. I was interviewed at the beginning of 1970 and offered a position, which I immediately accepted, even though this implied jumping into a field of which I knew nothing at all. So, thanks to this fortuitous meeting, I left the University of Padua and returned to Venice. And here begins my story.

2. THE VENICE PROBLEM AND THE 1970s

The phenomenon of *acqua alta*—i.e., the flooding of the city of Venice—is well known from past centuries and is recorded in the annals of the Most Serene Republic. **Figure 1** shows an aerial view of the present state of the Venetian Lagoon, which is separated from the Adriatic Sea at its northern extremity by the mainland and two long, narrow islands that define the three inlets to the lagoon. The western island is very narrow (at some points only 200 m wide), and the ancient Venetians used large boulders to protect it from wind waves generated during storms. As is evident in **Figure 1**, the coastal current flows southwestward, parallel to the coastline, following the isobaths of the very shallow water. The plumes of fresher water that exit from the lagoon and are diverted to the west by the coastal current are also evident. During the *acqua alta*, the Adriatic Sea invades the entire lagoon, raises the sea level, and floods different areas of the city, depending on its intensity.

The Venetian Lagoon is a man-made environment. The rivers that flow into it with multiple mouths would have completely replenished the entire lagoon with their sediment loads if the ancient Venetians had not intervened with the drastic solution of changing the river courses between the 1500s and the 1800s. The mouths of the major rivers flowing into the lagoon are now located along the northern and southern coastlines. Until the mid-1960s, the *acqua alta* phenomenon was not as frequent as it is today (see **Figure 4*c***, below); it occurred most commonly during the fall season, when particular meteorological conditions often produce a wind blowing from the southeast along the axis of the Adriatic. On November 4, 1966, the intensity and duration of this wind, the so-called scirocco wind, were so exceptional that the high water in the city reached

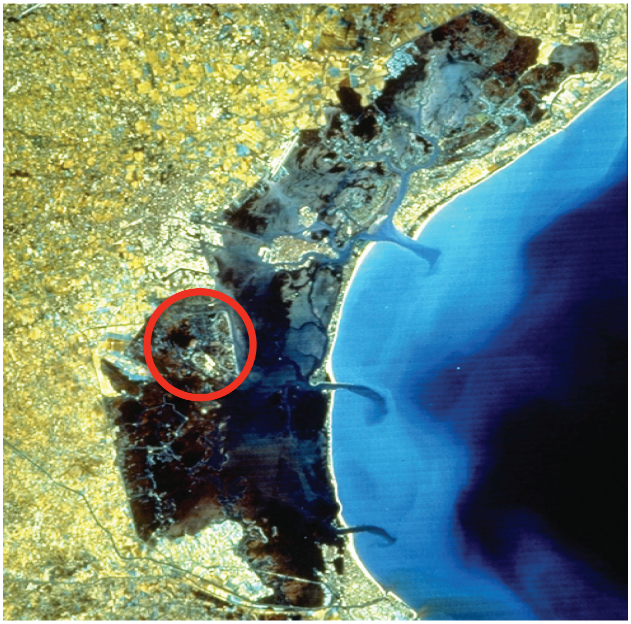


Figure 1

Aerial view of the Venetian Lagoon, showing the three inlets connecting the lagoon to the Adriatic Sea. The area circled in red is the industrial zone of Marghera, which was established in the 1920s. Adapted courtesy of Consorzio Venezia Nuova, Venice.

a level of 1.94 m and persisted for almost two days. **Figure 2** shows a picture of Piazza San Marco completely submerged in water. This extreme event focused the attention of the entire world on the city, leading to the establishment of the Institute for the Study of Great Masses.

At that time, it was already known, albeit in a qualitative way, that there are two causes for the high water, one geological and one due to the invasion of Adriatic Sea waters. The geological factor comprises both eustasy and subsidence. Eustasy is the phenomenon of long-term sea level change in response to geological and climatic conditions. Natural subsidence is linked to the progressive sinking of the regional earth surface because of the natural compaction of the underlying sediments, which characteristically occurs in lagoons and river deltas. The natural subsidence of the lagoon and the city of Venice amounts to ~0.5 mm per year. However, starting in the 1920s, a considerable portion of the lagoon was transformed into land to create the industrial region of Marghera (see **Figure 1**), which is clearly recognizable when arriving either by train or by plane. In the period from around 1930 to around 1970, the water necessary for the industries was removed from the system of aquifers underlying the lagoon. The complete collapse of some of these aquifers led to anthropic subsidence. The components of mean sea level change in Venice attributable to eustasy, natural subsidence, and anthropic subsidence were quantified and are shown in **Figure 3**. Even though the exploitation of the aquifers was stopped by law in the 1970s, giving rise to the small rebound shown in **Figure 3**, the final result is that the mean sea level in Venice is now 26 cm higher than it was at the beginning of the twentieth century, corresponding to a "lowering" of the city by 26 cm. Piazza San Marco, the lowest part of the city, is now flooded by high waters of 100 cm, which a century ago would not have caused flooding.

To this geological cause one must add the meteorological tide, i.e., sea level rise due to storm surge of the Adriatic Sea. The astronomical tidal excursion in the Adriatic is very small, in the

Figure 2

Piazza San Marco submerged in almost 2 m of water during the exceptional flood of November 4, 1966. Reproduced courtesy of Consorzio Venezia Nuova, Venice.

interval from −50 to +50 cm. However, the meteorological conditions, mostly due to cyclogenesis in the lee of the Alps, produce the scirocco wind that blows northwestward along the Adriatic Sea axis. The Adriatic Sea in fact has the geometric configuration of a long channel, with a ~3,000-m-deep southern end, the South Adriatic Pit, and a shallow shelf in the northern half, shoaling

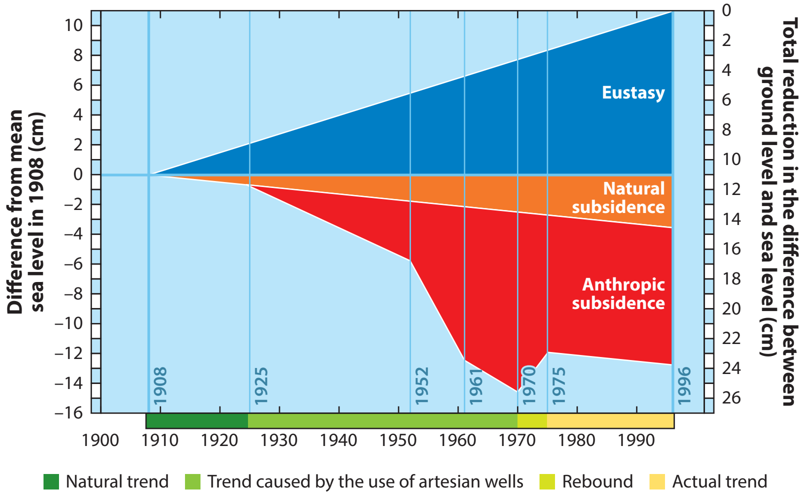
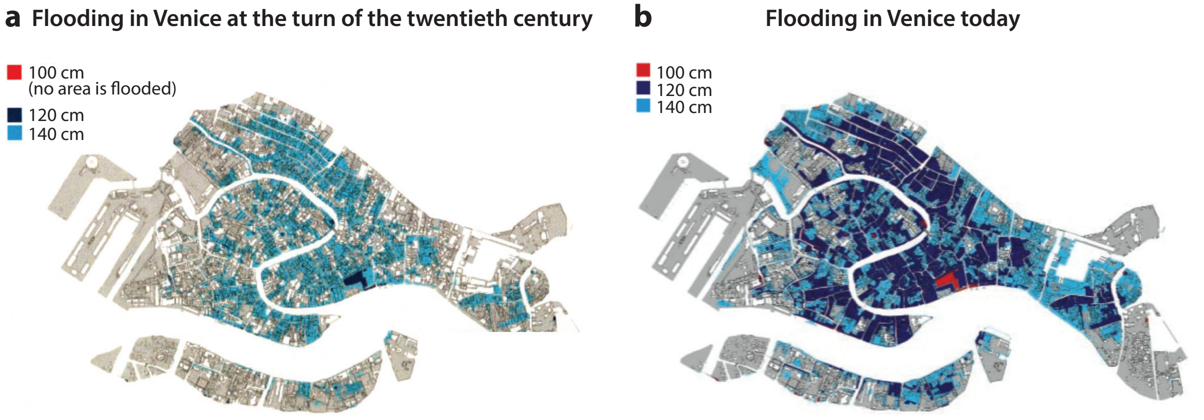
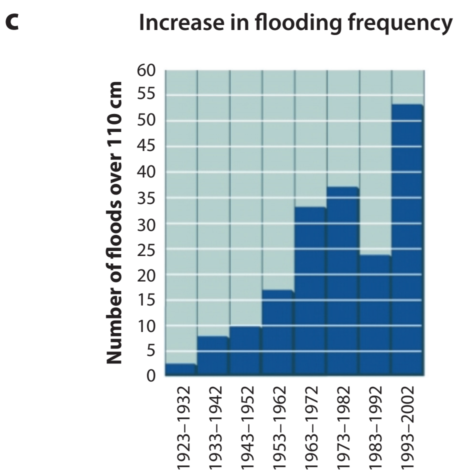


Figure 3

Components of the change in mean sea level in Venice (eustasy, natural subsidence, and anthropic subsidence) relative to the mean sea level in 1908. The net result has been an increase in the mean sea level in Venice of ~23 cm. Figure adapted from Gatto & Carbognin (1981), copyright © IAHS Press, by permission of Taylor & Francis Ltd, **http://www.tandfonline.com**, on behalf of IAHS Press.





d Exceptional floods through 2008

Date	High water (cm)
December 1, 2008	156
November 16, 2002	147
November 6, 2000	144
December 8, 1992	142
February 1, 1986	159
December 22, 1979	166
February 14, 1979	140
November 3, 1968	144
November 4, 1966	194
October 15, 1960	145
November 12, 1951	151

Figure 4

(*a*,*b*) Flooding of Venice at the beginning of the twentieth century (panel *a*) and today (panel *b*). (*c*) The increase in the frequency of flooding (high water >110 cm) between 1926 and 2005. (*d*) A list of exceptional floods (high water >140 cm) through 2008. Figure adapted courtesy of Consorzio Venezia Nuova, Venice.

from 200 m at the continental shelf break to ∼20 m in the northernmost extremity. The resulting storm surge produced by the scirocco wind elevates the sea level at the northern end, i.e., at the Venetian Lagoon. This phenomenon was first explained by Robinson et al. (1973) using a simple one-dimensional model. Furthermore, when the scirocco wind ceases, the Adriatic Sea exhibits natural seiches, the lowest of which has a period of ∼22 hours, very near to the K1 tide (Robinson et al. 1973). Therefore, a second high water is produced ∼22 hours later by the dominant seiche. Thus, the simple model of Robinson et al. (1973) had proven to already be successful in hindcasting observed sea level for numerous events.

The number of high waters and related flooding exceeding 100 cm has increased exponentially since the first half of the twentieth century. **Figure 4** shows the flooding of Venice at the turn of the twentieth century and today. The effects of the lowering of the city in the intervening period are quite evident: At the beginning of the twentieth century, a 100-cm high water left the city unaffected (**Figure 4*a***), whereas today, Piazza San Marco is completely flooded, and a 140-cm high water floods more than 80% of the city (**Figure 4*b***). **Figure 4*c*** illustrates the increase in the frequency of flooding between 1926 and 2005, and **Figure 4*d*** lists extreme flooding events through 2008. The dramatic high water of 1966 (194 cm) was a call to action, not only for scientific research but also for the design and adoption of protection measures, as had already been done for places like London (where the storm surges of the North Sea can invade the Thames) and the Netherlands (for the Scheldt in Rotterdam). Section 4 describes the adopted engineering solution, which is presently in the last phase of construction. Trincardi et al. (2016) very recently provided an exhaustive and excellent review of the Venice problem.

With this background of scientific issues, I went to work at the Institute for the Study of Great Masses, and Dr. Roberto Frassetto assigned me to investigate the general circulation and wind wave field of the Adriatic. During the 1970s, I produced several papers on these topics (Malanotte-Rizzoli & Battiston 1973; Hendershott & Malanotte-Rizzoli 1976; Cavaleri & Malanotte-Rizzoli 1978, 1981). Most important of all, Dr. Frassetto invited to the institute the most distinguished world scientists in meteorology and oceanography. Among them were Jule Charney, Arnt Eliasen, Pierre Welander, Allan Robinson, and Walter Munk, who spent a sabbatical year commuting between our institute and the Geophysical Observatory in Trieste. Through Walter, Professor Myrl Hendershott of the Scripps Institution of Oceanography was also invited to give lectures on the fundamentals of physical oceanography. Upon their recommendation, I was able to spend six months in 1971 at Scripps as a visiting scientist, working with Myrl Hendershott on the Adriatic circulation.

At this point, I realized the fundamental limitations of my university background for research in this emerging field: I might have known the Feynman diagrams, but I did not know what a Kelvin wave was! Under Myrl's prompting, I applied for my second PhD program, in physical oceanography at Scripps, which I started in 1974 and completed in a schizophrenic way, commuting every six months between Venice and California. I took only two quarters of basic courses, followed by the departmental exam and, one year later, the qualifying exam; I then defended my PhD thesis in May 1978. At Scripps I was the only woman in the physical oceanography program, and in Italy I became the first and, for quite some time, the only woman to obtain a PhD in physical oceanography.

After the departmental exam, I had a change of mind: I continued to work on the Venice problems in Italy, but for my PhD thesis, I wanted to carry out more fundamental research. Myrl, apart from having become my great friend, was also my adviser. Upon his suggestion, I began to read the work of Ed Lorenz, whose seminal papers on predictability and chaos fascinated me. Chaos has been defined as the third great discovery of the twentieth century, after relativity and quantum theory, and Lorenz's work became the motivation for my PhD thesis research.

Among Lorenz's papers, one, in particular, attracted my attention: "The Predictability of a Flow Which Possesses Many Scales of Motion" (Lorenz 1969). In it, Lorenz considered a highly idealized model of the atmosphere, the barotropic vorticity equation, to describe the dynamics of large-scale flows. He showed that an extremely small error in the initial conditions, confined to the smallest scales of motion, propagates to the larger scales, gradually affecting all of them. For atmospheric motions, this implies that all of the wavelengths, up to the planetary ones of 40,000 km, completely lose predictability in approximately two weeks. However, examples of long-lived structures are well known, both in the ocean and the atmosphere (see Section 3.1). Hence, a simple question arises: Can the same equations that lead to unpredictable behavior allow for a parameter range in which their solutions are instead long-lived, predictable structures?

I addressed this question starting from the same equation used by Lorenz, slightly modified by adding a variable topography in the quasi-geostrophic approximation. In the parameter range in which nonlinearity balances dispersion, I found solitary wave (soliton) solutions that, in a dissipation-less world, are completely predictable systems. The title of my PhD thesis was "Solitary Rossby Waves over Variable Relief and Their Stability Properties" (later published as two papers, Malanotte-Rizzoli & Hendershott 1980 and Malanotte-Rizzoli 1980).

3. 1981: GOING TO MIT

After defending my doctoral thesis, I stayed at Scripps for two years with a Green Scholarship, a postdoctoral fellowship offered to me by Walter Munk. During these two years I continued to commute between Italy and Scripps with a dual appointment, keeping my position as senior scientist at the institute in Venice.

Again, chance made its appearance. In 1979, Jule Charney spent a sabbatical year at UCLA, and he invited me to give a seminar on my research. As solitons were at that moment a hot topic, the 1980 Summer School in Geophysical Fluid Dynamics at the Woods Hole Oceanographic Institution (WHOI) was devoted to them. One morning, in August 1980, I received a telephone call from Jule, who asked me point-blank, "Paola, we have an opening at MIT for an assistant professor. Would you be interested?" In a split second, I took my decision and answered: YES! By that time, I had worked at the Institute for the Study of Great Masses in Venice for almost ten years and had received tenure, becoming a senior research scientist. This offer meant a permanent move to the United States, leaving my Italian job and my country, and starting all over. But I had no hesitation: Coming to MIT was an opportunity that occurs once in a lifetime, and I could not turn it down. In August 1980, I was interviewed by Ed Lorenz, who was the head of the Department of Meteorology and Physical Oceanography, and I started my academic life at MIT on February 1, 1981.

3.1. Coherent Structures in the Ocean and the Atmosphere

Turbulent systems with many degrees of freedom exhibit a mixing of phases that leads eventually to statistical equilibrium. In weather prediction, this randomness postulate leads to loss of predictability, as demonstrated by Lorenz (1969). Solitary waves violate this postulate; for them, nonlinearity plays the opposite role of preserving phase correlations against the effects of dispersion.

The concept of a solitary wave was introduced long ago by Russell (1838, 1845), who gave a famous description of his discovery in 1834, when he followed on horseback a wave of elevation propagating along a channel without a change of shape or amplitude. Since the nineteenth century, a large number of papers have appeared on the subject. In the early 1970s, Scott et al. (1973) provided a comprehensive review of solitary wave models in different fields (water waves, nonlinear optics, elementary particle theory, plasma physics, etc.). In the late 1970s, the possibility of the soliton's bearing on the predictability problem was stated by Leith (1978, p. 125): "Is such a new approach in the offing for weather prediction? . . . My own candidate for such an approach is the recognition, based on nonlinear wave theory, that many one-dimensional nonlinear systems with linear dispersion can have remarkably stable and completely predictable solutions called solitons." In the early 1980s, I discussed the predictability problem of planetary motions (Malanotte-Rizzoli 1982b) and, specifically, coherent structures as systems endowed with enhanced predictability (Malanotte-Rizzoli 1983). I also explored their stability (Malanotte-Rizzoli 1982c) and published comprehensive reviews of planetary solitary waves in geophysical flows (Malanotte-Rizzoli 1982a, 1992).

Because of this renewed interest, the 1980 Summer School in Geophysical Fluid Dynamics at WHOI was devoted to nonlinear coherent structures (Veronis & Mellor 1980). Examples of features endowed with long lifetimes are numerous. Perhaps the most famous is the Great Red Spot of Jupiter, which has persisted for centuries. A model for the persistence of the Great Red

Spot was proposed by Maxworthy & Redekopp (1976a,b) and Redekopp (1977), consisting of the superposition of two solitary waves, the first one an isolated depression, the second one an isolated elevation, both embedded in a mean shear flow. Examples of long-lived oceanic features for which solitary wave models have been proposed are Gulf Stream rings (Flierl 1979, Flierl et al. 1980) and, in general, the ubiquitous rings shed by western boundary currents, such as the Agulhas and North Brazil Currents. A final important example is atmospheric blocking consisting of a vortex pair embedded in westerly winds that persists beyond the synoptic timescale. Special types of solitary waves called modons have been proposed for the blocking dipole that are steady solutions of the barotropic vorticity equation (McWilliams 1980, McWilliams et al. 1981). I also proposed a barotropic solitary wave dipole as a model for blocking, a solution of the fully time-dependent barotropic vorticity equation, and further showed how an initial condition that is close enough to the permanent wave solution can evolve spontaneously into that solution (Malanotte-Rizzoli 1980). **Figure 5** shows this evolution. The initial condition consists of an elongated dipole in the barotropic stream function. The strong nonlinearity makes the initial eddy evolve through a steepening process (shown clearly in **Figure 5**), which makes the eddy more symmetrical, thus increasing the dispersive effects. When the balance between nonlinearity and dispersion is finally reached, the dipole evolves without a change of shape or speed, i.e., as a solitary dipole.

The inclusion of baroclinicity was carried out by Malguzzi & Malanotte-Rizzoli (1984, 1985) and Malanotte-Rizzoli & Malguzzi (1987), who developed an analytical theory with solutions in the form of stationary dipole structures superimposed on a mean westerly wind. Malanotte-Rizzoli & Hancock (1987) performed an in-depth comparison between theory and data. A unified approach for isolated anomalies in westerly jet streams, including blocking, was proposed by Haines & Malanotte-Rizzoli (1991) and Haines et al. (1993a). Further relevant studies of nonlinear waves and coherent vortex structures were carried out by Flierl et al. (1987) and Malanotte-Rizzoli et al. (1988).

In the ocean, coherent, long-lived vortex structures, the rings, have been shown to be ubiquitously shed by the strong western boundary currents. Warm- and cold-core rings are powerful agents of mixing of ocean properties (temperature, salinity, etc.) across the strong thermal fronts associated with the Gulf Stream and the Kuroshio. Rings continuously shed by the Agulhas and North Brazil Currents, among others, can travel long distances into the ocean interior, providing major transports of different water masses. The ubiquitous mesoscale eddy field and its highly nonlinear counterparts, rings and vortices, have changed our picture of the ocean circulation from linear, quasi-steady currents and gyres to a fully turbulent, continuously evolving flow.

3.2. The Mediterranean Sea and the Physical Oceanography of the Eastern Mediterranean Program

While working at the Institute for the Study of Great Masses in Venice and on the Adriatic Sea dynamics, I had regularly attended the meetings of the Commission Internationale pour l'Exploration Scientifique de la Mer Méditerranée (CIESM), held every other year in a Mediterranean venue. At these meetings, I was struck by the difference in knowledge between the western and eastern sub-basins of the Mediterranean. The western sub-basin had been studied much more because of its connection to the Atlantic Ocean through the Strait of Gibraltar and because of an international collaborative program led by Henry Stommel in the early 1970s to investigate the deep convection occurring in the Gulf of Lyons in winter, which leads to the formation of the Western Mediterranean Deep Water.

The pictures of the eastern Mediterranean's general circulation and water masses went back to Nielsen (1912), Pollak (1951), Wust (1961), and Ovchinnikov (1966). Professor Allan Robinson of

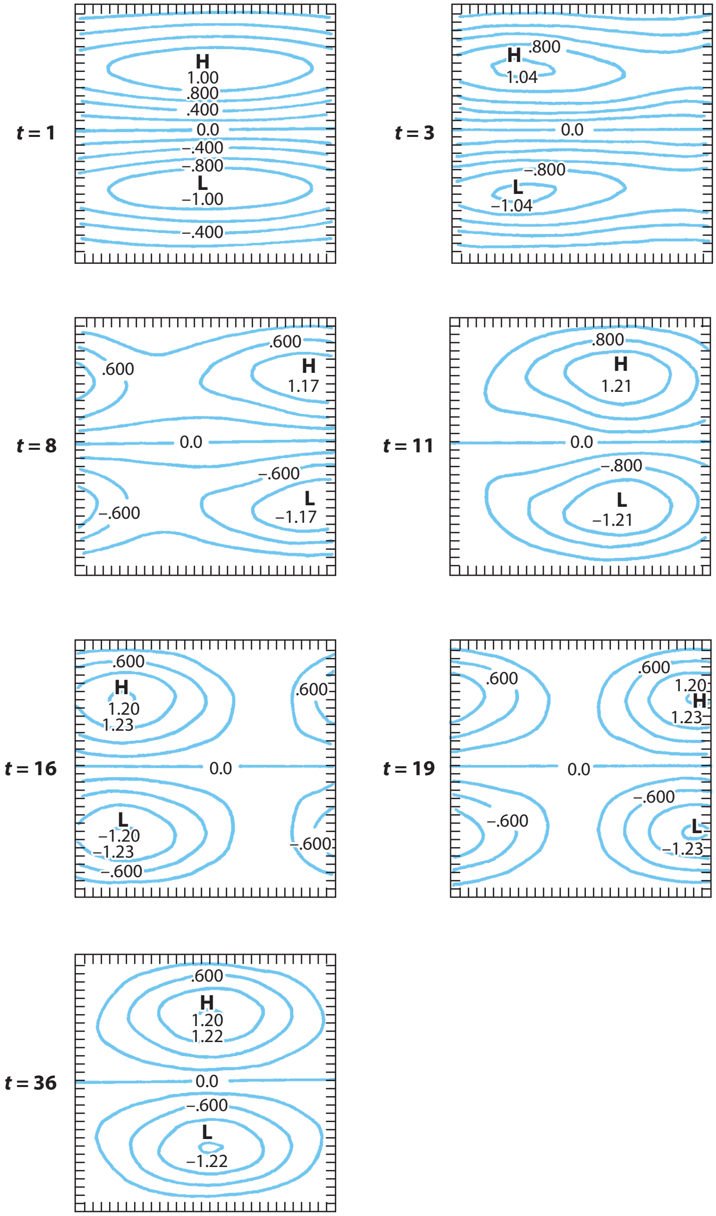


Figure 5

Evolution of the initial condition (*upper left panel*, $t = 1$) into a solitary dipole ($t = 36$) through adjustment and equilibration of nonlinearity versus dispersion. Abbreviations: H, high; L, low. Adapted from figure 5 of Malanotte-Rizzoli (1980), courtesy of Elsevier Science.

Harvard University had become interested in the Mediterranean and, in particular, in the eastern sub-basin. He and I were of like mind and took action to establish a scientific program by calling on the eastern Mediterranean oceanographic community. A round table was organized in 1982 at the CIESM meeting in Monte Carlo, Monaco, with the sponsorship of the United Nations Educational, Scientific, and Cultural Organization and the International Oceanographic Commission.

The leading scientists of the eastern Mediterranean from Italy, the former Yugoslavia, Greece, Israel, Turkey, France, and Germany were present. The Physical Oceanography of the Eastern Mediterranean (POEM) Program was then launched under the joint chairmanship of Professor Robinson and myself (Malanotte-Rizzoli & Robinson 1988, Robinson et al. 1992).

I am very proud of having been the scientific coleader of POEM. When we started in 1982, the pictures recurrently shown of its general circulation were those mentioned above plus a qualitative and sometimes incorrect description of its water masses. When we concluded in 1995 (fieldwork) and 2003 (with a special issue of the *Journal of Geophysical Research* devoted to POEM), the knowledge of the eastern Mediterranean phenomenology and dynamics was firmly established by extensive fieldwork and related modeling studies. Malanotte-Rizzoli et al. (2014) later published a comprehensive review on this topic.

The Mediterranean Sea, in particular the eastern Mediterranean, provides a laboratory basin for processes of global relevance (Malanotte-Rizzoli 1994, Bergamasco & Malanotte-Rizzoli 2010, Malanotte-Rizzoli et al. 2014). Water mass formation processes in the eastern sub-basin are of two types. The traditional picture shows deep convection occurring in the southern Adriatic that leads to the formation of the Southern Adriatic Deep Water, as was already recognized in the pioneering work of Pollak (1951). The Adriatic Deep Water spreads out from the Strait of Otranto and becomes the Eastern Mediterranean Deep Water. Second, and most importantly, intermediate convection in the Levantine Basin leads to the formation of Levantine Intermediate Water. This water mass spreads through the entire basin, exiting from Gibraltar and forming the well-known Mediterranean salty-water tongue, which reaches the northern Greenland and Labrador Seas (Reid 1994) and preconditions the formation of the North Atlantic Deep Water, the crucial ingredient of the global conveyor belt.

The establishment of the eastern Mediterranean phenomenology is based on the POEM fieldwork and the successive POEM-BC. During POEM phase I, which took place from 1984 to 1987, five general hydrographic surveys were carried out jointly by research vessels from Italy, Greece, Turkey, Israel, and Germany. POEM then evolved into POEM-BC, which took place from 1991 to 1995, added biological and chemical components, and included three joint general hydrographic surveys. The culmination of POEM-BC was in 1995 with the Levantine Intermediate Water Experiment, a major fieldwork project that lasted four months and aimed at identifying the successive phases of water mass formation and spreading pathways of these masses from the formation sites (Malanotte-Rizzoli et al. 2003).

The rich observational data set obtained in this extensive fieldwork led to the definition of multiple scales of motion present in the basin. These scales range from the mesoscale, energetic, and ubiquitous eddy fields; to the sub-basin scale of the upper thermocline and wind-driven circulation; to the basin-scale closed thermohaline circulation cell. **Figure 6*a*** shows the major features of the upper thermocline circulation. Malanotte-Rizzoli et al. (1997) revisited the analysis for the Ionian basin and proposed the more detailed pattern shown in **Figure 6*b***. Both panels show the major permanent cyclones and anticyclones as well as the permanent currents and jets connecting them. The most startling finding in POEM-BC phase II, which took place in 1995, related to the eastern Mediterranean closed thermohaline cell (Roether & Schlitzer 1991, Roether et al. 1996, Malanotte-Rizzoli et al. 1999). Until the late 1980s, the closed thermohaline cell was driven by the southern Adriatic deep convection. In 1995, the startling finding was that the engine of the closed thermohaline cell had shifted to the southern Aegean and Cretan Seas, with Cretan Intermediate Water and Cretan Deep Water spreading out of the Cretan arc straits, simultaneously pushing to the west and lifting the less dense Eastern Mediterranean Deep Water of Adriatic origin. This event is now known as the Eastern Mediterranean Transient, and a vast amount of literature has been devoted to it (e.g., Klein et al. 1999, Lascaratos et al. 1999, Theocharis et al. 1999). A

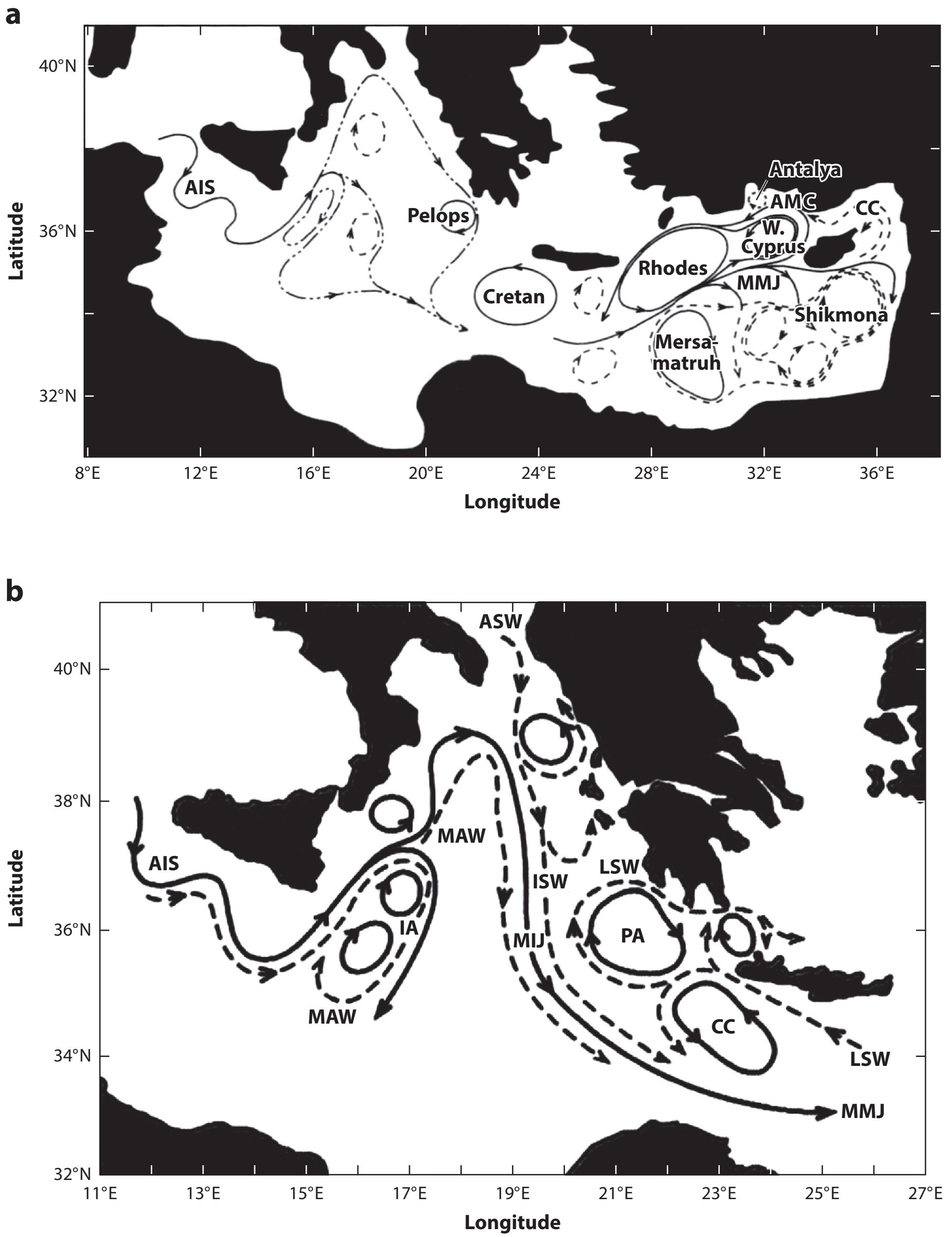


Figure 6

(*a*) Schematic of the upper thermocline circulation in the eastern Mediterranean. Abbreviations: AIS, Atlantic-Ionian Stream; AMC, Asia Minor Current; CC, Cilician Current; MMJ, Mid-Mediterranean Jet. (*b*) Schematic of the upper thermocline circulation for the Ionian Sea based on a revisited analysis. Abbreviations: AIS, Atlantic-Ionian Stream; ASW, Adriatic Surface Water; CC, Cretan Cyclone; IA, Ionian Anticyclones; ISW, Ionian Surface Water; LSW, Levantine Surface Water; MAW, Modified Atlantic Water; MIJ, Mid-Ionian Jet; MMJ, Mid-Mediterranean Jet; PA, Pelops Anticyclone. Adapted from figures 7*b* and 8*b* of Malanotte-Rizzoli et al. (1999), courtesy of Elsevier Science.

further discovery was that this shift of the source of deep water was already occurring in 1991 (Malanotte-Rizzoli et al. 1999), and different dynamical scenarios have been proposed to explain this transition (Tsimplis et al. 2006). The final, intriguing possibility is that multiple equilibria exist for the eastern Mediterranean thermohaline cell. Because of the eastern Mediterranean's short renewal time (Roether & Schlitzer 1991), it was possible to observe the Eastern Mediterranean Transient, which, in this scenario, would then lead to a different equilibrium state of the basin (Ashkenazy et al. 2012).

3.3. Data Assimilation in Oceanography

Data assimilation is by now a fully established field in oceanography, so much so that various assimilation procedures are now an essential part of numerical modeling at all the major atmosphere/ocean modeling centers in the world, including the National Center for Atmospheric Research, the Goddard Space Flight Center, and the Geophysical Fluid Dynamics Laboratory in the United States and the European Centre for Medium-Range Weather Forecasts in the United Kingdom. The history of data assimilation in oceanography is relatively short (starting in the early 1980s), but this is not the case in meteorology. In fact, the term data assimilation was coined in meteorology in the early 1960s, referring to the methodology by which observations are melded into model simulations to improve the forecasting skill of operational meteorological models.

Clearly a primary reason for this lag has been the lack of adequate data sets. Until the early 1990s, the available oceanographic observations were so few compared with their meteorological counterparts, and so sparse in space and time, that the assimilation methods were almost ineffective at improving the ocean simulations. The present oceanographic data sets are almost comparable to the meteorological ones, i.e., synoptic and with global coverage. This observational revolution occurred with the advent of satellite oceanography, and the lack of adequate ocean data has been partially resolved.

A second important reason for the delayed development of ocean data assimilation was the lack of an urgent and obvious motivation, such as the need to forecast the weather and to produce better and longer forecasts. By now, ample oceanographic motivation exists for two main objectives. The first is ocean state estimation, i.e., obtaining a four-dimensional (space/time) realization of the oceanic state consistent with the available data sets to map the evolution of ocean processes. The example most used in the oceanographic community is the Simple Ocean Data Assimilation (SODA) data set developed by Carton et al. (2000a,b). The second objective is to carry out ocean predictions on various spatial and temporal scales. This objective was initially neglected and even looked down on by part of the oceanographic community, which considered prediction to be just an operational, engineering goal. The most startling contradiction of this myopic view is climate, because the problem of future climate change is exactly a prediction problem, as clearly demonstrated by the various reports of the Intergovernmental Panel on Climate Change (IPCC). Other prediction problems of the large-scale ocean variability relate to the meridional overturning circulation in the Atlantic and the El Niño phenomenon in the tropical Pacific. Finally, regional mesoscale ocean forecasts are also important in frontal regions such as the Gulf Stream system and, in general, in all of the western boundary currents of the world ocean. There, the highly energetic mesoscale eddy field modulates the larger-scale gyre circulation.

The term data assimilation was coined in meteorology, and a term with a slightly different connotation, but dealing with very similar if not identical methods, is borrowed from solid earth geophysics, i.e., inverse theory. This term is used, for instance, in books by Bennett (1992) and Tarantola (2005) and in many papers by Wunsch (1978, 1988, 1989, 1996). I will not list the many contributions now available in the literature, and instead refer readers to a paper by Ghil & Malanotte-Rizzoli (1991), which is still topical and provides a concise but exhaustive review of the theoretical aspects of data assimilation, from the sequential methods (such as the Kalman filter and its derivatives) to the variational adjoint method of control theory. I also refer readers to the paper by Malanotte-Rizzoli & Tziperman (1996) for an equally concise but comprehensive overview of the motivation and purposes of data assimilation in oceanography.

I became very interested in data assimilation in the late 1980s. I was intrigued by the type of constraint that each data assimilation method provided to the ocean model. My first studies were therefore rather idealized, sometimes even analytical, and aimed to understand how the data affected the dynamics of the scales of motions under investigation (Malanotte-Rizzoli & Holland 1986, 1988; Malanotte-Rizzoli et al. 1989; Capotondi et al. 1995a,b). I was also interested in comparing the effectiveness of different methods, again in idealized or semi-idealized settings (Haines et al. 1993a,b; Fukumori & Malanotte-Rizzoli 1995; Gunson & Malanotte-Rizzoli 1996a,b; Malanotte-Rizzoli et al. 1996; Jiang & Malanotte-Rizzoli 1999; Buehner & Malanotte-Rizzoli 2003; Zang & Malanotte-Rizzoli 2003; Chen et al. 2009; Wei & Malanotte-Rizzoli 2009). Most of the above studies used the sequential Kalman filter or one of its derivatives. Studies were also carried out using the variational adjoint approach (Yu & Malanotte-Rizzoli 1996, 1998).

Simultaneously to these idealized investigations, more realistic applications became important after the establishment by the US Navy of the Synoptic Ocean Prediction (SYNOP) program. Regional mesoscale prediction was so important to the US Navy that the Office of Naval Research established this multiyear observational and modeling program in the Gulf Stream system in the early 1980s. The program covered the Gulf Stream from its detachment from the coastline at Cape Hatteras to its meandering in the northwestern Atlantic before it becomes the North Atlantic Current. I was an active participant in SYNOP and in its successor, the Data Assimilation and Model Evaluation Experiment (DAMEE), which lasted until the late 1990s (Holland & Malanotte-Rizzoli 1989; Malanotte-Rizzoli & Young 1992, 1995).

I now give a specific example to show how assimilation of real data can constrain a model simulation in realistic settings to produce better estimates of oceanographic fields, at least in part of the ocean model domain. The model used is a reduced gravity primitive equation model of the Atlantic between 30°S and 30°N based on a model originally developed by Gent & Cane (1989). It is constrained by the climatological fields at the northern and southern boundaries, and its domain is shown in **Figure 7*a***. (For details of the general circulation model, see Buehner et al. 2003.) The assimilation scheme is a reduced-rank, stationary Kalman filter, an approximation of the extended Kalman filter.

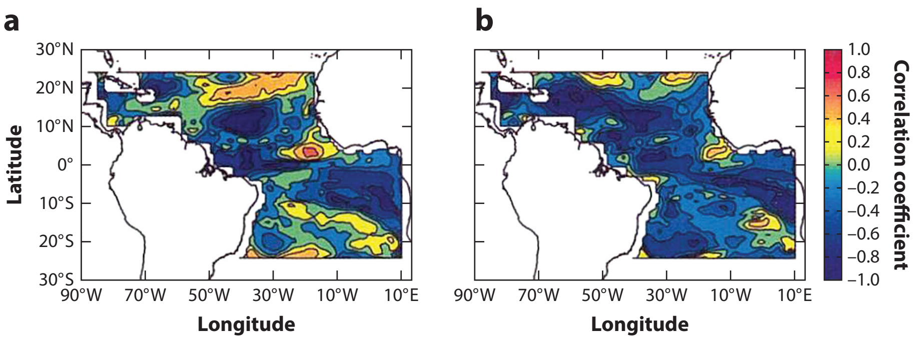


Figure 7

Correlation over the period January 1, 1996, to January 1, 2000, between the TOPEX/Poseidon sea-surface height anomaly and the depth of the 14°C isotherm in (*a*) a control run and (*b*) an assimilation run using real altimetry data. Adapted from figure 21 of Buehner et al. (2003), courtesy of Elsevier Science.

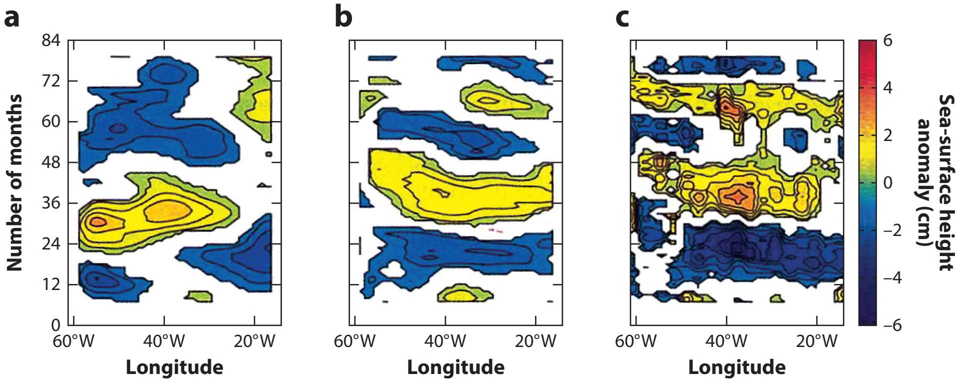


Figure 8

Time series of sea-surface height anomaly along 10°N from January 1, 1993, to January 1, 2000, after filtering with a 12-month running mean for (*a*) a control run, (*b*) an assimilation run using real altimetry data, and (*c*) the TOPEX/Poseidon data. Adapted from figure 22 of Buehner et al. (2003), courtesy of Elsevier Science.

The assimilation data set consists of the TOPEX/Poseidon sea-surface height anomaly (SHA) data, which are dense in space over the model domain. One of the major goals of the assimilation is to show how the subsurface thermocline structure is dynamically constrained by the SHA. We choose the 14°C isotherm as a proxy for the base of the thermocline. After the simulation without data assimilation (i.e., the control run), we carry out another simulation with assimilation of the TOPEX/Poseidon SHA data over the period January 1, 1996, to January 1, 2000. The initial state for both simulations is taken to be the fully spun-up state on January 1, 1996. A simple way of determining the connection between SHA and the subsurface temperature field is to calculate the correlation between the SHA and the 14°C thermocline depth. **Figure 7** shows the correlation over the last four years of the simulations between the TOPEX/Poseidon SHA data and the 14°C isotherm depth from a control run and an assimilation run. A considerable reduction in the correlation coefficient due to the assimilation occurs over most of the areas of the model domain that have a strongly negative correlation coefficient. The largest changes, approaching −1, occur in the equatorial region within 10° of latitude of the equator.

Figure 8 shows the time series of SHA along 10°N after filtering with a 12-month running mean for the control run, the assimilation run, and the TOPEX/Poseidon data. These results show that the assimilation is able to significantly improve the interannual variability of SHA at 10°N, where the difference between the simulation and the observations is reduced on average by 31%. The conclusion is that SHA is a powerful constraint of the subsurface thermal structure, but only in the narrow equatorial band where the dynamics is dominated by the first baroclinic mode.

3.4. The Tropical Oceans

By the late 1990s, I began to feel the need to start a new project, albeit without stopping work on the Mediterranean Sea or on data assimilation. One might say that my "renewal time" is 5–7 years! In parallel with work on the major topics discussed above, I also worked on ocean acoustic tomography using modeling simulations of gyre-scale tomographic arrays (Malanotte-Rizzoli 1985, Malanotte-Rizzoli & Holland 1985). I even participated in a tomographic experiment in the Gulf Stream with bottom-mounted source/receivers. The most relevant publications on this experiment are those by Agnon et al. (1989) and Chester et al. (1994). I also worked on modeling the Black Sea ecosystem, one of the most polluted seas in the world—a "eutrophic soup," as it has been called. Three papers by Oguz et al. (1999, 2001, 2003) are the most representative publications. I do not devote a specific section to either of these topics, as I do not consider my related contributions to be among the most important. Furthermore, ocean acoustic tomography has not maintained the promises made when the idea was first proposed. For a variety of reasons, it has in fact disappeared as an alternative, or complementary, measurement with respect to other observational systems.

I had so far worked in the midlatitudes, where the ocean is mostly a passive system responding to atmospheric surface forcing such as wind stress and heat fluxes. A part of the world ocean in which the ocean itself becomes a primary factor driving the atmosphere above is the tropical ocean. Here, coupled atmosphere-ocean modes are of paramount importance to the earth's climate. The El Niño/La Niña phenomenon in the tropical Pacific is the most well-known and most studied example. I became very interested in investigating and understanding these large-scale coupled ocean-atmosphere modes of variability and how they affect not only the global climate, but, equally importantly, the regional climates. As the tropical Atlantic was not as thoroughly studied as the Pacific, it was natural for me to transfer from the Atlantic midlatitudes to the tropical Atlantic band, where the ocean deeply affects the local climates of Africa and Brazil.

Studies aimed at understanding the low-frequency variability of the tropical oceans have hypothesized that shallow teleconnections between the subtropics and tropics could constitute the oceanic branch of slow coupled ocean-atmosphere modes (Gu & Philander 1997, Lazar et al. 2002). Various mechanisms could be at play within these connections, involving either advection of mean temperature by perturbations of the mean circulation or advection of sea-surface temperature (SST) anomalies by the mean circulation itself. It is therefore plausible that subduction of water masses in the tropics and low subtropics has a significant role in affecting the equatorial thermocline. In the Pacific, the observational evidence shows that the core of the Equatorial Undercurrent (EUC) lies in the range 15–25°C, implying that the source region for this water is approximately between 20° and 40° in both hemispheres, where these isotherms outcrop (Wyrtki & Kilonski 1984). The most striking observational example is given by Fine et al. (1981) and Fine (1987), who showed the presence of a tritium subsurface maximum centered on the equator that persists regardless of time sampling. They concluded that high-tritium subtropical source waters are transported equatorward by the interior geostrophic flow after subduction. In the Atlantic, the observational evidence for exchanges between the subtropics and tropics is more ambiguous, in part because of the meridional overturning circulation. However, the Atlantic EUC core lies in the same temperature range as the Pacific EUC (Fratantoni et al. 2000), indicating that the source regions for these waters are again in the subtropics.

Because of the much greater ambiguity in observational evidence of the Atlantic subtropical-tropical cells (STCs), a series of Climate Variability and Predictability (CLIVAR) workshops was held. The first was held in Venice in 2000, with subsequent workshops held in Paris, France, in 2001; Kiel, Germany, in 2002; and Miami, United States, in 2003, along with special symposia held at the conferences of the International Association for the Physical Sciences of the Oceans. These meetings later resulted in a book (Goni & Malanotte-Rizzoli 2003), and my contribution to the topic led to several papers (Malanotte-Rizzoli et al. 2000, Jochum & Malanotte-Rizzoli 2001, Inui et al. 2002, Lazar et al. 2002, Kroger et al. 2005).

The collective body of observational evidence led to the definition of the shallow STCs as constituting the oceanic thermocline connection capable of modulating tropical variability (Liu 1994, Liu et al. 1994, McCreary & Lu 1994, Liu & Philander 1995, Lu & McCreary 1995, Gu & Philander 1997, Lu et al. 1998, Rothstein et al. 1998, Harper 2000, Malanotte-Rizzoli et al.

2000, Hazeleger et al. 2001, Inui et al. 2002, Lazar et al. 2002, Kroger et al. 2005). In the Atlantic, Marshall et al. (2001) established Tropical Atlantic Variability (TAV) as a dominant climate signal in the Northern Hemisphere. TAV is defined as a covarying fluctuation between tropical SST and the trade winds straddling the Intertropical Convergence Zone (ITCZ), and it has been shown to affect precipitation anomalies in North Africa and South America. In the shallow STCs, equatorward flow within the upper subtropical thermocline is compensated by poleward flow in the surface layers. The STC is closed by subduction in the tropics and upwelling at the equator.

Snowden & Molinari (2003) provided a thorough review of the observational evidence of the Atlantic STCs. The results of numerical simulations by Malanotte-Rizzoli et al. (2000) gave a detailed picture of the communication pathways involved in the subtropical-tropical exchanges by examining float trajectories. The northern STC reflects the presence of the ITCZ, which occupies a small region in the eastern Pacific (because of this ocean's width) and a much larger region in the Atlantic. Here, pathways from the subtropics to the tropics exist for floats deployed between 20°N and 30°N. The most striking pattern was for a set of 30 floats deployed at a depth of 50 m in an array covering the entire Atlantic basin longitudinally at 21°N; as shown in **Figure 9**, the injected floats reached the EUC in a zigzag pattern determined by the North Equatorial Countercurrent and flowed around a semiclosed region into which they could not penetrate.

For the southern STC (not shown in **Figure 9**), all of the floats injected west of ~11°W migrated to the western boundary current and the North Brazil Current, some directly, others

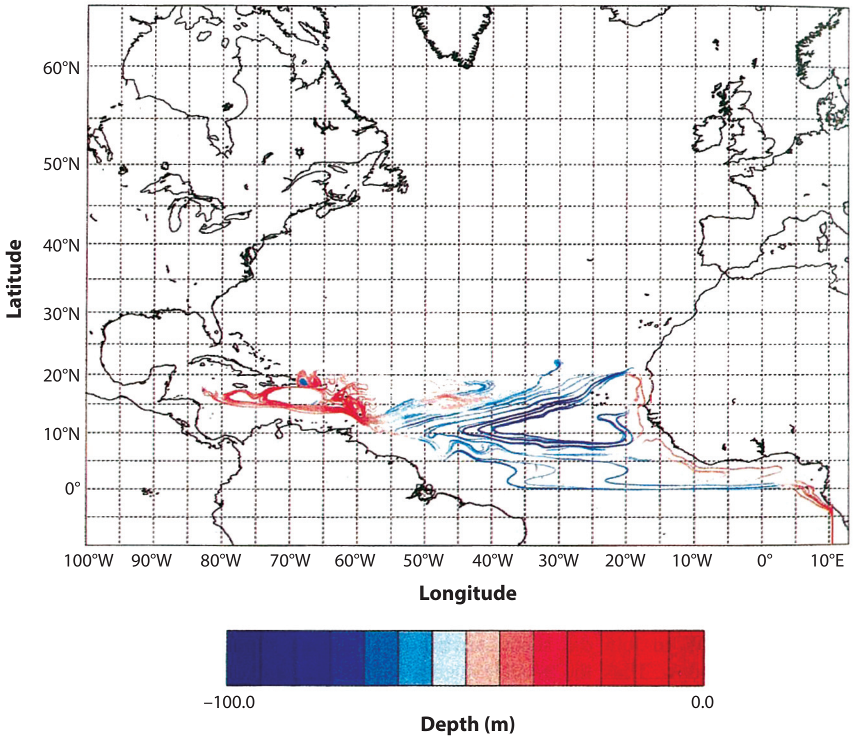


Figure 9

Trajectories over 20 years of 30 floats deployed at a depth of 50 m in an array covering the entire Atlantic basin longitudinally at 21°N. Adapted from figure 11 of Malanotte-Rizzoli et al. (2000), courtesy of Elsevier Science.

following more convoluted pathways determined by the southern equatorial currents. Some of the floats entrained into the North Brazil Current overshot and crossed the equator, but then retroflected and joined the EUC in a path well known observationally.

Even though the Pacific is much wider than the Atlantic, the pattern of the Pacific STCs is quite similar to that of the Atlantic ones. In particular, the asymmetry of the northern and southern STCs and the pattern of float trajectories in the Northern Hemisphere shown in **Figure 9** are also evident in the Pacific. This asymmetry is due to the presence in both oceans of the ITCZ, whose average position is shifted north of the equator and produces an asymmetry in the pattern of precipitation and droughts affecting the local climates of North Africa and Brazil. The asymmetry of the ITCZ for the nearby continental lands is much more important in the Atlantic than in the Pacific due to the smaller width of the basin. The asymmetry of the ITCZ also produces the island of upwelling shown in **Figure 9** (see the references cited above). This upwelling island creates a region of high potential vorticity (PV) penetrating to depth, and hence a PV barrier is created for the water columns, and the floats subducted north of 15°N. In the language of the ventilated thermocline (Luyten et al. 1983), and taking the conceptual analog of a two-layer model, subducted water columns in the inviscid, quasi-linear interior must conserve f/h_2, where f is the Coriolis parameter and h_2 is the thickness of the lower layer. In their movement to the equator, f decreases, and the columns cannot pass through the high-PV pool, where their thickness h_2 would increase because of the vortex stretching due to Ekman upwelling. Hence, they are deflected westward and can reach the equator only by moving around the PV barrier (Malanotte-Rizzoli et al. 2000).

3.5. Climate Science: The Future of Oceanographic Research

The IPCC reports have firmly established that global warming is unequivocal and that this warming is by and large anthropogenic. Hence, in the last few years, climate research has become the top priority because of the clear consequences of global warming, such as glacier melting, sea level rise, an increased frequency of extreme events, and so on. The importance of the climate problem cannot be overstated. Climate science, with its daunting complexity, is arguably the greatest challenge presently facing not only oceanography but the earth sciences in general. The IPCC reports have focused on projections over 100 years (i.e., until 2100) of global averages of important quantities such as global mean surface air temperature and global mean sea level rise (i.e., of integral quantities as the most robust measures for prediction). However, regions particularly exposed to the consequences of global warming need regional predictions on a decadal timescale. I do believe that the present and future of oceanographic research lies in the understanding, simulation, and prediction of regional climates—a problem even more complex than the prediction of global average properties, in view of the enormous differences among such regional domains.

Given this perspective, by the second half of 2000, I felt that the time had come to start a new, climate-oriented research project. The opportunity was provided in 2007 by the invitation of the Singapore government to establish a substantial research presence of MIT faculty in Singapore. What later became the Singapore-MIT Alliance for Research and Technology (SMART) was then started as an MIT-owned entity. Interdisciplinary research groups were formed, one of which was the Centre for Environmental Sensing and Modeling (CENSAM), in which I played a role. The National Research Foundation of Singapore supported it, and CENSAM officially started on January 1, 2008.

Climate research also became of great importance for the CENSAM program, with a specific focus on the present and future climate of the Maritime Continent and its consequences for Singapore. The Maritime Continent is shown in **Figure 10**. Its oceanic component comprises the Indonesian Throughflow, which is the major conduit from the Pacific to the Indian Ocean

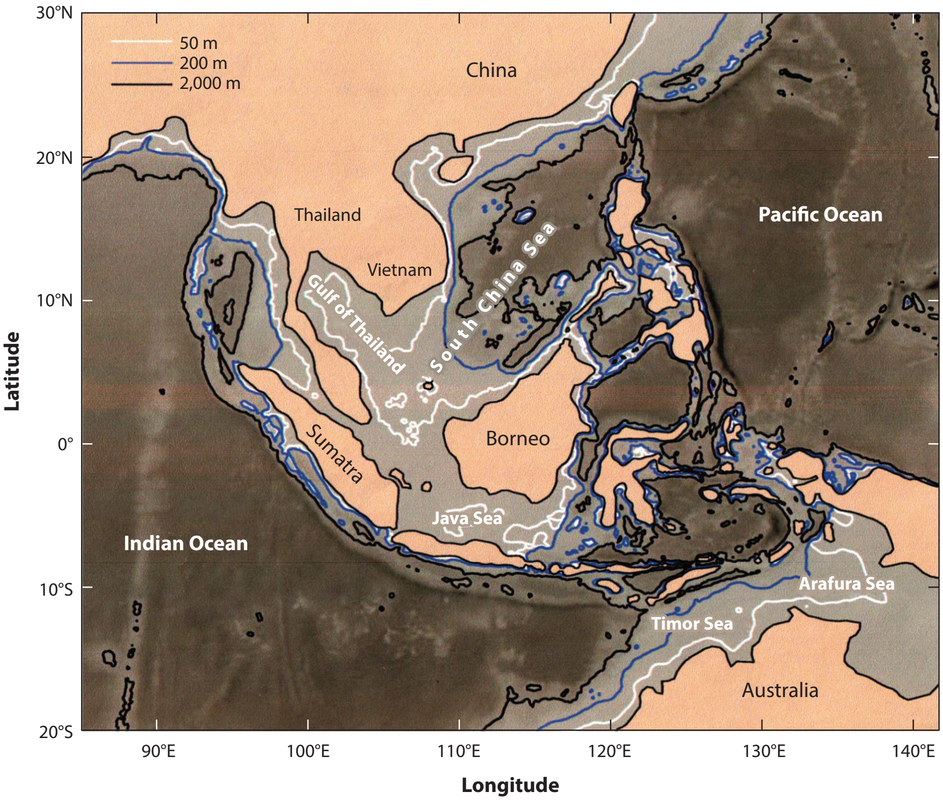


Figure 10

The Maritime Continent in Southeast Asia. Adapted courtesy of Dr. Penfei Xue.

(Gordon et al. 2012). The major objective was then to establish a high-resolution, regional coupled atmosphere-ocean model capable of providing stable and realistic simulations of the ocean climatology without flux correction.

The requirement of having no flux correction is crucial. Most regional coupled models and ocean-only models do not reach a stable simulation of the ocean SST and instead exhibit biases and drifts—often significant—away from the observed ocean climate (for a review of the coupled models of the Maritime Continent, see Wei et al. 2013). These biases and drifts imply an incompatibility between some of the heat or moisture forcings provided by the atmospheric model and those actually required by the ocean model. This deficiency is remedied by relaxing the ocean SST to the observations, which is effectively a correction to the model atmospheric fluxes.

We chose a numerical model designed to resolve complex geographical configurations and topographies (such as the Indonesian Throughflow system), the Finite-Volume Coastal Ocean Model (FVCOM) (Chen et al. 2003, 2006). FVCOM is embedded in the MIT global ocean model, which provides boundary conditions for temperature, salinity, and velocity at the Pacific and Indian Ocean open boundaries and surface forcings, i.e., wind stress and heat/moisture fluxes, the latter for the ocean-only simulations. FVCOM is coupled to the MIT Regional Climate Model (MRCM), whose domain is the Maritime Continent (**Figure 10**), through the OASIS3 coupler. MRCM provides wind stress, solar heat fluxes, and latent and sensible heat to FVCOM, which

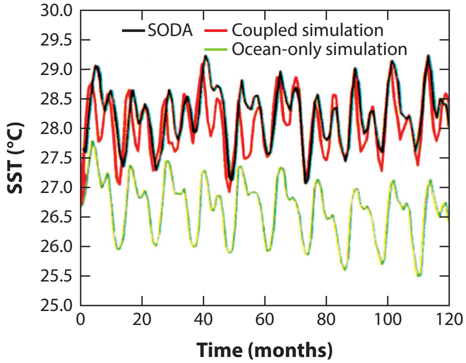


Figure 11

Coupled (*red line*) and ocean-only (*green line*) simulations of monthly, domain-averaged SST, along with a SODA SST reanalysis (*black line*) for comparison. The decade of the 1960s was used to spin up the models, and the simulations were carried out for the 1970s starting from the same initial condition on January 1, 1970. Abbreviations: SODA, Simple Ocean Data Assimilation; SST, sea-surface temperature. Adapted from figure 8*a* of Wei et al. (2013), courtesy of Springer.

gives SST back to MRCM. (For details of the models and coupling procedure, see Wei et al. 2013 and Xue et al. 2014.)

Figure 11 shows an example of the SST drift away from the present climatology—specifically, a comparison of a coupled simulation with an ocean-only simulation under the MIT General Circulation Model (MITgcm) fluxes along with a SODA (Carton et al. 2000a,b) reanalysis. The decade of the 1960s was used to spin up the models, and the simulations were carried out for the 1970s. The figure shows the domain-averaged SST as the most robust measurement of model skill. The ocean-only simulation exhibits a cold bias of −1.5°C to −2.2°C and a cold drift, with a 1.5°C decrease over ten years. The coupled simulation is stable and reproduces very well the SODA climatology of the 1970s without any correction to the fluxes of the atmospheric model. The abnormal cold bias and drift of the SST in the ocean-only simulation under the MITgcm total heat flux can be explained as follows. First, the MITgcm flux is on average 25 W/m^2 weaker than the coupled one, which explains the cold SST bias. Second, the resolution of the MITgcm flux is extremely coarse (4° in latitude-longitude), which is typical of global climate models. This means that the small seas of the Indonesian archipelago are not resolved, and a single grid point comprises the entire South China Sea. With this coarse resolution, the yearly cycle of the heat flux is basically the same over the oceanic domain and is also basically invariant over the 1970s. In this cycle, the heat loss in winter exceeds the heat gain in summer, which produces the cold drift of the SST.

The priority for Singapore is to use the coupled model for decadal projections of local precipitation and local sea level. These are arguably the most important variables for domains particularly exposed to the consequences of global and local warming. **Figure 12** shows regions vulnerable to sea level rise, among which are the islands comprising Singapore and a northeastern portion of Italy, where my home, Venice, is located.

4. BACK TO VENICE: THE ENGINEERING SOLUTION

I began consulting for CVN in 1995. A special law for the safeguarding of Venice was approved by the government in 1984. In 1994, the Governmental Council of Public Works gave the go-ahead to proceed to the executive phase and assigned to CVN the mandate of planning, designing,

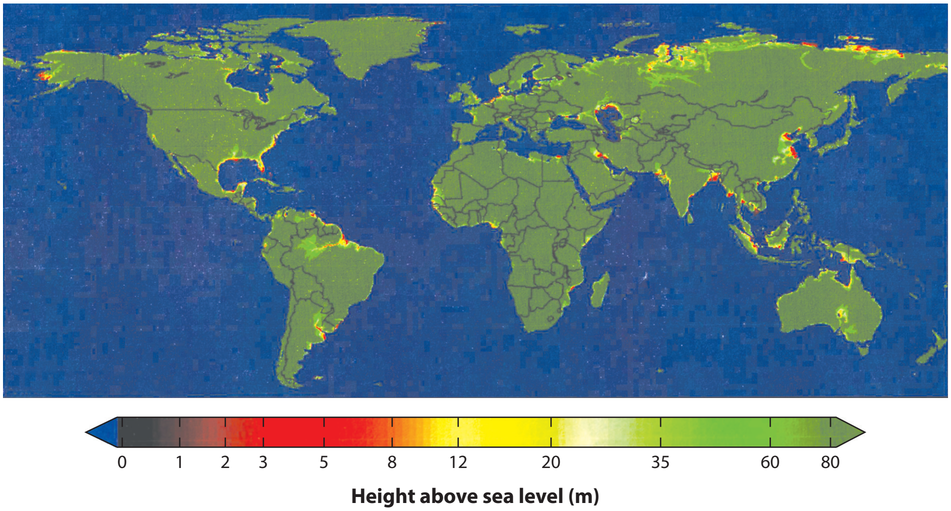


Figure 12

Regions vulnerable to sea level rise (areas shown in *red*).

and constructing the project to prevent the flooding of the lagoon and the city. This implied isolating the lagoon from the northern Adriatic Sea, whose storm surges were responsible for the flooding—i.e., blocking the three inlets that allow communication between the lagoon and the sea.

As usual in Italy, whatever solution one government accepts, the next government rejects, nominating a new committee to study the issue and propose a new solution. As Italian governments have an average lifetime of six to eight months (the government of 2015–2016 is a rare exception), this implies the formation of one governmental committee after another, endless discussions among different parties, and continuous obstruction to concrete actions. In particular, the local government of the city at that time and the Green Party were furious objectors to the closing of the inlets. The most common argument was that the closing would completely pollute the lagoon with the wastes discharged by the cities along the lagoon's internal coastline, in particular by the Marghera industrial zone (**Figure 1**). Venice has no sewage system and is "washed out" twice a day by the M2 tide. One of the alternative solutions proposed was to permanently reduce the width of the three inlets, thus drastically reducing the flow exchanges with the sea. Hydrodynamic and ecosystem modeling of the entire lagoon and the adjacent northern Adriatic showed that no irreversible damage to the water quality would be produced even from closures lasting one week. On the other side, permanent restrictions of the inlets would drastically reduce the flow through them and transform the lagoon into a polluted, eutrophic soup! The length of time for which the inlets would be closed under average events is ∼5 hours. For the most extreme events, like the one in 1966, the barriers would stay closed for 22 hours while the sea level remains above 110 cm, plus another 10 hours while the sea level remains above 100 cm. (For detailed explanations of the technical details, see **http://www.mosevenezia.eu**.)

CVN hired a group of MIT professors as consultants, comprising a civil and a mechanical engineer and a hydrologist. However, because problems such as the *acqua alta*—i.e., the storm surge of the Adriatic Sea, the forcing of the lagoon circulation by the sea through the open inlets, and so on—were physical oceanographic problems, I too was hired. It helped that I knew the Venice problems inside and out! The first part of our mandate was to assess the environmental impact produced on the lagoon by movable barriers at the inlets, as required by the laws of the

European Union. Hydrodynamic and ecosystem modeling was part of this effort. After years of planning and discussions to answer all of the objections raised by the city and the Greens at both the local and national levels, the foundation stone was laid in May 2003.

First of all, an artificial island had to be built in the Lido inlet (the widest one in **Figure 1**). Because this inlet is too large to support a single mobile barrier, the project involved constructing four mobile barriers, each comprising mobile gates of different numbers and dimensions depending on the characteristics of the individual inlet. After a sure prediction of high water, the mobile gates would rise one after the other, blocking the incoming Adriatic surge. By 2000, the models for sea level prediction had evolved from the very simple ones constructed in the 1970s. They were extremely sophisticated, up-to-date hydrodynamic models comprising the lagoon and the adjacent northern Adriatic. The computerized MOSE control center in the Venetian Arsenal has been operational since October 2011, forecasting the sea level and reproducing the hydraulic effects of virtual raising and lowering of the mobile barriers. The computerized system allows decisions to be made about barrier closing and opening maneuvers and therefore about when and for how long the MOSE gates are in operation. Raising the gates and completely blocking the water flow takes only 30 minutes, followed by another 30 minutes to bring them to the required working angle; lowering them takes only 15 minutes.

Figure 13 shows a schematic of one gate of the modular mobile barriers and its functioning. The simple hydraulic principle is based on buoyancy. In normal conditions, the gates are full of water and lie on the bottom, invisible at the surface. When high water is predicted to reach 110 cm, the water is expelled from the gates by pressurized air, and the gates float above sea level. The maximum external sea level rise that the gates can sustain is 3 m, as shown in **Figure 13*d***.

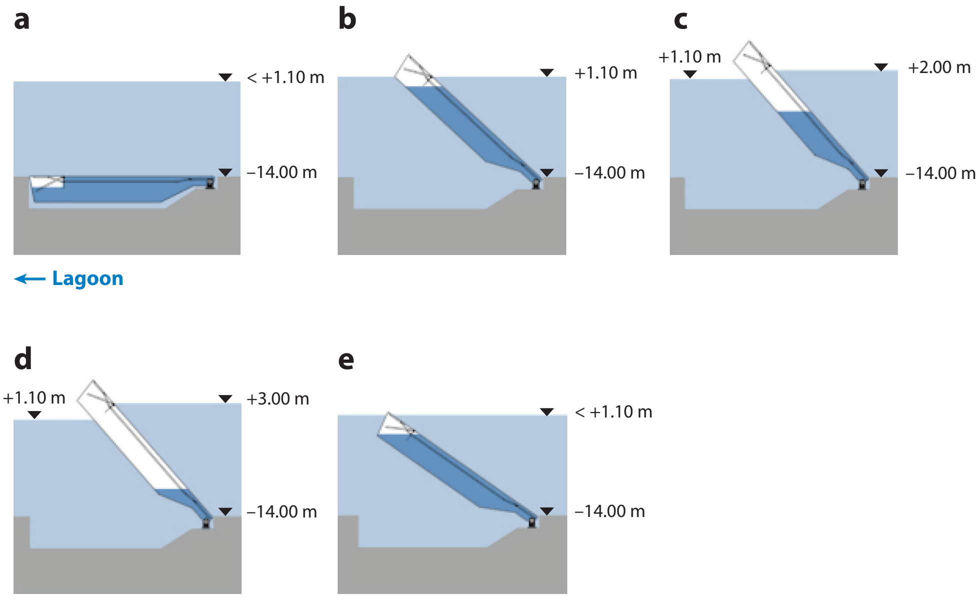


Figure 13

The buoyancy-based functioning of the modular gates of the Venice inlet barriers. (*a*) Under normal conditions, the gate is filled with water and rests on the bottom. (*b–d*) When high water above 110 cm is predicted, pressurized air forces the water out, and the gate floats above sea level. (*e*) When the water level drops back below 110 cm, the gates again fill with water and return to the bottom. Adapted courtesy of Consorzio Venezia Nuova, Venice.

Figure 14

Public demonstration of the raising of the first completed barrier in the Lido inlet. Reproduced courtesy of Consorzio Venezia Nuova, Venice.

When the storm surge ends, the gates are again filled with water and return to the bottom. The first barrier, in the left half of the Lido inlet, was completed in 2014. A public demonstration was given and is shown in **Figure 14**, with the individual gates clearly evident. The construction of the entire system of four barriers is presently predicted to be completed in 2018 and constitutes one of the most sophisticated engineering systems in the world.

5. MY STUDENTS

The oceanography program at MIT is conducted jointly with WHOI, and is in fact called the MIT/WHOI Joint Program in Oceanography and Applied Ocean Science and Engineering. I was the MIT director of the program for 12 years, from 1997 to 2009. Our program and the oceanography program at the Scripps Institution of Oceanography are rated the two top such programs in the world, and an amicable rivalry exists between them to attract the best students. In physical oceanography, we often joke that students graduating from one institution become professors at the other. This joke is actually a reality: Quite a number of Scripps professors in physical oceanography are graduates of the MIT/WHOI joint program and vice versa. I am one such example.

I enjoy teaching tremendously, even though it requires a lot of preparation, especially for the first year I teach a new course. And our students are very bright and ask very intelligent questions—more than those asked by our peers at seminars! Over the course of 35 years, I have taught all the core (and more!) courses of our program, and the effort is incredibly rewarding: It is a great satisfaction to explain a new concept to a class that responds with an animated, intelligent discussion. When I came to MIT in 1981, I was the only woman at MIT in physical oceanography. I still am, but I have now been joined by several younger female colleagues at WHOI who also are active teachers. Another great reward is to serve on a student's PhD committee, in which very often we learn something new. During one scientific meeting at the American Geophysical Union, I was sitting in a row in which all of the other seats were occupied by MIT/WHOI joint program students on whose committees I had served! Counting them, I have been a committee member for 53 students in physical oceanography, meteorology, geophysics, and ocean engineering.

But perhaps the greatest satisfaction of all is to advise a student in her or his research towards a PhD or MS degree. To be an advisor means not only to steer a student towards carrying out a piece of original research and to follow her or him to the ultimate goal of a successful defense; it means to become the mentor of the student, an advocate, and ultimately a friend. I have established wonderful relationships with my past students, many of whom still correspond with me and come to see me whenever they are in town. I am very proud of having been the principal advisor of 22 students, mostly for a PhD and some for an MS degree, who went on to successful careers in academia, research, or industry. I consider this to be one of the greatest achievements of my career.

6. REFLECTIONS

There are times in which a moment of pause and reflection is appropriate. This moment has been, for me, the writing of this article, in which I have revisited the vicissitudes of my career.

The first thing anyone reading this article will notice is that I am not a specialist who has focused during the entire course of her or his career on one research core, from which specialized contributions branch out. As an example, I could have been only a theoretical fluid dynamicist, a numerical modeler, an observationalist, or a climate scientist. In a sense, I have been all of them in different phases of my career. As I noted above, my "renewal time" is 5–7 years, meaning that on this timescale, I feel the need to reinvent myself and start a new project, albeit without leaving some of the previous ones. This may be because I am a daughter of my own country, Italy, which saw the development of the Roman Empire and the great Renaissance of Rome, Florence, and, most importantly, Venice. For the multiplicity of my interests, in science and apart from science, I like to think of myself as a renaissance woman. And it may be for this multiplicity of interests that I had the honor of being made a Fellow of the American Meteorological Society in 2002 and a Fellow of the American Geophysical Union in 2006.

Second, I have also mentioned the importance of chance, i.e., of being in the right place at the right time. Chance is the Roman goddess Fortuna, a powerful one in the Roman Olympus. While the Romans revered Fortuna, and were careful not to offend her, they also believed that everybody creates her or his own Fortuna. Being in the right place at the right time is useless if you do not grasp the opportunity offered to you: *Audentes Fortuna iuvat*. But then you must also build upon your Fortuna with dedication and perseverance. All my life, I have aimed to grow in scientific understanding and, hopefully, excellence. When a chance to grow presented itself, I have never hesitated: Better to try and fail than to refuse the challenge because of fear. This is the best advice I can give to any student or young scientist: Be bold, grasp your Fortuna, and build on it.

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LITERATURE CITED

Agnon Y, Malanotte-Rizzoli P, Cornuelle BD, Spiesberger JL, Spindel RL. 1989. The 1984 bottom mounted Gulf Stream tomographic experiment. *J. Acoust. Soc. Am.* 85:1958–66

Ashkenazy Y, Stone PH, Malanotte-Rizzoli P. 2012. Box modeling of the Eastern Mediterranean Sea. *Phys. A* 391:1519–31

Bennett AF. 1992. *Inverse Methods in Physical Oceanography*. Cambridge, UK: Cambridge Univ. Press

Bergamasco A, Malanotte-Rizzoli P. 2010. The circulation of the Mediterranean Sea: a historical review of experimental investigations. *Adv. Oceanogr. Limnol.* 1:9–22

Buehner M, Malanotte-Rizzoli P. 2003. Reduced-rank Kalman filters applied to an idealized model of the wind-driven ocean circulation. *J. Geophys. Res.* 108:3192

Buehner M, Malanotte-Rizzoli P, Busalacchi AJ, Inui T. 2003. Estimation of the tropical Atlantic circulation from altimetry data using a reduced-rank stationary Kalman filter. See Goni & Malanotte-Rizzoli 2003, pp. 49–92

Capotondi A, Malanotte-Rizzoli P, Holland WR. 1995a. Assimilation of altimeter data into a quasigeostrophic model of the Gulf Stream system. Part I: dynamical considerations. *J. Phys. Oceanogr.* 25:1130–52

Capotondi A, Holland WR, Malanotte-Rizzoli P. 1995b. Assimilation of altimeter data into a quasi-geostrophic model of the Gulf Stream system. Part II: assimilation results. *J. Phys. Oceanogr.* 25:1153–73

Carton JA, Chepurin G, Cao X, Giese BS. 2000a. A Simple Ocean Data Assimilation analysis of the global upper ocean. Part I: methodology. *J. Phys. Oceanogr.* 30:294–309

Carton JA, Chepurin G, Cao X. 2000b. A Simple Ocean Data Assimilation analysis of the global upper ocean. Part II: results. *J. Phys. Oceanogr.* 30:311–26

Cavaleri L, Malanotte-Rizzoli P. 1978. A wind prediction model in the Adriatic Sea. In *Turbulent Fluxes Through the Sea Surface*, *Wave Dynamics and Prediction*, ed. A Favre, K Hasselmann, pp. 629–45. New York: Plenum

Cavaleri L, Malanotte-Rizzoli P. 1981. Wind wave prediction in the Adriatic Sea. Theory and numerical experiments. *J. Geophys. Res.* 86:19961–74

Chen C, Beardsley RC, Cowles G. 2006. An unstructured grid, finite-volume coastal ocean model (FVCOM) system. *Oceanography* 19(1):78–89

Chen C, Liu H, Beardsley RC. 2003. An unstructured, finite-volume, three-dimensional, primitive equation ocean model: application to coastal ocean and estuaries. *J. Atmos. Ocean. Technol.* 20:159–86

Chen C, Malanotte-Rizzoli P, Wei J, Beardsley RC, Lai Z, et al. 2009. Validation of Kalman filters for coastal ocean problems: an experiment with FVCOM. *J. Geophys. Res.* 114:C05011

Chester D, Malanotte-Rizzoli P, Lynch J, Wunsch CI. 1994. The eddy radiation field of the Gulf Stream as measured by ocean acoustic tomography. *Geophys. Res. Lett.* 21:181–84

Fine RA. 1987. The penetration of tritium into the tropical Pacific. *J. Phys. Oceanogr.* 17:553–64

Fine RA, Reid JL, Ostlund HG. 1981. Circulation of tritium in the Pacific Ocean. *J. Phys. Oceanogr.* 11:3–14

Flierl GR. 1979. Baroclinic solitary waves with radial symmenty. *Dyn. Atmos. Oceans* 3:15–38

Flierl GR, Larichev VD, McWilliams JC, Reznik GM. 1980. The dynamics of baroclinic and barotropic solitary eddies. *Dyn. Atmos. Oceans* 5:1–41

Flierl GR, Malanotte-Rizzoli P, Zabusky NJ. 1987. Nonlinear waves and coherent vortex structures in barotropic beta plane jets. *J. Phys. Oceanogr.* 17:1408–38

Fratantoni DM, Johns WE, Townsend TL, Hurlburt HE. 2000. Low latitude circulation and mass transport pathways in a model of the tropical Atlantic Ocean. *J. Phys. Oceanogr.* 30:1944–66

Fukumori I, Malanotte-Rizzoli P. 1995. An approximate Kalman filter for ocean data assimilation: a reduced-dimension, static, linearized Kalman filter. *J. Geophys. Res.* 100:6777–93

Gatto P, Carbognin L. 1981. The Lagoon of Venice: natural environmental trend and man-induced modification. *Hydrol. Sci. Bull.* 26:379–93

Gent PR, Cane MA. 1989. A reduced gravity, primitive equation model of the upper equatorial ocean. *J. Comput. Phys.* 81:444–80
Ghil M, Malanotte-Rizzoli P. 1991. Data assimilation in meteorology and oceanography. In *Advances in Geophysics*, Vol. 33, ed. R Dmowska, B Saltzmann, pp. 141–266. Cambridge, UK: Academic
Goni G, Malanotte-Rizzoli P, eds. 2003. *Interhemispheric Water Exchange in the Atlantic Ocean*. Elsevier Oceanogr. Ser. Vol. 68. Amsterdam: Elsevier
Gordon AL, Huber BA, Metzger EJ, Susanto RD, Hurlburt HE, Adi TR. 2012. South China Sea throughflow impact on the Indonesian throughflow. *Geophys. Res. Lett.* 39:L11602
Gu D, Philander SGH. 1997. Interdecadal climate fluctuations that depend on exchanges between the tropics and extratropics. *Science* 275:805–7
Gunson JR, Malanotte-Rizzoli P. 1996a. Assimilation studies of open-ocean flows. Part I: estimation of initial and boundary conditions. *J. Geophys. Res.* 101:28457–72
Gunson JR, Malanotte-Rizzoli P. 1996b. Assimilation studies of open ocean flows. Part II: error measures with strongly nonlinear dynamics. *J. Geophys. Res.* 101:28473–88
Haines K, Malanotte-Rizzoli P. 1991. Isolated anomalies in westerly jet streams: a unified approach. *J. Atmos. Sci.* 48:510–26
Haines K, Malanotte-Rizzoli P, Morgan M. 1993a. Persistent jetstream intensifications: a comparison between theory and data. *J. Atmos. Sci.* 50:145–54
Haines K, Malanotte-Rizzoli P, Young RE, Holland WR. 1993b. Method intercomparison for the assimilation of altimetry data into a shallow water model. *Dyn. Atmos. Oceans* 17:89–133
Harper S. 2000. Thermocline ventilation and pathways of tropical-subtropical water mass exchange. *Tellus* 52:330–45
Hazeleger W, DeVries P, van Oldenborgh GJ. 2001. Do tropical cells ventilate the Indo-Pacific equatorial thermocline? *Geophys. Res. Lett.* 28:1763–66
Hendershott MC, Malanotte-Rizzoli P. 1976. The winter circulation of the Adriatic Sea. *Deep-Sea Res*. 23:353–70
Holland WR, Malanotte-Rizzoli P. 1989. Along-track assimilation of altimeter data into an ocean circulation model: space versus time resolution studies. *J. Phys. Oceanogr.* 19:1507–34
Inui T, Lazar A, Malanotte-Rizzoli P, Busalacchi AJ. 2002. Wind stress effects on the Atlantic subtropical-tropical circulation. *J. Phys. Oceanogr.* 32:2257–76
Jiang S, Malanotte-Rizzoli P. 1999. On the predictability of regional oceanic jet streams: the impact of model errors at the inflow boundary. *J. Mar. Res.* 57:641–69
Jochum M, Malanotte-Rizzoli P. 2001. On the influence of the meridional overturning circulation on the tropical-subtropical pathways. *J. Phys. Oceanogr.* 31:1313–23
Klein B, Roether W, Manca BB, Bregant D, Bitzel V, et al. 1999. The large deep water transient in the eastern Mediterranean. *Deep-Sea Res.* 46:371–414
Kroger J, Busalacchi AJ, Malanotte-Rizzoli P, Ballabrera-Poy J. 2005. Decadal variability of shallow cells and equatorial sea surface temperature in a numerical model of the Atlantic. *J. Geophys. Res.* 110:C12003
Lascaratos A, Roether W, Nittis K, Klein B. 1999. Recent changes in deep water formation and spreading in the Mediterranean Sea: a review. *Prog. Oceanogr.* 44:5–36
Lazar A, Inui T, Busalacchi AJ, Malanotte-Rizzoli P, Wang L, Murtugudde R. 2002. Seasonality of the ventilation of the tropical Atlantic. *J. Geophys. Res.* 107:18-1–17
Leith CE. 1978. Objective methods for weather prediction. *Annu. Rev. Fluid Mech.* 10:107–28
Liu Z. 1994. A simple model of the mass exchange between the subtropical and tropical ocean. *J. Phys. Oceanogr.* 24:1153–65
Liu Z, Philander SGH. 1995. How different wind stress patterns affect the tropical-subtropical circulations of the upper ocean. *J. Phys. Oceanogr.* 25:449–62
Liu Z, Philander SGH, Pakanowski RC. 1994. A GCM study of tropical-subtropical upper-ocean water exchange. *J. Phys. Oceanogr.* 24:2606–23
Lorenz EN. 1969. The predictability of a flow which possesses many scales of motion. *Tellus* 21:289–307
Lu P, McCreary JP. 1995. Influence of the ITCZ on the flow of thermocline water from the subtropical to the equatorial Pacific Ocean. *J. Phys. Oceanogr.* 25:3076–88

Lu P, McCreary JP, Klinger BA. 1998. Meridional circulation cells and the source waters of the Pacific Equatorial Undercurrent. *J. Phys. Oceanogr.* 28:62–84

Luyten JL, Pedlosky J, Stommel HM. 1983. The ventilated thermocline. *J. Phys. Oceanogr.* 13:292–309

Malanotte-Rizzoli P. 1980. Solitary Rossby waves over variable relief and their stability. Part II: numerical experiments. *Dyn. Atmos. Oceans* 4:261–94

Malanotte-Rizzoli P. 1982a. Planetary solitary waves in geophysical flows. In *Advances in Geophysics*, Vol. 24, ed. B Saltzmann, pp. 147–224. Cambridge, UK: Academic

Malanotte-Rizzoli P. 1982b. The predictability problem of planetary motions. In *Topics in Ocean Physics*, ed. AR Osborne, P Malanotte-Rizzoli, pp. 184–204. Amsterdam: North Holland

Malanotte-Rizzoli P. 1982c. The stability of planetary solitary waves. In *Topics in Ocean Physics*, ed. AR Osborne, P Malanotte-Rizzoli, pp. 148–83. Amsterdam: North Holland

Malanotte-Rizzoli P. 1983. Coherent structures in planetary flows as systems endowed with enhanced predictability. In *The Predictability of Fluid Motions*, ed. G Holloway, BJ West, pp. 223–47. New York: Am. Inst. Phys.

Malanotte-Rizzoli P. 1985. Long-range inversions for ocean acoustic tomography. *J. Geophys. Res.* 90:7098–116

Malanotte-Rizzoli P. 1992. Planetary waves in the oceans and atmosphere. In *Encyclopedia of Earth Systems Science*, ed. WA Nieremberg, pp. 609–16. Cambridge, UK: Academic

Malanotte-Rizzoli P. 1994. Modeling the general circulation of the Mediterranean. In *Ocean Processes in Climate Dynamics: Global and Mediterranean Examples*, ed. P Malanotte-Rizzoli, AR Robinson, pp. 307–21. Amsterdam: Kluwer

Malanotte-Rizzoli P, Artale V, Borzelli-Eusebi GL, Brenner S, Crise A, et al. 2014. Physical forcing and physical/biochemical variability of the Mediterranean Sea: a review of unresolved issues and directions for future research. *Ocean Sci.* 10:281–322

Malanotte-Rizzoli P, Battiston L. 1973. The influence of refraction due to bottom topography on the distribution of wave energy along the coastline of the lagoon of Venice. *Un. Oceanogr. France* 5:7–12

Malanotte-Rizzoli P, Fukumoru I, Young RE. 1996. A methodology for the construction of a hierarchy of Kalman filter/smoothers for nonlinear primitive equation models. In *Modern Approaches to Data Assimilation in Ocean Modeling*, ed. P Malanotte-Rizzoli, pp. 297–317. Amsterdam: Elsevier

Malanotte-Rizzoli P, Hancock PJ. 1987. Coherent structures in a baroclinic atmosphere. Part IV: a comparison between theory and data. *J. Atmos. Sci.* 44:2506–29

Malanotte-Rizzoli P, Hendershott MC. 1980. Solitary Rossby waves over variable relief and their stability. Part I: the analytical theory. *Dyn. Atmos. Oceans* 4:247–60

Malanotte-Rizzoli P, Holland WR. 1985. Gyre scale acoustic tomography: modeling simulations. *J. Phys. Oceanogr.* 15:416–38

Malanotte-Rizzoli P, Holland WR. 1986. Data constraints applied to models of the ocean general circulation. Part I: the steady case. *J. Phys. Oceanogr.* 16:1665–82

Malanotte-Rizzoli P, Holland WR. 1988. Data constraints applied to models of the ocean general circulation. Part II: the transient case. *J. Phys. Oceanogr.* 18:1093–107

Malanotte-Rizzoli P, Malguzzi P. 1987. Coherent structures in a baroclinic atmosphere. Part III: block formation and eddy forcing. *J. Atmos. Sci.* 44:2493–505

Malanotte-Rizzoli P, Manca BB, Marullo S, Ribera d'Alcalá M, Roether W, et al. 2003. The Levantine Intermediate Water Experiment (LIWEX) Group: Levantine Basin—a laboratory for multiple water mass formation processes. *J. Geophys. Res.* 198:8101

Malanotte-Rizzoli P, Manca BB, Ribera d'Alcalá M, Theocharis A. 1997. A synthesis of the Ionian sea hydrography, circulation and water mass pathways during POEM-Phase I. *Prog. Oceanogr.* 39:153–204

Malanotte-Rizzoli P, Manca BB, Ribera d'Alcalá M, Theocharis A, Brenner S, et al. 1999. The Eastern Mediterranean in the 80s and the 90s: the big transition in the intermediate and deep circulations. *Dyn. Atmos. Oceans* 29:365–95

Malanotte-Rizzoli P, Robinson AR. 1988. POEM: Physical Oceanography of the Eastern Mediterranean. *Eos* 69:194–203

Malanotte-Rizzoli P, Tziperman E. 1996. The oceanographic data assimilation problem: overview, motivation and purposes. In *Modern Approaches to Data Assimilation in Ocean Modeling*, ed. P Malanotte-Rizzoli, pp. 3–17. Amsterdam: Elsevier

Malanotte-Rizzoli P, Young RE. 1992. How useful are localized clusters of traditional oceanographic measurements for data assimilation? *Dyn. Atmos. Oceans* 17:23–62

Malanotte-Rizzoli P, Young RE. 1995. Assimilation of global versus local datasets into a regional model of the Gulf Stream system. Part I: data effectiveness. *J. Geophys. Res.* 100:24773–96

Malanotte-Rizzoli P, Young RE, Haidvogel DB. 1988. Numerical simulations of transient boundary forced radiation. Part II: the modon regime. *J. Phys. Oceanogr.* 18:1546–69

Malanotte-Rizzoli P, Young RE, Haidvogel DB. 1989. Initialization and data assimilation experiments with a primitive equation model. *Dyn. Atmos. Oceans* 13:349–78

Malanotte-Rizzoli P, Young RE, Hedstrom K, Arango H, Haidvogel DB. 2000. Water mass pathways between the subtropical and tropical ocean in a climatological simulation of the North Atlantic ocean circulation. *Dyn. Atmos. Oceans* 32:331–72

Malguzzi P, Malanotte-Rizzoli P. 1984. Nonlinear Rossby waves over non-uniform zonal wind and atmospheric blocking. Part I: the analytical theory. *J. Atmos. Sci.* 41:2620–28

Malguzzi P, Malanotte-Rizzoli P. 1985. Coherent structures in a baroclinic atmosphere. Part II: a truncated model approach. *J. Atmos. Sci.* 42:2463–77

Marshall J, Kushnir Y, Battisti D, Chang P, Czaja A, et al. 2001. North Atlantic climate variability: phenomena, impacts and mechanisms. *Int. J. Climatol.* 21:1863–98

Maxworthy T, Redekopp LG. 1976a. New theory of the Great Red Spot from solitary waves in the Jovian atmosphere. *Nature* 260:509–11

Maxworthy T, Redekopp LG. 1976b. A solitary wave theory of the Great Red Spot and other observed features in the Jovian atmosphere. *Icarus* 29:261–71

McCreary JP, Lu P. 1994. On the interaction between the subtropical and equatorial ocean circulation: the subtropical cell. *J. Phys. Oceanogr.* 24:466–97

McWilliams JC. 1980. An application of equivalent modons to atmospheric blocking. *Dyn. Atmos. Oceans* 5:43–66

McWilliams JC, Flierl RG, Larichev VD, Reznik GM. 1981. Numerical studies of barotropic modons. *Dyn. Atmos. Oceans* 5:219–39

Nielsen JN. 1912. Hydrography of the Mediterranean and adjacent waters. In *Report of the Danish Oceanographic Expedition 1908–1910 to the Mediterranean and Adjacent Waters*, Vol. 1, ed. J Schmidt, pp. 72–191. Copenhagen: Andr. Fred Høst & Søn

Oguz T, Cokacar T, Malanotte-Rizzoli P, Ducklow HW. 2003. Climate warming and accompanying changes in the ecological regime of the Black Sea during 1990s. *Glob. Biochem. Cycles* 17:1088

Oguz T, Ducklow HW, Malanotte-Rizzoli P, Murray J, Vedernikov VI, Unluata U. 1999. A physical-biochemical model of plankton productivity and nitrogen cycling in the Black Sea. *Deep-Sea Res. I* 46:597–636

Oguz T, Malanotte-Rizzoli P, Ducklow HW. 2001. Simulations of phytoplankton seasonal cycle with multi-level and multi-layer physical-ecosystem models: the Black Sea example. *Ecol. Model.* 144:295–314

Ovchinnikov IM. 1966. Circulation in the surface and intermediate layers of the Mediterranean. *Oceanology* 6:48–59

Pollak MI. 1951. The sources of deep water of the Eastern Mediterranean Sea. *J. Mar. Res.* 10:128–52

Redekopp LG. 1977. On the theory of solitary Rossby Waves. *J. Fluid Mech.* 82:725–45

Reid JL. 1994. On the total geostrophic circulation of the North Atlantic Ocean: flow patterns, tracers and transports. *Prog. Oceanogr.* 33:1–92

Robinson AR, Malanotte-Rizzoli P, Hecht A, Michelato A, Roether W, et al. (POEM Group). 1992. General circulation of the eastern Mediterranean. *Earth Sci. Rev.* 32:285–309

Robinson AR, Tomasin A, Artegiani A. 1973. Flooding of Venice: phenomenology and prediction of the Adriatic storm surge. *Q. J. R. Meteorol. Soc.* 99:688–92

Roether W, Manca BB, Klein B, Bregant D, Georgopoulos D, et al. 1996. Recent changes in the eastern Mediterranean deep water. *Science* 271:333–35

Roether W, Schlitzer R. 1991. Eastern Mediterranean deep water renewal on the basis of chlorofluoromethane and tritium data. *Dyn. Atmos. Oceans* 15:333–54

Rothstein LM, Zhang R-H, Busalacchi AJ, Chen D. 1998. A numerical simulation of the mean water pathways in the subtropical and tropical Pacific Ocean. *J. Phys. Oceanogr.* 28:322–43

Russell JS. 1838. Report of the Committee on Waves. In *Report of the Seventh Meeting of the British Association for the Advancement of Science*, pp. 417–96. London: John Murray

Russell JS. 1845. Report on waves. In *Report of the Fourteenth Meeting of the British Association for the Advancement of Science*, pp. 311–90. London: John Murray

Scott AC, Chu FYF, McLaughlin DW. 1973. The soliton: a new concept in applied science. *Proc. IEEE* 61:1443–83

Snowden D, Molinari RL. 2003. Subtropical cells in the Atlantic Ocean: an observational summary. See Goni & Malanotte-Rizzoli 2003, pp. 287–312

Tarantola A. 2005. *Inverse Problem Theory and Methods for Model Parameter Estimation*. Philadelphia: SIAM

Theocharis A, Nittis K, Kontoyannis H, Papageorgiou E, Balopoulos E. 1999. Climate changes in the Aegean Sea influence in the Eastern Mediterranean thermohaline circulation. *Geophys. Res. Lett.* 26:1617–20

Trincardi FA, Barbanti M, Bastianini A, Benettazzo L, Cavaleri J, et al. 2016. The 1966 flooding of Venice: what time taught us for the future. *Oceanography* 29(4):In press. doi: 10.5670/oceanog.2016.87

Tsimplis MN, Zervakis V, Josey SA, Peneva EL, Struglia MV, et al. 2006. Changes in the oceanography of the Mediterranean Sea and their link to climate variability. In *Mediterranean Climate Variability*, ed. P Lionello, P Malanotte-Rizzoli, R Boscolo, pp. 227–82. Dev. Earth Environ. Sci. Vol. 4. Amsterdam: Elsevier

Veronis G, Mellor FK, eds. 1980. *1980 summer school study program in geophysical fluid dynamics: coherent features in geophysical flows*. Tech. Rep. WHOI-80-53, Woods Hole Oceanogr. Inst., Woods Hole, MA

Wei J, Malanotte-Rizzoli P. 2009. Validation and application of an ensemble Kalman filter in the Selat Pauh in Singapore. *Ocean Dyn.* 60:395–401

Wei J, Malanotte-Rizzoli P, Eltahir E, Xue P, Zhang D. 2013. Coupling of a regional atmospheric model (RegCM3) and a regional oceanic model (FVCOM) over the maritime continent. *Clim. Dyn.* 43:1575–94

Wunsch CI. 1978. The North Atlantic general circulation west of 50°W determined by inverse methods. *Rev. Geophys. Space Phys.* 16:583–620

Wunsch CI. 1988. Transient tracers as a problem in control theory. *J. Geophys. Res.* 93:8099–110

Wunsch CI. 1989. Tracer inverse problems. In *Oceanic Circulation Models: Combining Data and Dynamic*, ed. DLT Anderson, J Willebrand, pp. 1–78. Amsterdam: Kluwer

Wunsch CI. 1996. *The Ocean Circulation Inverse Problem*. Cambridge, UK: Cambridge Univ. Press

Wust G. 1961. On the vertical circulation of the Mediterranean Sea. *J. Geophys. Res.* 66:3261–71

Wyrtki K, Kilonsky B. 1984. Mean water mass and current structure during the Hawaii-to-Tahiti Shuttle Experiment. *J. Phys. Oceanogr.* 14:242–54

Xue P, Eltahir E, Malanotte-Rizzoli P, Wei J. 2014. Local feedback mechanisms of the shallow water region around the Maritime Continent. *J. Geophys. Res.* 119:6933–51

Yu L, Malanotte-Rizzoli P. 1996. Analysis of the North Atlantic climatologies using a combined OGCM/adjoint approach. *J. Mar. Res.* 54:867–913

Yu L, Malanotte-Rizzoli P. 1998. Inverse modeling of seasonal variability in the North Atlantic Ocean. *J. Phys. Oceanogr.* 28:902–22

Zang X, Malanotte-Rizzoli P. 2003. A comparison of assimilation results from the ensemble Kalman filter and the reduced-rank extended Kalman filter. *Nonlinear Proc. Geophys.* 10:477–91