



A brief history of physical oceanography with Mediterranean examples

Paola Malanotte-Rizzoli¹

Received: 12 October 2023 / Accepted: 31 October 2023
© The Author(s) 2023

Abstract

Oceanography, or Oceanology, is a very broad name covering all the traditional sciences (physics, chemistry, biology etc.) which can be studied in the ocean context. Hence the distinction must be made using the specific names of Physical, Chemical or Biological Oceanography. This particular review is devoted to the history of Physical Oceanography, a discipline which remained at the empirical stage until roughly the middle of last century, with a slow development of the rigorous, mathematical approach and analysis required to fully understand the processes and dynamics at all space/time scales. This review wants to introduce the uninformed reader to this relatively new science, providing a concise but hopefully comprehensive outline of the milestones of its history, from the adventurous beginnings of the past centuries, to the successive, very recent theoretical and observational advances. In this progress, the scientific “giants” who made possible these advances are also presented. Their choice constitutes not only the author’s personal opinion but that of the oceanographic community at large which recognizes their crucial impact in making physical oceanography the quantitative, exact science of today. It is the author’s privilege to have personally known most of them, not only as teachers but as mentors and friends.

Keywords Physics of the oceans · Meteorology · Climate · History

1 Introduction

“Oceanography” or “Oceanology” is a very broad name encompassing under its denomination all the sciences which can be applied to the ocean, i.e. physics, chemistry, biology etc. Hence it can be broadly defined as the science studying the ocean in its multiple aspects. The oceans cover more than 70% of the earth, separate the continents and a multiplicity of islands of different dimensions are dispersed in their vastity. From a “romantic” point of view, the first oceanographers are the adventurous sea captains who dared to face the unknown water expanse, most of them going in

search of riches and a few in the quest for knowledge. The names of these last ones are now part of our history, some have given name to continents (America, Amerigo Vespucci) or countries (Columbia, Cristoforo Colombo). In this spirit, the absolute first oceanographer can be considered Odysseus, who roughly 1000 years B.C. left Ithaca again and crossed the entire Mediterranean driven by his insatiable desire for knowledge. Figure 1 depicts Odysseus in his ship with the companions directed towards the Hercules’ columns (Gibraltar) to exit and venture into the southern ocean until the entire ship is “swallowed” by the abyss, as famously depicted in Dante’s *Inferno*, canto XXVI.

All the seafarers of the past left their hard-acquired knowledge of ocean currents in their log-books, sometimes even sketching rough maps of their patterns. These log-books were precious not only for recording the commercial routes but because they constituted the first atlases of the global ocean circulation. Interestingly, the first person to chart the most famous of these currents, the Gulf Stream, was the American statesman Benjamin Franklin in 1768. The traditional story says that, when he was working in London as postmaster for the mail to and from the American

“This peer-reviewed paper belongs to the Topical Collection motivated by the Conference “The Mediterranean System: a Hotspot for Climate Change and Adaptation” organized in Rome at the Accademia Nazionale dei Lincei on March 21-22, 2023”.

✉ Paola Malanotte-Rizzoli
rizzoli@mit.edu

¹ Massachusetts Institute of Technology, 54-1426 77
Massachusetts Avenue, Cambridge, MA 02139, USA



Consider well the seed that gave you birth
 you were not made to live as vulgar brutes
 but to aspire to knowledge and great worth

Dante, XXVI Inferno

Fig. 1 Ulysses' voyage after leaving Ithaca towards the Hercules columns as depicted by Dante in Inferno XXVI. Verses translation by the author

colonies, he asked his cousin, Timothy Folger, captain of a merchant ship, why it took his ship so much less time to reach England from America than the official mail ships. Folger's answer was that the British mail captains evidently did not know about the Gulf Stream! The famous Franklin-Folger chart is shown in Fig. 2 (Richardson 1980).

Going back in time, Count Luigi Ferdinando Marsigli can be considered the "lost" father of physical oceanography. He was born in 1658 in Bologna where he studied botany and mathematics. He arguably wrote the first history of the sea, appropriately entitled "*Histoire Physique de la mer*", published in 1725, showing a true appreciation of the topic as a real science. But unfortunately his pioneering efforts are today forgotten. He was followed ~ 150 years later by Matthew Fontaine Maury, who produced the first "Pilot Charts of the Ocean", analyzing the existing log-books, for which he is mostly remembered. He also published the "Physical Geography of the Sea", treating the ocean as a whole worthy of scientific study.

The first scientific oceanographic expedition can be considered the 1870 voyage of HMS Challenger. It lasted 1000 days covering more than 68,000 nautical miles, yielding a wealth of information and gathering data at 362 oceanographic stations on temperature, currents, water chemistry, ocean floor deposits and identifying many new organisms.

The scientific results of the Challenger were published in a 50-volume, 29,500 pages report that took 23 years to complete! After this first gigantic effort, other oceanographic expeditions followed over all the oceans, including the Mediterranean. Until ~ the 50 s of last century, however, oceanography, and in particular physical oceanography, the object of this review, remained a descriptive science without roots in basic physics and fluid dynamics. This development was rather different from meteorology which evolved into a rigorous dynamical approach and understanding roughly starting at the beginning of last century. Why did physical oceanography trail so much behind its twin scientific sister, meteorology? The reason is twofold: motivation and data availability. There is, however, a further reason, which lies at the core of the difference between the two fluids: why was (and still is) the dataset available for the ocean so much smaller than the one available for the atmosphere? A brief discussion of the similarities, and differences, between the two fluids illustrates the fundamental reasons of the different time evolution in their advancement.

1.1 Motivation

The rapid growth of dynamic meteorology was driven by the crucial need to forecast the weather. Our daily lives



Fig. 2 Map the of Gulf Stream by Benjamin Franklin, 1786

are governed by the weather conditions which profoundly affect, and determine, human activities from the daily to the monthly and even longer time scales. Hence the enormous effort to predict the weather since the early 1900s. The enormous progress in this endeavor was due to the advent of computers and the prodigious growth in computer power with the related numerical weather models. Today weather forecasts are routinely made up to 10 days in advance in the great weather centers distributed all over the world in every nation. On the other side, the need to forecast ocean currents is not important for the oceanographic community at large. Substantial interest for forecasting and nowcasting the ocean circulation especially at the mesoscale (see Sect. 3) exists for the navies, fisheries and off-shore drilling operations. The most pressing interest of physical oceanographers, though, is the optimization of the existing datasets for the purpose of deepening and broadening our understanding of ocean dynamics and processes at the regional, basin and global scales. At the present time, a number of global model-data synthesis are routinely available to the oceanographic community to carry out numerical simulations impossible with actual instrumentation in the actual ocean. They provide

realizations of the ocean circulation and climate extremely realistic and with the necessary three-dimensional resolution needed for understanding the underlying dynamical processes. Among them, arguably the most used reanalysis is SODA (Simple Ocean Data Assimilation, Carton and Giese 2008) which has undergone successive implementations and is available online at the NCAR-Climate Data Guide. The most sophisticated reanalysis combining state-of-the-art numerical ocean models together with the adjoint method of control theory (Ghil and Malanotte-Rizzoli 1991; Malanotte-Rizzoli 1996) is the now multi-decadal effort at NASA of ECCO (Estimating the Circulation and Climate of the Ocean, Wunsch et al. 2009) which has provided a richness of dynamical insights and simulations which would have been impossible 30 years ago.

1.2 Datasets

A comparison between the meteorological and oceanographic datasets is most appropriate for the 80 s, i.e. before the observational revolution of the 90 s prompted by the advent of satellites designed to measure dynamical ocean

properties, such as sea level. Together with parallel advances in in theoretical approaches, physical oceanography is now at the level of sophistication of dynamic meteorology, and a new name has been coined, geophysical fluid dynamics, to describe the science addressing the two fluids at the same time (Pedlosky 1987, second edition) which offers the most sophisticated theoretical treatment of the dynamics of atmospheric and oceanic motions.

Figure 3a (Ghil and Malanotte-Rizzoli 1991) shows the meteorological observations available over a 12-h period centered at 12 GMT for January 9, 1979. For each panel the type of observations are indicated as well as the experimental vessels, ranging from the sparse marine drifting buoys (Fig. 3a, top left panel); to geostationary satellites measuring wind velocity components (Fig. 3a, left panel, second from top); to surface temperatures measured by polar orbiting satellites, with their orbital bands evident (Fig. 3a, right panel, first from top). The richness of the meteorological dataset over 12 h period was already staggering ~40 years ago. By contrast, Fig. 3b shows the horizontal distributions

of oceanographic observations at the sea surface until 1980, specifically 3b (top panel) and 3b (middle panel) the surface temperature for the Northern hemisphere winter and summer, respectively; 3b (lowest panel) for the northern summer surface salinity. The paucity of the surface salinity observations with respect to temperature is evident and reflects the much more laborious experimental apparatus based on the chemical titration method of the early times. Nowadays the CTD probe (Conductivity-Temperature-Depth) measures the conductivity of sea water related to the total content of > 30 chemicals dissolved in ionized form. The crucial difference is that Fig. 3b shows the number of surface oceanographic observations collected over 80 years of field measurements. The number of the latter ones is $O(10^{**7})$ collected at ~500,000 hydrographic stations. Compared to the number of atmospheric observations over 12 h, there are (10^{**2}) more ocean observations in a period (10^{**5}) times longer, i.e., (10^{**3}) FEWER ocean observations. This rough estimate does not, however, take into account the different time and space scales of the phenomena characterizing the two

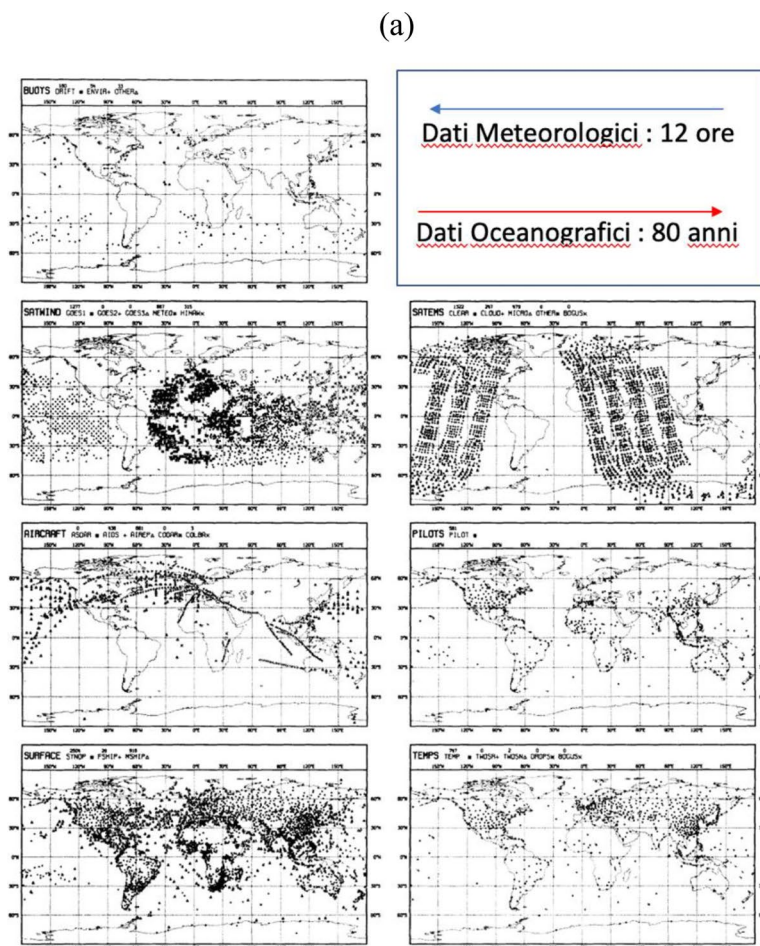


Fig. 3 Summary of available data in 1980; a Meteorological observations in situ and from satellites gathered every 12 h; b Oceanographic surface observations over 80 years since the beginning of last century

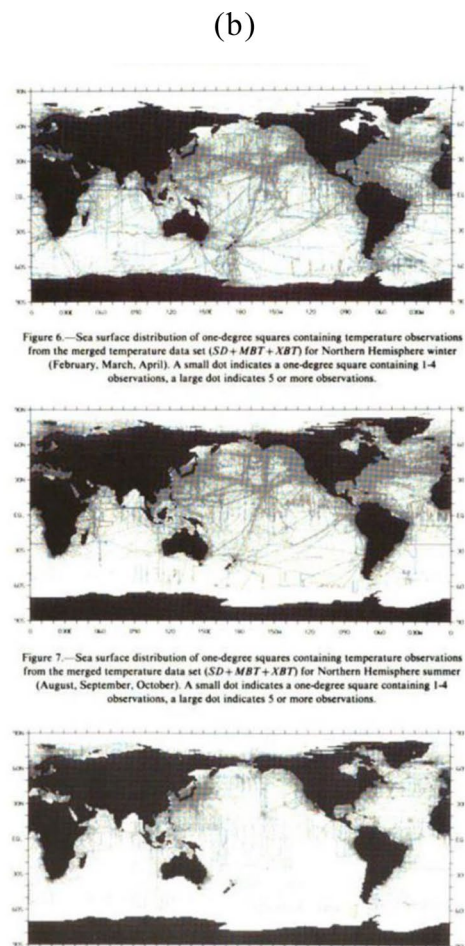


Figure 6.—Sea surface distribution of one-degree squares containing temperature observations from the merged temperature data set (SD + MBT + XBT) for Northern Hemisphere winter (February, March, April). A small dot indicates a one-degree square containing 1-4 observations, a large dot indicates 5 or more observations.

Figure 7.—Sea surface distribution of one-degree squares containing temperature observations from the merged temperature data set (SD + MBT + XBT) for Northern Hemisphere summer (August, September, October). A small dot indicates a one-degree square containing 1-4 observations, a large dot indicates 5 or more observations.

fluids. Only with respect to the space scale, the dynamically important one, defined by the Rossby deformation radius (Pedlosky 1987, second edition) is $O(10^{**2})$ for the ocean and $O(10^{**3})$ for the atmosphere. Correcting for the longer ocean time scales, this requires an observational frequency 10 times lower for the ocean. The final estimate, corrected for both space and time scales, is that in the 80 s there were (10^{**4}) fewer observations for the ocean than for the atmosphere. This is the second important reason why the development of physical oceanography trailed behind dynamic meteorology by $\sim 30\text{--}40$ years.

There is, however, a more fundamental cause for this delay, which lies in the physical extension, geographical distribution and dynamical/thermodynamical differences between the two geofluids covering the earth, which we now briefly discuss.

1.3 Similarities and differences between the atmosphere and ocean

The earth's system is composed of five major parts, or sub-systems: the atmosphere, hydrosphere, biosphere, cryosphere, and geosphere. The solid earth moves on the average very slowly compared to the time scales of human activity and can be considered for all our purposes as stationary. The atmosphere and ocean, on the other side, move at time scales of the same order of our experience and their space–time changes must be considered and studied not only for basic scientific knowledge but for practical societal purposes.

The two fluids can be considered as twins, but not identical twins. Even though they are presently investigated within the same theoretical framework, Geophysical Fluid Dynamics (Pedlosky 1987, second edition), their differences are profound. These differences constitute the fundamental reason for the vast disparity, even today, in the datasets available for them. This brief summary is not meant to be all-inclusive, but a discussion of their most important dissimilarities and the consequences on the measurements of the two fluids properties.

- I. The atmosphere is bounded below by the solid earth/ocean surface but is unbounded in height, theoretically extending to infinity. It surrounds continuously the entire earth as the entire orography is but a small perturbation compared to the unbounded vertical scale. Atmospheric motions propagate all around the earth and constitute an uninterrupted, circular flow. At sea level, air is ~ 784 times less dense than pure water.

The oceans are comprised among horizontal boundaries, the vastly irregular bottom topography, whose vertical scales can be about three times greater than the average ocean depth (the abyssal trenches reach $\sim 11,000$ km.)

and by the sea surface, a material interface separating the heavy ocean fluid from the light gaseous atmosphere. A further complication is added by the presence of great continents extending from north to south, as well as innumerable islands of different sizes, making their exploration and the connected measurement problem much more difficult.

- II. Both the atmosphere and the ocean are forced, dissipative systems. But the atmosphere is forced only thermally, by equator-to-pole and land-sea temperature differences. The thermal forcing of atmospheric motions changes on slow time scales. The major component of ocean circulation, at least in the upper layer ~ 500 m deep, is the wind-driven one, mechanically forced by the wind stress which acts mostly on the rather short seasonal/annual time scales. The second component of ocean circulation, driven by thermal/haline fluxes and called the thermohaline circulation, dominates mostly the deep/abyssal layers, with much longer time scales up to millennial ones.
- III. The thermal forcing of the atmosphere, i.e., the global distribution of incoming solar radiation at its top, is relatively well known and well measured, constituting the top boundary condition which affects all atmospheric motions. The thermodynamic fluxes reaching the ocean surface, however, are modified by the intervening atmosphere by reflection and absorption at the sea surface. Their direct measurement is very difficult and, until recently, they were mostly estimated through parameterization provided by empirical bulk formulae. The observational revolution provided by the advent of satellites has allowed to significantly overcome these deficiencies.
- IV. The basic equations of motion are the same for both fluids, i.e.

Conservation of momentum

Conservation of mass

Equation of state

First law of thermodynamics

Simplifications and difficulties:

Atmosphere

- a. Can be treated in first approximation as a perfect gas
- b. The equation of state is linear
- c. Has only one thermodynamic variable, temperature (T)
- d. The atmosphere is compressible and vertical convection plays a crucial role in atmospheric dynamics

Ocean

- a. A further thermodynamic variable is given by salinity. However, sea water is not a pure chemical solution, implying a unique functional relationship among three thermodynamic variables defining the equation of state. About > 30 chemical substances are dissolved in sea water, roughly in constant proportions. Salinity (S) is a concept based on this assumption and a “creation” of oceanographers with dimensionless unit PSU (Practical Salinity Unit). The equation of state is an empirical polynomial in (T, S) powers best fitted to all the available measurements worldwide and at all times.
- b. This is the major complexity underlying oceanic dynamics.

A major simplification is that water is basically incompressible, and the ocean has a stable vertical stratification. Mixing across isopycnal surfaces is inhibited and oceanic motions occur mostly along the isopycnals.

XXII. Finally, arguably the fundamental difference affecting the measurement problem is that the ocean is opaque to electromagnetic radiation. Atmospheric measurements depend on light waves for probing vertically the fluid and exploring its interior from satellites. This is not possible for the ocean where electromagnetic radiation at all wavelengths is absorbed in the upper ~ 100 m. layer. Only acoustic waves can penetrate into the interior, but the extraction of information from the acoustic pathways, which led to the development of Ocean Acoustic Tomography (Munk and Wunsch 1979) is so complex and the instrumentation so expensive that it has been practically abandoned for the exploration of the large ocean circulation.

This short summary clearly shows that the ocean is a much less tractable system than the atmosphere, still mostly unmeasured in the abyssal depths. The oceanic problem is hence a formidable challenge especially considering its crucial importance in controlling the earth’s climate.

2 The stationary linear ocean

In this brief review of the history of physical oceanography, I will discuss the milestones marking the most important advances and introduce the scientists who made them possible.

Until the ‘50 s of last century, the ocean observations were so widely distributed in space and sparse in time (Fig. 3b), that the best, and only possible, way to understand the underlying circulation was to use all of them as a whole, thus filling the space/time gaps. This approach produced maps hopefully capturing the major oceanic features. The

underlying, and partially correct, assumption was that melding in this way all the available observations, the motions with space/time scales smaller than the largest and longest ones would be filtered out and the “average” circulation would emerge. This procedure is still adopted, albeit in a much more sophisticated manner, to construct the “climatologies” of specific basins and for specific time intervals. Interestingly, because of the smallness of the Mediterranean sea and its location in temperate mid-latitude, the first complete hydrographic surveys were carried out in this basin in the early 1900s. In the insert of Fig. 4, the average winter circulation is shown of the basin. Seasonal pictures were reconstructed from the surveys made by the Danish Oceanographic Expeditions in 1908–1910, published by J. Schmidt in 1912.

On the global scale, the first comprehensive picture of the circulations with the detailed distribution of currents was published in the two volumes by Sverdrup et al. (1942), also shown in Fig. 4. The first volume was devoted to ocean physics and dynamics, the second one to the other disciplines (chemistry, biology). These volumes constituted the compendium of the entire knowledge of the oceans for generations of oceanographers. The picture shown in Fig. 4 is Harald Sverdrup, a Norwegian oceanographer and meteorologist. After working at the university of Bergen, he emigrated to the US and in 1936 became the first director of the Scripps Institution of Oceanography (SIO) founded in La Jolla, California in 1903. Scripps became a department of the University of California at S. Diego in 1912, and is one of the top oceanographic institutions in the entire world.

Sverdrup’s name was given to the unit of ocean transport, $1 \text{ Sv} = 10^6 \text{ m}^3/\text{sec}$. for his pioneering contributions to the field. First and foremost, he pioneered the dynamical analysis of the upper layer ocean circulation (Sverdrup 1947). Being also a meteorologist, he was able to relate quantitatively the horizontal transport of the upper ~ 500 m of the ocean to the wind, but not simply its velocity or stress, but to the vertical component of its curl: $\text{curl}_z = \frac{d\tau_y}{dx} - \frac{d\tau_x}{dy}$, with (τ_x, τ_y) , the x (east–west) and y (south–north) components of the stress, respectively. This balance is now in fact called the Sverdrup balance and the circulation pattern shown in Fig. 4 represents the wind-driven, upper layer circulation. The stress curl produces a “torque”, i.e. rotational motions in the different ocean basins which are called “gyres” and are separated by the lines of zero curl. The different gyres have been emphasized in Fig. 4. In the Atlantic and Pacific oceans, both extending from the North to the South poles and differing mainly in horizontal extensions, as the yearly wind-stress curlz are basically identical and the resulting gyres quite similar: northern polar gyres, northern subtropical gyres and southern subtropical gyres. They are separated by the equatorial system of currents, where the curlz is basically



Harald Sverdrup

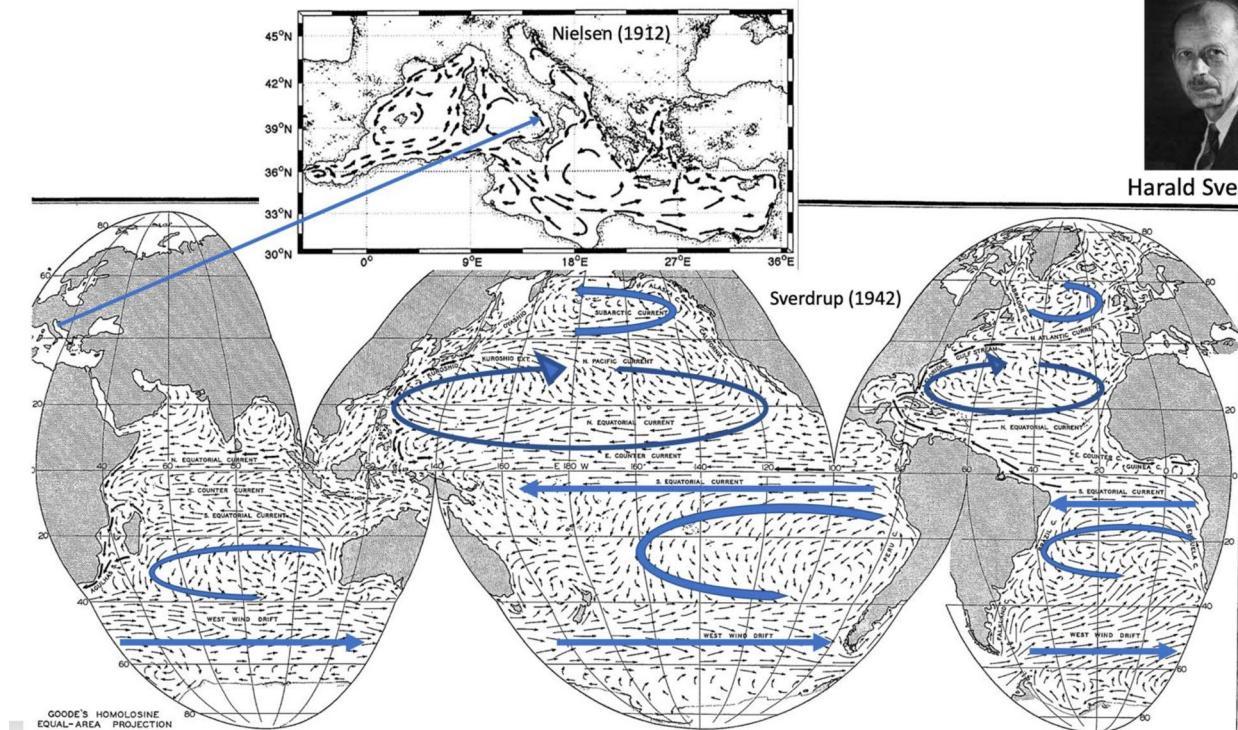


Fig. 4 Representation of the wind-driven global ocean surface circulation reconstructed from the available hydrographic surveys in 1942; Upper left insert: the same for the Mediterranean sea; Right top insert picture: Harald Sverdrup

horizontal; and in the south, at the continents' ends, the enormous Antarctic Circumpolar Current, also wind-driven, which surrounds the entire Antarctica. The land–ocean asymmetry in the Indian continent leaves only the southern subtropical gyre and the equatorial system. The Sverdrup balance is valid only for the ocean interiors away from the western ocean boundaries near the continents. Here strong intense currents are present called the “western boundary currents” which close the Sverdrup circulation patterns.

A famous contribution by Henry Stommel (1948) demonstrated analytically that this western intensification is due to the latitudinal variation of the Coriolis force, the apparent force due to the rotation of the earth. Among the western boundary currents, the most famous is the Gulf Stream, known since antiquity, in the northern Atlantic ocean (See also Fig. 2). Its equivalent in the Pacific ocean is the Kuroshio current along the western coast of Japan. Both are quite evident in Fig. 4, and western-intensified boundary currents are present along all the western boundaries of the world oceans, i.e. the eastern continental boundaries. Stommel did not, however, went a step further unifying his explanation of the western ocean intensification with the interior Sverdrup balance. The unification of these different ideas was due to Walter Munk, Sverdrup's only student at SIO. His groundbreaking synthesis provided the first complete theoretical picture of the wind-driven circulation, and is shown in Fig. 5

(Munk 1950). Munk carried out an analytical calculation closing the open ocean interiors in Sverdrup balance through horizontal boundary layers along the ocean western sides. There horizontal friction is necessary to dissipate the energy and vorticity inputs by the wind in the basin interiors, allowing for the Coriolis force variation with latitude. Figure 5 shows the idealized analytical solution in a square basin, with the yearly wind curl profile reproduced on the left and the identifications of the idealized interior gyres together with the western boundary currents. The three papers by Sverdrup, Stommel and Munk marked the beginning of the modern era of dynamical oceanography and constitute the “initiation” of every student in the field. Munk, arguably the ocean giant of last century, is shown in the insert of Fig. 5. He died at 101 years of age and was one of the mentors of the present author taking her to Scripps for her ocean studies. Also shown is the author with Walter in his last year of age.

3 The 70s: the discovery of the weather of the ocean

The linear structure of the large scale ocean currents and general circulation is the result of the gross undersampling of ocean properties. The hydrographic stations of the

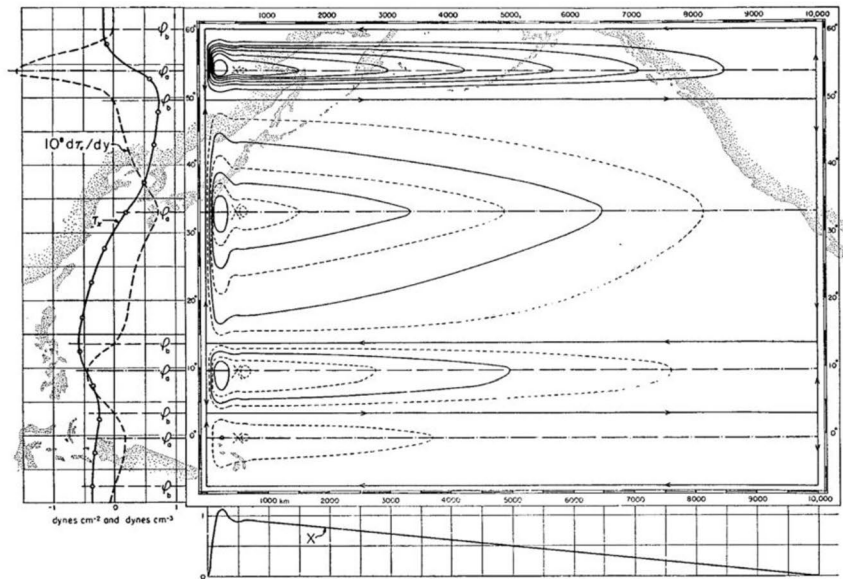
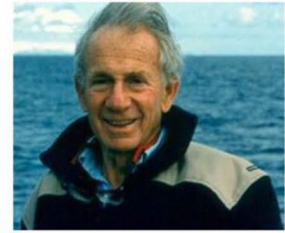


Fig. 2. The mean annual zonal wind stress $\tau_z(y)$ over the Pacific and its curl $d\tau_z/dy$ are plotted on the left, the function $X(x)$ on the lower part. These functions have been combined graphically according to equation (22) to give mass transport streamlines $\psi(x, y)$. The transport between adjacent solid lines is 10×10^{12} g sec $^{-1}$, or 10 million metric tons sec $^{-1}$. The total transport between the coast and any point x, y is $\psi(x, y)$. The chart of the Pacific has a uniform distance scale throughout. In the relatively narrow northern portion, the transport is greatly exaggerated.



Walter Munk
"The Einstein of the Ocean"
New York Times



Fig. 5 Left panel: analytical model by Munk of the wind-driven surface circulation on the basis of the wind yearly meridional profile, drawn on the left; Pictures in the right insert; Walter Munk, upper panel; Munk at 101 with the author, lower panel

experimental surveys of the time were separated by distances often greater than 500 km and by time intervals even greater than 5 or 10 days, depending on the total time required for an oceanographic vessel to cross an entire ocean. Only in the 70 s the meteorological example of the synoptic/mesoscale energetic storms, such as cyclones/anticyclones embedded in the planetary scale atmospheric circulation, motivated oceanographers to search for analogous ocean features. New experiments were planned to discover them. The first one was the US-UK MODE-I (Mid-Ocean Dynamic Experiment), 1971–1974 followed by POLYMODE (combining MODE with the USSS Polygon, Robinson 1982). They led to the discovery of the mesoscale eddy field, the "weather" of the ocean. The POLYMODE array is shown in Fig. 6c.

Cyclonic(L)/anticyclonic(A) vortices with space scales of ~ 100 –150 km were mapped moving continuously into, across and out of the observational array, as shown in Fig. 6a. The mesoscale eddy field contains most of the ocean eddy kinetic energy, and we know now that the nonlinear interactions over a continuous spectrum of eddy motions are crucially important in affecting the large scale circulation. The eddy field depicted in Fig. 6a presents their evolution over a 5 months period.

Further mesoscale features were also discovered in the same period. They were the highly nonlinear "rings", high amplitude coherent and long-lived vortex structures, with

diameters $O(\sim 200$ km). They are produced by the nonlinear instabilities of the jet currents, the Gulf Stream in the case shown in Fig. 6b, as well as by all the jet-like western boundary currents (Kuroshio, Aghoulas, North Brazil etc.). Cold and warm Gulf Stream rings are depicted in Fig. 6b, which also illustrates pictorially their generation mechanism. Strong, unstable meanders bend from the Stream northward or southward. The bending often reach the limit in which the meander neck breaks and the ring detaches from the current and propagates northward or southward in rigid body rotation. The meanders bending southward give birth to rings containing in their core the cold and fresh water of the northern Gulf of Maine, as well as its biochemical properties and, often, garbage released in the gulf coastal waters. They are the "cold-core" rings which propagate southwestward and reach the coasts of the Carolinas and Florida. The meanders bending northward give birth to rings containing the warm, salty water of the southern Sargasso sea. They are the "warm core" rings, also in rigid body rotation, propagating northwestward. They are more short-lived than the cold-core ones as they impinge on the Gulf of Maine shallow coastal waters and are destroyed there. The cold-core rings south of the Stream, on the other side, can be very long-lived. Ring Bob was followed for ~ 6 months thanks to a drifting instrument deployed in its core at birth which

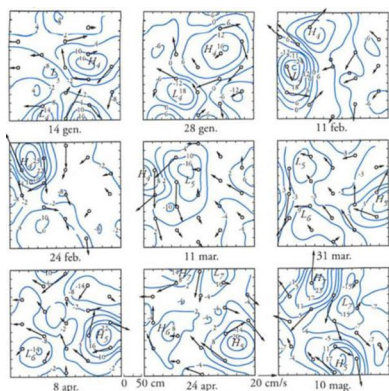


Fig. 4. Mappe dedotte dall'esperimento sinottico POLYMODE.

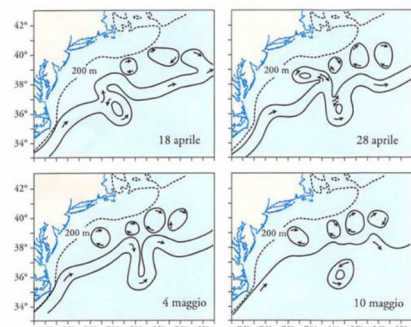


Fig. 5. Esempio di interazione fra corrente e anello, con riattaccamento, avvezione e formazione di altri anelli.

The ubiquitous mesoscale eddy field
Cyclons/ Anticyclons

a

Long Lived Structures
RINGS

b

MODE
Mid-Ocean Dynamics Experiment
1971 – 1974
26° N – 69° W 300 Km²

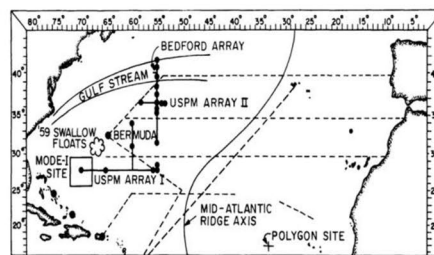


Fig. 4

c

Fig. 6 The discovery of ocean weather in the 70 s; Right panel, 6c, Instrument array of the MODE experiment; Upper left panel, 6a: synoptic maps of the mesoscale cyclones and anticyclones propagating

through the observational MODE array; Lower left panel: warm and cold core rings generated by nonlinear instabilities of the Gulf Stream front

remained trapped inside it. The rings are powerful mixing agents across the Gulf Stream front which inhibits other mixing mechanisms such as internal linear waves. Two important observational experiments of the Office of Naval Research were devoted to study these structures in the 80 s, the cold and warm core ring experiments.

In the Mediterranean sea their counterpart was the theoretical and observational program POEM (Physical Oceanography of the Eastern Mediterranean, 1984–1995 for the field surveys). Figure 7 shows the logo of the program, and the title of the EOS paper of the American Geophysical Union (AGU) introducing it to the international ocean community. The program mapped for the first time in a rigorous way the large scale circulation of the basin, its permanent currents, gyres and the embedded mesoscale eddy field (Malanotte-Rizzoli et al. 2013). This picture is also shown in Fig. 7.

The discovery of the weather of the ocean made the ocean circulation picture at different, interacting scales of motion very similar to the already discovered atmospheric one. And the underlying dynamics common to the two fluids began to emerge and to be studied.

4 The revolution of the 90s: theory and methodology

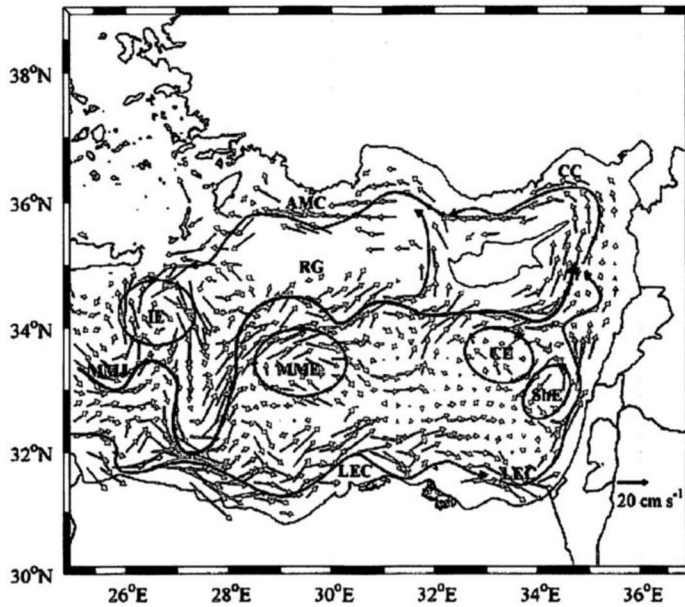
The great achievement which started in the 80 s and culminated in the 90 s was the unification of the theoretical foundations for ocean and atmospheric sciences. A new body of fluid mechanics was created for the earth fluids, i.e. Geophysical Fluid Dynamics, GFD. This name today applies to all the theoretical developments which, starting from the equations of motion common to the atmosphere and ocean, diversify their behavior considering their mechanical and thermodynamic properties. A great number of books on the topic has been written in the last decades. Among them, the first, pioneering and justly famous one is the book by Joseph Pedlosky, with the first edition in 1984 and the second revised one in 1987. This book is shown in the left panel of Fig. 8 and can be found in the personal library of every fluid earth scientist near the 1942 Sverdrup, Johnson & Fleming treatise of Sect. 2. To provide the reader with a theoretical example, the lower right panel shows the equations of the quasi-geostrophic



Full Access

POEM: Physical Oceanography of the Eastern Mediterranean (1984 – 2009)

Paola Malanotte-Rizzoli, Allan R. Robinson



POEM 25th Anniversary

Rome (Italy) 7th-9th November 2011

Fig. 7 Upper panel: Eos announcement of the POEM program, 1987; Lower right panel: POEM logo; Lower left panel: the mesoscale eddy field and meandering currents of the Eastern Mediterranean mapped by the POEM surveys

(QG) approximation introduced for atmospheric motions by Jule Charney (1948). Twenty years elapsed before the QG equations were modified for the ocean and began to be extensively used. In the GFD book of Fig. 8, the QG equations for the atmosphere are in page 358, those for the ocean in page 364.

4.1 Numerical modeling

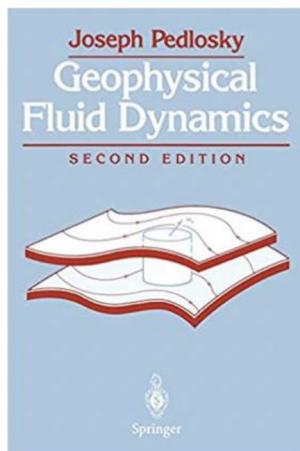
Again, because of the need for weather prediction, the beginning of numerical modeling started for the atmosphere. And again, Jule Charney, with his mentor John Von Neumann at Princeton, was the pioneer in developing the first forecasting numerical models in the early 60 s with the rudimentary computers of the time. The exponential growth of computer power in the following decades led first to the giant supercomputers of the 70–80 s. They were bypassed by the advent of Information Technology (IT), which led to the personal computers and the present cell phones, both of which have become indispensable tools in our daily life. Again, numerical models of ocean circulation followed the atmospheric ones. Nowadays the present generation of climate and Earth System models are routinely used in all the numerical centers

of the world, coupling together all the different components of the climate system needed for realistic simulations and climate projections, as exemplified by the Intergovernmental Panel on Climate Change (IPCC) Reports. For the earth fluids, the numerical models are now capable to resolve all the energetic scales of motion, from the global ones to the mesoscale and submesoscale, short only of the microturbulence ones. Quantum computing, now beginning to be explored, may lead to even further unimaginable progress in the field.

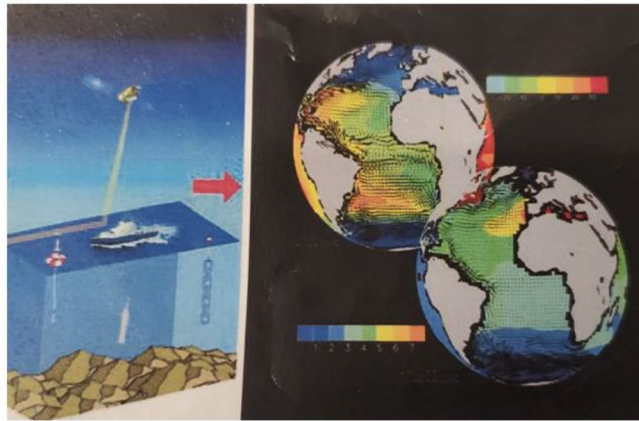
4.2 Data assimilation

Data assimilation refers to the methodologies allowing to combine numerical models with the existing observations of the fluid at study. History repeats itself and data assimilation was pioneered decades ago because of the necessity of weather forecasting. Nowadays all the world weather centers have diverse assimilation packages combined with atmospheric models and have reached the capability of providing 10 days forecasts.

Among the methodologies for prediction, the most useful ones are the sequential Kalman filter and its modifications (Ghil and Malanotte-Rizzoli 1991). On the other side, as



ATMOSPHERE : Page 358
OCEAN : Page 364



$$\frac{\partial \zeta_g}{\partial t} = -\mathbf{v}_g \cdot \nabla (\zeta_g + f) + f_o \frac{\partial \omega}{\partial p}$$

$$\frac{\partial \vartheta}{\partial t} = -\mathbf{v}_g \cdot \nabla \vartheta + \omega N^2$$

The equations above make up the quasi-geostrophic theory of atmospheric motions introduced by Charney in a 1948 paper. This theory became the foundation of modern dynamical meteorology and oceanography.

Fig. 8 The theoretical revolution of the 90 s. Left panel: cover of the second edition of Geophysical Fluid Dynamics, Pedlosky 1987; Lower right panel: the quasi-geostrophic equations discovered by

Charney 1948; Upper right panel: representation of the observational basis and Atlantic ocean circulation at the surface and mid-depth evaluated by the ECCO synthesis

already discussed in subSect. 2, the most important objective of ocean data assimilation is to obtain a synthesis of the available datasets with the dynamical simulations provided by the numerical models which act as interpolators/extrapolators of the observations in space/time. As a consequence, the best assimilation methods for this purpose are the variational ones. The most sophisticated is the adjoint method borrowed by control theory which gives a “best fit” of the numerical trajectory to the observational points. The dynamical equations of motion themselves are used as constraints in the minimization of a quadratic norm which gives the error between the true, unknown value of a variable and the observed one, through the use of Lagrangian multipliers. The best example of such synthesis is ECCO (Estimating the Circulation and Climate of the Ocean), a collaboration among American and European universities which started at MIT in 1999 (Wunsch et al. 2009). Figure 8c synthesizes visually the ECCO system, the left panel showing the observational platforms providing data in real time to the National Aeronautics and Space Administration (NASA) where ECCO is presently routinely evaluated and distributed to the community of users. The right panel shows

the average circulation at the surface (top) and at 2000 m depth in the Atlantic ocean. The colored fields, and related color palettes, represent the average temperature distributions. Particularly evident at 2000 m depth is the well-known salty/warm Mediterranean water tongue exiting from the strait of Gibraltar and spreading into the Atlantic interior. For a review of the assimilation methodologies most useful and used in ocean sciences see Malanotte-Rizzoli (1996).

5 The revolution of the '90s: the new observations

The decade of the 90 s marked also the development of satellite altimetry and the execution of two major, worldwide observational programs, the World Ocean Circulation Experiment (WOCE 1990–1995) and the ARGO program of Lagrangian floats.

Satellite altimetry and WOCE were spearheaded by Carl Wunsch of MIT. His picture is shown in the upper right insert of Fig. 9. In 1992 the satellite TOPEX/Poseidon was launched, a collaborative effort between NASA (US)

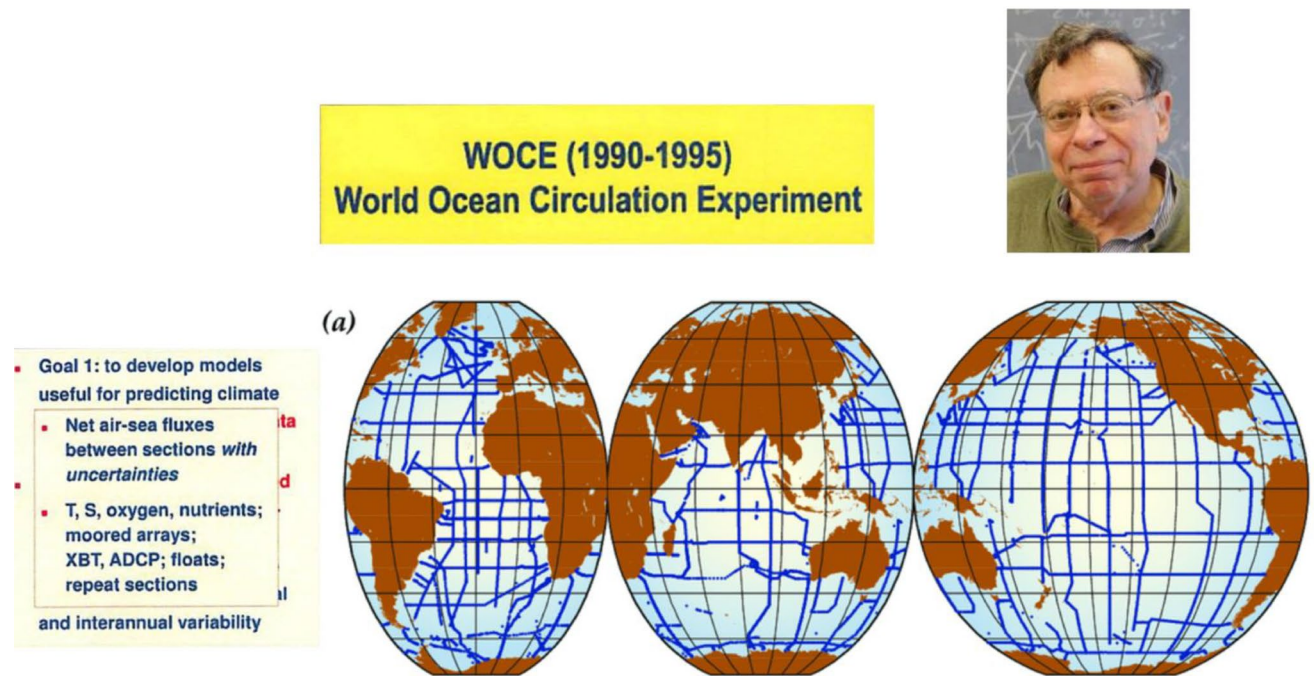


Fig. 9 Map of the WOCE hydrographic surveys covering the world ocean, measured quantities listed on the left. Upper insert: picture of Carl Wunsch

and CNES (France). It was equipped with the most accurate radar altimeter of the time. The altimeter measures the ellipsoidal height of the sea surface which has then to be compared with the reference equipotential gravitational surface, namely the geoid. Changes in the geoid are due to the distribution of continental masses, orography and ocean bathymetry, and they can reach displacements of $> \pm 100$ m. Superimposed to the geoid is the ocean topography, with maximum displacements of ± 1 m. Hence the ocean topography is “noise” with respect to the geoid, and the altimeter must extract this noise from the total signal. The TOPEX repeat period was of 10 days, in which the satellite monitored almost completely the shape of the earth’s surface. The success of the TOPEX/Poseidon mission was beyond expectation, firstly for the satellite lifetime which quite exceeded its projected lifetime of 5 years. Secondly, the altimeter data were of unprecedented precision, with a rms (root-mean-square) error of ~ 3 cm. (Stammer and Wunsch 1994). Satellite oceanography allowed to fully resolve the ubiquitous mesoscale eddy field in all its complexity,

A number of more and more precise altimeters, both for measurement precision and for horizontal ground resolution were successively launched, i.e., ERS1 1991; ERS2 1995; GFO 1998; Jason 1, 2001 etc.

WOCE was designed to begin in conjunction with the TOPEX mission. The network of hydrographic surveys covering the entire globe is shown in Fig. 9, with the observational timeframe 1990–1995, later extended to 1998. It

was followed by an analysis and modeling phase that ran until 2002, used resources from nearly 30 countries and has provided a complete, unique picture of the world ocean three-dimensional circulation and property distributions in the decade of the 90 s. Unfortunately a great omission can be noticed in Fig. 9: no WOCE transect was planned to cross the Mediterranean sea, due to the lack of interest in this marginal basin of the Anglo-Saxon oceanographic community which dominated the field in the 80–90 s. This disregard has very recently been changed by the last IPCC AR6 report of 2021–2022, in which a special Cross-Chapter has been devoted to the Mediterranean defined as “a hotspot for climate change” (IPCC WGII 2022).

Finally, a very important, still ongoing observational project was launched in 2000, the ARGO pilot program of floats of the Global Ocean Observing System. Argo was planned in conjunction with the JASON earth observing satellites. The names are revealing: Jason was the mythical Greek hero searching for the golden fleece of the winged ram Chrysomallus. Jason’s companions in the search were called the Argonauts, from the name of their ship, Argo. Hence the observational companions at sea of the Jason satellite were called the ARGO floats, also in search of the “golden” pathways of oceanic water masses. The ARGO floats are deployed at the reference depth of 2000 m. Every 10 days they rise to the sea surface measuring continuous profiles of temperature, salinity, depth. Nowadays more than 30,000 floats have been deployed by 34 countries, obtaining 2

million profiles of these properties together with subsurface velocity measurements (Roemmich and Owens 2000). The ARGO system covers densely the entire global ocean including the Mediterranean sea and is shown in Fig. 10. In the Mediterranean map, insert in the upper left, different sub-basin are differentiated with different water mass distributions, evolving from the eastern to the western basins (Fedele et al. 2022). Differently from the WOCE hydrographic sections which provide Eulerian observations localized in space and time, the ARGO floats provide Lagrangian measurements, i.e. they follow the pathways of the water masses and major currents and their evolution from a sub-basin to another. Hence they give the picture of the evolving ocean circulation and its seasonal/yearly changes, proving to be the most invaluable and successful observational platform of the last decades.

6 The twenty-first century: the science of climate change

The history of physical oceanography in the twenty-first century is the history of the science of climate change, the challenge to be faced by humans to adapt to the evolving global environment. The science of climate comprises all the traditional sciences, hence is the most complex one requiring

an interdisciplinary as well as multidisciplinary approach. In the middle of last century the development of quantum mechanics and the discovery of nuclear power led to the development of terrible weapons of destruction. However, the consequences of not taking the necessary, enormously difficult measures to change the policies of greenhouse gases emissions and other human induced environmental disasters may lead to an irreversible change of the earth as we have known it in past centuries until today, even beyond any possibility of adaptation. Figure 11 shows a pictorial rendition of the climate system with all its components and their interactions with multiple pathways of connection.

The realization of this impending challenge led to the creation of the Intergovernmental Panel on Climate Change (IPCC) established in 1998 by the United Nations Environmental Program (UNEP) and the World Meteorological Organization (WMO). Its mission is to provide policy makers with regular scientific assessments on the state of knowledge of climate change.

The first IPCC Assessment Report (FAR) was issued in 1990 and emphasized that the importance and complexity of the problem required a full international cooperation. The successive second (SAR 1999) and third (TAR 2001) focused the attention on the impacts of climate change and the need for adaptation. The later reports AR4, 2007, winner of the Nobel prize for peace; AR5, 2013–2014; and the most

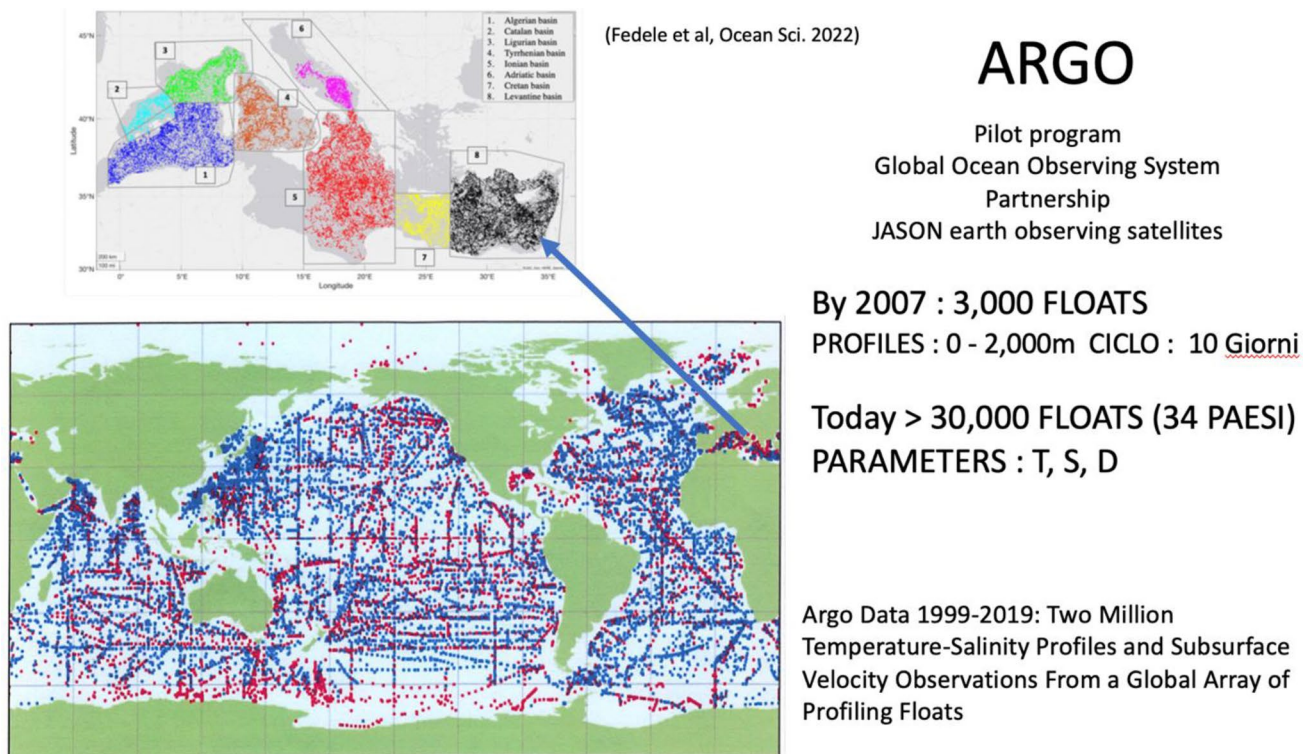


Fig. 10 Distribution of the ARGO floats over the world ocean in 2019. Upper left panel: the same in the Mediterranean sea (Fedele et al. 2022)

Charney Report (1979)

**Carbon dioxide and climate :
A scientific assessment**

“We estimate the most probably global warming for a doubling of CO₂ to be near 3°C with a probable error of +/- 1.5°C”

IPCC (2007) :

“The equilibrium climate sensitivity is *likely* to be in the range 2°C to 4.5°C with a best estimate value of about 3°C”

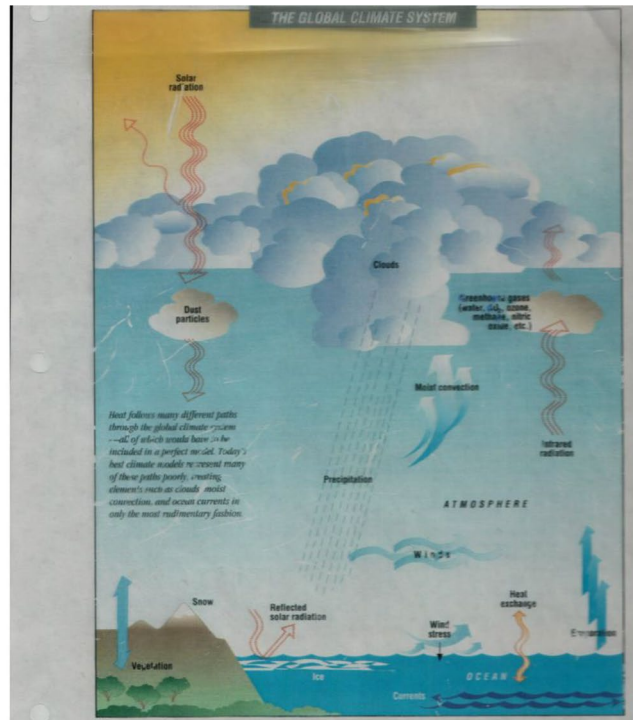


Fig. 11 Right panel: pictorial representation of the climate system; left panel: results of the Charney Report (1979) and of the IPCC AR4. Insert: picture of Jule Charney

recent AR6, 2021–2022, have involved the cooperation of thousands of scientists from all the world nations scrutinizing all the most recent observational and theoretical aspects of climate science. The IPCC reports have become the most authoritative assessments of the present state of the earth and of the future projected scenarios of its evolution in the next ~ two centuries.

Very interestingly, the problem was already known in a restricted scientific community ~ 30 years before. In 1979, a science giant, Jule Charney (already mentioned in Sect. 4 for introducing the quasi-geostrophic approximation for atmospheric and oceanic motions) convened a group of scientists interested in climate at the Woods Hole Oceanographic Institution named “The ad hoc Group on Carbon Dioxide and Climate”. The resulting report, in which the concept of “climate sensitivity” was first defined and which is now known as the “Charney Report” (1979) produced the first comprehensive assessment of the effects of carbon dioxide as the primary greenhouse gas. Its summary, visionary statement was: “We estimate the most probable global warming for a doubling of CO₂ to be near 3 C with a probable error of ± 1.5 C”. In 2007, the IPCC AR4 Report stated: “The equilibrium climate sensitivity is *likely* to be in the range 2–4.5 C with a best estimate value of ~ 3 C”. Jule Charney’s picture is in the insert of Fig. 10.

A review of climate science is well beyond the scope of this short history of Physical Oceanography. The literature

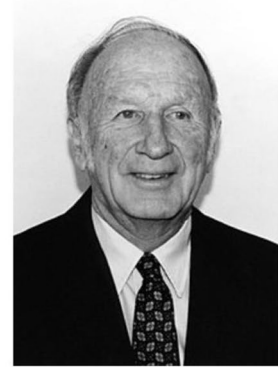
on the topic has by now become enormous, both in terms of present science and in terms of mitigation and adaptation measures. The reader is referred to the latest IPCC AR6 Report (2021 WGI 2022 WGII) for a comprehensive review.

7 Epilogue: the beauty of chaos

In 1960 a little man with bright blue eyes, named Ed Lorenz, created a weather model on his computer at the Massachusetts Institute of Technology. The model consisted of three nonlinear deterministic equations representing a simple box atmosphere heated from below and cooled from above. The remarkable result was that the computer calculations never repeated the same sequence when they were started from an initial point different from the one in the first, original calculation. Even when changing the initial condition by a very small quantity (3 truncation digits versus 6 truncation digits), the trajectories of the two calculations diverged very quickly. These experimentations marked the discovery of chaos (Lorenz 1963, 1969).

Chaos has been defined as the third major scientific discovery of last century, after relativity and quantum mechanics. Chaos characterizes the evolution of a nonlinear, deterministic system with extreme sensitivity to the initial conditions. The atmospheric weather is chaotic. But also the ocean circulation is chaotic: in the ‘70 s the weather of the ocean was

THE TURBULENT CHAOTIC OCEAN



ECCO model-data synthesis

Fig. 12 The turbulent chaotic ocean in the NASA-ECCO model data synthesis. Insert: picture of Edward Lorenz

discovered (Sect. 3), i.e. the ubiquitous, energetic mesoscale eddy field, the equivalent of the synoptic/mesoscale field of the atmosphere.

I conclude this brief history of physical oceanography with a picture of the turbulent, chaotic ocean, i.e. the NASA realization of the ECCO model system (Sect. 4.2) in Fig. 12. Ed Lorenz is shown in the insert.

The Atlantic Gulf Stream meanders off the Atlantic coast at Cape Hatteras into the ocean interior shedding eddies northward and southward of its mean path; the little Mediterranean sea is also filled with smaller eddies and meandering currents. But there is order in disorder: notice the big vortical structures (rings) propagating parallel to the equator and crossing unchanged the entire Atlantic. These are coherent nonlinear structures which violate the principle of chaos being endowed with a longer lifetime, and hence predictability, than the smaller mesoscale cyclonic and anticyclonic vortices. The atmospheric equivalent are the hurricanes, surviving longer times in contrast to the weather cyclonic/anticyclonic storms. Figure 12 shows the richness of the fluid world largely dominated by the chaos discovered by Lorenz. No greater genius could conclude the sequence of giants who have made the history of physical oceanography.

Funding 'Open Access funding provided by the MIT Libraries'.

Declarations

Conflict of interest I hereby declare that I have no conflict of interest with the regulations of Rendiconti Lincei-Springer.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Carton JA, Giese BS (2008) A reanalysis of ocean climate using simple ocean data assimilation (SODA). *Mon Wea Rev* 136(8):2999–3017
- Charney JG (1948) On the scale of atmospheric motions. *Geophysiske Publikasjoner* 17(2):17
- Charney JG (1979) Carbon dioxide and Climate: a Scientific Assessment. In: Ad Hoc Study Group on Carbon Dioxide and Climate, WHOI, p 18
- Fedele G, Mauri E, Notarstefano G, Poulain PM (2022) Characterization of the atlantic water and the levantine intermediate water in the Mediterranean Sea using 20 years of ARGO data. In: *Ocean Sciences, Special Issue: advances in interdisciplinary studies at multiple scales in the Mediterranean sea*

- Ghil M, Malanotte-Rizzoli P (1991) Data assimilation in meteorology and oceanography. *Adv Geophys* 33:141–266
- IPCC (2022) WGII Sixth Assessment Report, Cross-Chapter Paper 4: Mediterranean Report, p 50
- Lorenz EN (1963) Deterministic nonperiodic flow. *J Atmos Sci* 20:130–141
- Lorenz EN (1969) The predictability of a flow which possesses many scales of motion. *Tellus XXI* 3:289–307
- Malanotte-Rizzoli P (1996) Modern approaches to data assimilation in ocean modeling. *Elsevier Oceanogr Ser* 61:455
- Malanotte-Rizzoli P (2013) Physical forcing and physical/biochemical variability of the Mediterranean sea: a review of unresolved issues and directions for future research. *Ocean Sci Discuss.* <https://doi.org/10.5195/osd-10.1205>
- Munk W, Wunsch C (1979) Ocean acoustic tomography: a scheme for large scale monitoring. *Deep-Sea Res Part A* 26(2):123–161
- Munk W (1950) On the wind-driven ocean circulation. *J Meteor* 7:79–93
- Pedlosky J (1987) *Geophysical fluid dynamics*. Second edition, p 710
- Richardson PL (1980) Oceanography: the Past. In: *Proc.3rd International Congress on the History of Oceanography*, WHOI
- Robinson AR (1982) Dynamics of ocean currents and circulation: results of POLYMODE and related investigations. In: Osborne AR, Malanotte-Rizzoli P (eds.), *Topics in ocean physics*, Amsterdam-New York, pp 1–78
- Roemmich D, Owens WB (2000) The ARGO project: global ocean observations for understanding and prediction of climate variability. *Oceanography* 13:45–50
- Stammer D, Wunsch C (1994) Preliminary assessment of accuracy and precision of TOPEX/POSEIDON altimeter data with respect to the large scale ocean circulation. *J Geophys Res Oceans* 99:24584–24604
- Stommel HM (1948) The westward intensification of wind-driven ocean currents. *Trans Am Geophys Union* 29(2):202–206
- Sverdrup HU, Johnson MW, Fleming RH (1942) *The Oceans: their physics, chemistry and general biology*. New York, Prentice Hall, p 1087
- Sverdrup HU (1947) Wind-driven currents in a baroclinic ocean. *Proc Nat Acad Sci USA* 33:318–326
- Wunsch C, Heimback P, Ponte RM, Fukumori I, ECCO-GODAE Consortium Members (2009) The global general circulation of the ocean estimated by the ECCO Consortium. vol 22, pp 88–103

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.