Measuring the Sea: Marsili's Oceanographic Cruise (1679–80) and the Roots of Oceanography

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ABSTRACT

The first in situ measurements of seawater density that referred to a geographical position at sea and time of the year were carried out by Count Luigi Ferdinando Marsili between 1679 and 1680 in the Adriatic Sea, Aegean Sea, Marmara Sea, and the Bosporus. Not only was this the first investigation with documented oceanographic measurements carried out at stations, but the measurements were described in such an accurate way that the authors were able to reconstruct the observations in modern units. These first measurements concern the "specific gravity" of seawaters (i.e., the ratio between fluid densities). The data reported in the historical oceanographic treatise *Osservazioni intorno al Bosforo Tracio* (Marsili) allowed the reconstruction of the seawater density at different geographic locations between 1679 and 1680. Marsili's experimental methodology included the collection of surface and deep water samples, the analysis of the samples with a hydrostatic ampoule, and the use of a reference water to standardize the measurements. A comparison of reconstructed densities with present-day values shows an agreement within 10%–20% uncertainty, owing to various aspects of the measurement methodology that are difficult to reconstruct from the documentary evidence. Marsili also measured the current speed and the depth of the current inversion in the Bosporus, which are consistent with the present-day knowledge. The experimental data collected in the Bosporus enabled Marsili to enunciate a theory on the cause of the two-layer flow at the strait, demonstrated by his laboratory experiment and later confirmed by many analytical and numerical studies.

1. Introduction

In 1628, Benedetto Castelli (1577–1644), a friend and pupil of Galileo (1564–1642), recognized that the existing information on water currents was very limited. In his book *Della Misura delle Acque Correnti* (Castelli 1660), he wrote the following:

> The truth is that the information on things near our senses is often more abstruse and concealed than our knowledge of things far away, and also far greater and more subtle is our comprehension of the movement of the planets and the periods of the stars than that we have of rivers and seas.

Many Galilean scientists of the sixteenth and seventeenth centuries were aware that the knowledge regarding natural waters would not progress unless experiments were directly carried out in the natural world. Some scientists were interested in the composition and movement of natural waters, speculating that their properties could change depending on the geographical context. Therefore, new instruments and rigorous measurement methodologies had to be established in order to carry out in situ observations. These intentions are evident from an analysis of the manuscripts documenting the activities and research projects of the members of the Accademia del Cimento (the Experiments Academy in English), funded in 1657 (Boschiero 2007), and the Royal Society of London, established in 1660 (Birch 1756), thereafter referred to as the Royal Society.

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Regarding the circulation of surface waters, members of the Accademia del Cimento had highlighted the need to collect information on current directions in different geographical areas in order to reconstruct their complex structure and identify any eventual regularities. Between 1649 and 1656, Vincenzo Viviani (1622–1703) writes the following (Galilei et al. 1942):

> Write to England, Spain, Holland and Leghorn as per the draft to follow, asking whether it is true that the currents of the sea flow from North to South [...]. Let it be diligently observed and let expert opinion be sought as to whether the currents of the sea come from north to south; whether they may even come now from one direction, now from another; let mariners of various nations be questioned as to the movement of these currents in the English seas [...]. See whether it is true that when the sea is made rough by a little wind then it becomes agitated also unto its depths; this by having divers go underwater and then questioning them [...]. Think too of ways to observe this when they cannot dive deeply enough.

Regarding the Royal Society, a document containing "Propositions of some experiments to be made by the Earl of Sandwich in his present voyage [in the Mediterranean]" was prepared in a meeting on 14 June 1661. The "Propositions" of the Royal Society to the Earl of Sandwich in his journey to the Mediterranean included inquiries regarding the depth of the sea, horizontal and vertical variations in salinity, the pressure of the seawater, tides and currents in the Strait of Gibraltar, and the luminescence of seawater.

In 1660 Boyle (1627–91) instructed a list of questions reported in Hunter (2005), three of which follow below:

> Of the Gravity of Sea-waters, in reference to fresh waters and to one another. Whether it vary not in Summer and Winter, and on other accounts, especially the difference of Climates. And whether in the same season the Seas gravity proceed only from the greater or lesser proportion of salt that is in it, and not something also from other causes.
>
> Of the motions of Sea. Of those caused by the winds, and of their Effects the waves... [...]. How deep Storms move the Sea, beneath the level of the water when it is calme?
>
> Of the currents in the Sea, the places wherein they are observd. [...] And whether there be any submarine currants that reach not to the surface of the water?

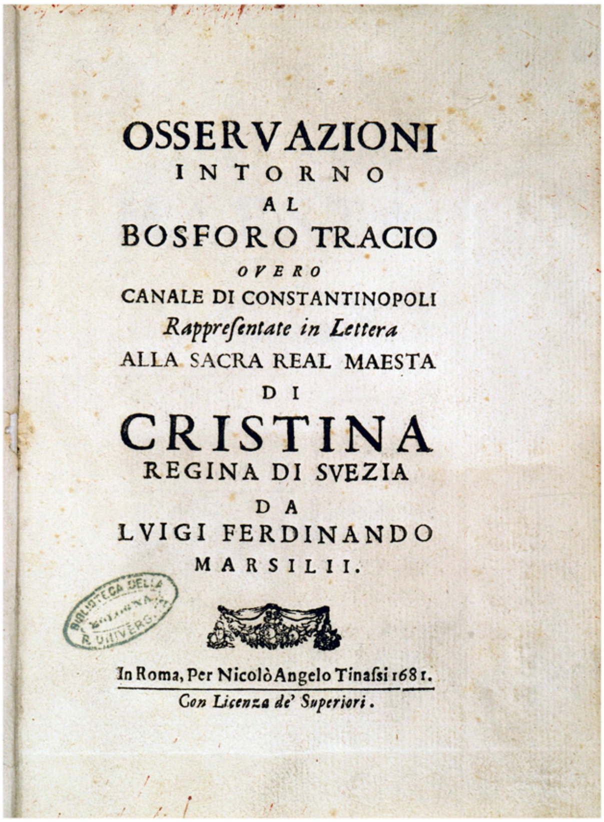
In 1674 Boyle published an essay "Tracts consisting of Observations about the Saltness of the Sea [...]", reported in Hunter and Davis (1999). Boyle's essay describes laboratory measurements of saltwaters and other fluids together with the measurement of the "specific weight" (equal to the ratio of fluid densities, defined in section 3) of sea samples collected in different parts of the World Ocean. He describes the methodology needed to carry out the water sampling near the sea bottom and reports about the relative weights of fresh- with respect to saltwater. However, we cannot precisely reconstruct the measurement methodology and interpret the numbers of the essay in terms of modern density.

The methodology of a modern scientific oceanographic investigation requires that seawater is sampled at stations with a precise georeferencing and timing. This paper shows evidence of when and where such first oceanographic investigation was carried out. We argue that the following conditions should be satisfied: (i) the observations should be documented in detailed form for the geographic position and the time of the year, and (ii) a description of the observing methodology should be available, for the measured values to be reconciled with modern seawater measurements.

To our knowledge, Count Luigi Ferdinando Marsili (1658–1730) was the first observer to use a robust methodology to carry out quantitative, well-organized in situ measurements of seawater density with precise specification of time and location. A short biography of Marsili is given in the appendix, while more complete accounts are also available in Stoye (1994) and Lovarini (1930).

Marsili's letters and travel notes from 1679–80, summarized in his famous treatise *Osservazioni intorno al Bosforo Tracio* (Marsili 1681), are the first scientific reports of an oceanographic survey (Fig. 1). For the first time in scientific history, he demonstrated that "the sea could be measured." Investing in a methodology that would prove the value of quantitative and repeatable measurements, he determined the dynamical seawater property that is density and shared this knowledge with others through a meticulous recording of his observations. However, his work remained unrecognized until rediscovered in the twentieth century (Defant 1961; Deacon 1971). In 2005, a review of the work of Marsili was carried out (Soffientino and Pilson 2005), and his treatise was translated into English (Soffientino and Pilson 2009). Unlike these previous works, in this paper we aim to reconstruct the measurements in modern physical units and compare them with present-day observations. We also review Marsili's creative experimental investigation of the fluid dynamical behavior of sea straits, which continues to be a demanding area of ocean science.

In his treatise, Marsili not only reports on in situ ocean observations for the first time ever but also develops a comprehensive scientific methodology to study the sea, from in situ measurements to hypothesis testing in a laboratory experiment. Marsili collected seawater samples both at the sea surface and at depth, at various


OSSERVAZIONI
INTORNO
AL
BOSFORO TRACIO
OVERO
CANALE DI CONSTANTINOPOLI
Rappresentate in Lettera
ALLA SACRA REAL MAESTA
DI
CRISTINA
REGINA DI SVEZIA
DA
LVIGI FERDINANDO
MARSILII.

In Roma, Per Nicolò Angelo Tinassi 1681.
Con Licenza de' Superiori.

FIG. 1. Title page of Marsili's treatise (Marsili 1681).

geographical locations along the cruise track. His analysis of seawater properties from these samples enabled him to acquire the experimental evidence necessary to formulate a conceptual model of the water circulation in the Bosporus. He was thus able to explain the existence of two current systems inside the Bosporus, an upper one running from the Black Sea to the Marmara Sea and a lower one running in the opposite direction. He directly measured both the magnitude of the current and the depth at which the current changed direction. Finally, he set up a laboratory experiment to verify the reasons for the existence of opposite currents in the Strait.

In this paper we describe the water-sampling stations, discussing the density measurement technique reconstructed from the manuscripts, and we perform the conversion of 1679–80 density measurements to SI units. We also discuss the current inversion depth measured in the Bosporus and convert it into SI units. In addition we provide an overview of the well-known laboratory experiment he carried out to explain the two-layer exchange flow at the Bosporus (Gill 1982).

In section 2 we describe Marsili's cruise track. Section 3 reports on the data collection and measurement methodology employed. In section 4 we reconstruct the seawater density from historical measurements and compare them with present day measurements. In section 5 we reconstruct the depth measurements of the current inversion at the Bosporus, and in section 6 we discuss the laboratory experiment. Section 7 concludes with a discussion on the significance of Marsili's work for modern oceanography.

2. The 1679–80 "observations of natural things" from Venice to Constantinople

While still a medical student at the University of Padua, in July 1679 Marsili received authorization to join the group of functionaries accompanying Pietro Civran, the new Venetian ambassador to Constantinople. Marsili's chief aim was to acquire the diplomatic skills and military expertise necessary for a military and political career. However, he also wanted to observe nature, attempting to show how measurements of the marine environment could be obtained in practice.

The two galleys, with Marsili on board one of them, set sail from Venice probably on 22 September 1679, sailing through the Mediterranean Sea to arrive at the Bosporus in about six months. Their route to Constantinople is described in Marsili's notes contained in the *Oriental Manuscripts*, which are the collection of manuscripts that Marsili donated to the University of Bologna in 1712. A reconstruction of the voyage from these documents is presented in Fig. 2: the route was probably close to the coastlines, with the ship stopping in a series of ports.

During the cruise and during his stay in Constantinople, Marsili collected water samples in the Adriatic Sea, Aegean Sea, Dardanelles, Marmara Sea, and Bosporus. Marsili's return journey from Constantinople started on 22 August 1680, this time following a terrestrial route. Approximately one year after his return to Italy, the first edition of his treatise (Marsili 1681) was published, containing all his measurements and the description of the laboratory experiment.

Figure 3 shows the table from the original treatise illustrating the stations where Marsili performed measurements. He meticulously indicated the location, the time of the stations, and the weight of rings used in the measurements, in accordance with the technique to be described in the next section. Figure 3 is a masterpiece of the Galilean experimental methodology developed by the Accademia del Cimento scientists who started the process of standardization and reproducibility of scientific laboratory experiments. They established the need for a precise reporting of the measurement technology used in experiments and a

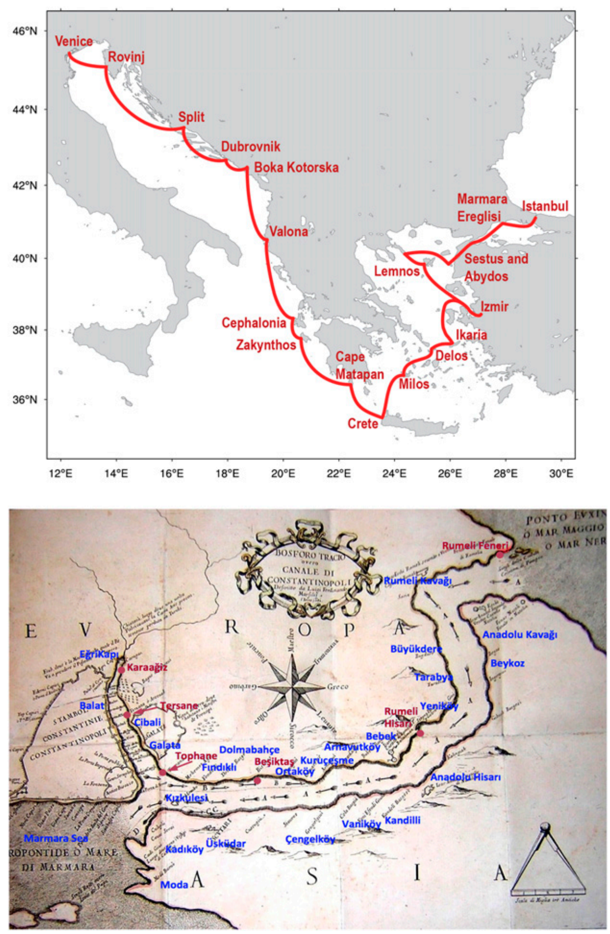


FIG. 2. (top) Map showing a reconstruction of the voyage from Venice to Constantinople according to the description Marsili gives in the *Oriental Manuscripts*. (bottom) Original map of Bosporus from Marsili (1681). Present names of locations are overwritten on the map originals; the station location names where the water samples were collected (as indicated in Table 1) are in red, and the presumed locations at the coast indicated by dots.

careful listing of the measurement values. The Museo Galileo in Florence collects all of Galileo's student manuscripts, and the first study of these manuscripts is given in Galilei et al. (1942).

From the timing of the 15 stations listed in Fig. 3, it is clear that the first four, from Smirne (Izmir) to the Marmara Sea, were done as in a modern oceanographic survey. The stations from Toppana to "The Fanali" and at "Besiktas" were carried out while Marsili was in Istanbul, and they can be called monitoring stations. The station locations in the Istrian Peninsula and Venice were carried out in the return journey. Thus the first oceanographic investigation in the history of science is composed of 4 stations from an oceanographic survey and 11 from monitoring stations.

The digital version of Marsili's table shown in Fig. 3, considering only the Aegean Sea, Marmara Sea, and Bosporus stations, is given in Table 1. The three stations in the Istrian Peninsula and in Venice were not studied because the measurements were probably done with a different set of instruments or a different methodology as no description of them are given in the treatise. Marsili probably wrote notes in the *Oriental Manuscripts*, but we could not find them at this time. Thus only a total of 12 stations and their measurements will be considered in this paper.

3. The 1679–80 density measurements

a. Data collection instruments

Marsili's experimental procedure for sampling seawater is described in the treatise: he indicates how to collect samples from different depths using containers closed by valves. He describes the use of "vessels" or "copper containers" equipped with valves guaranteeing that water samples collected from a certain depth did not mix with other water during transit through the water column. Marsili must certainly have been aware of Boyle's work (Hunter and Davis 1999), which was printed in a Latin version in Bologna in 1675. Marsili describes his sampling procedure as follows:

> I was likewise curious to investigate the inner and deeper parts; nor was this fruitless, as I used a vessel closed with a valve, which, having the use of it, I opened using a rope whilst it was still under the water.

This passage is proof of how Marsili had equipped himself with vessels closed by a valve that were attached to a rope so that they could be lowered into deep waters. Once the specified depth had been reached, Marsili speaks of "opening"' the valve, after which he would presumably close it. Whereas Boyle mentions two valves, both opening upward, Marsili refers only to a single valve. He thus probably used a slightly different type of vessel to that described by the English scientist. We can get an idea of the vessel closed by two valves by looking at the drawings of Hooke's water bucket (Deacon 1965; McConnell 1982) reproduced in Fig. 4. It is clear that Marsili's procedure is a practical translation of the idea expressed in Boyle's work, though it is not clear exactly what sampling technology Marsili used. Interestingly, to bring water up from below the sea level, an instrument working on the same principle as a pump was proposed to the Earl of Sandwich in his travels in the Mediterranean Sea. The idea of using a pump was subsequently abandoned in favor of a cylinder with a valve at each end (Deacon 1971).

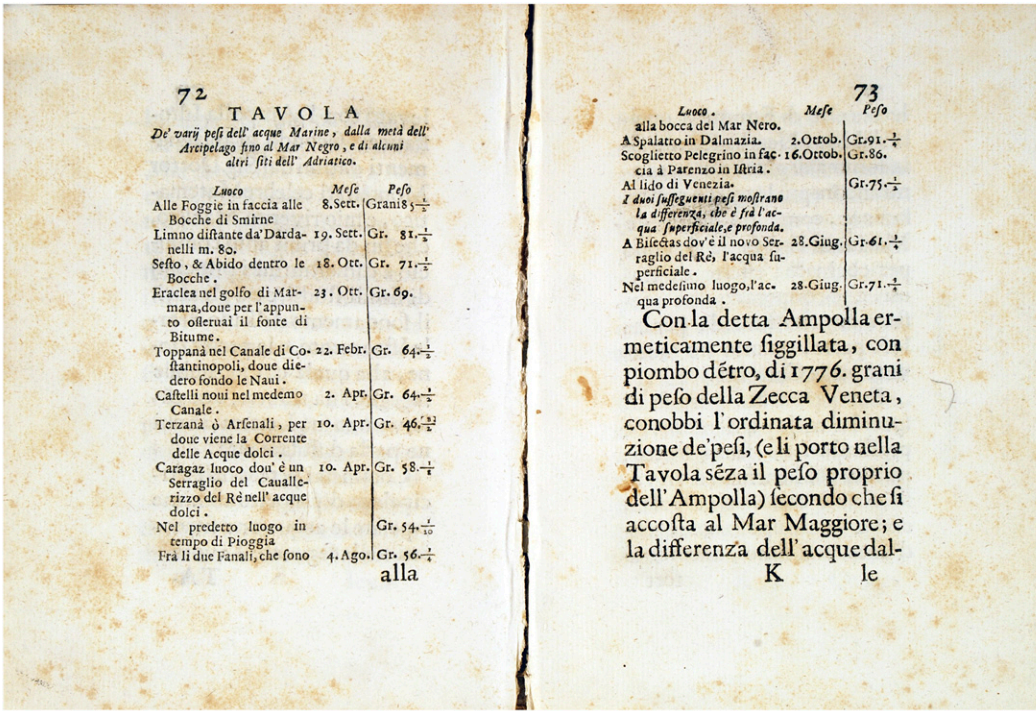


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TAVOLA

De' varij peſi dell' acque Marine, dalla metà dell' Arcipelago fino al Mar Negro, e di alcuni altri ſiti dell' Adriatico.

Luoco	*Meſe*	*Peſo*
Alle Foggie in faccia alle Bocche di Smirne	8. Sett.	Grani 85.$\frac{1}{2}$
Limno diſtante da' Dardanelli m. 80.	19. Sett.	Gr. 81.$\frac{1}{2}$
Seſto, & Abido dentro le Bocche.	18. Ott.	Gr. 71.$\frac{1}{2}$
Eraclea nel golfo di Marmara, doue per l'appunto oſſeruai il fonte di Bitume.	23. Ott.	Gr. 69.
Toppanà nel Canale di Coſtantinopoli, doue diedero fondo le Naui.	22. Febr.	Gr. 64.$\frac{1}{2}$
Caſtelli noui nel medemo Canale.	2. Apr.	Gr. 64.$\frac{1}{2}$
Terzanà ò Arſenali, per doue viene la Corrente delle Acque dolci.	10. Apr.	Gr. 46.$\frac{3}{4}$
Caragaz luoco dou' è un Serraglio del Cauallerizzo del Rè nell' acque dolci.	10. Apr.	Gr. 58.$\frac{1}{8}$
Nel predetto luogo in tempo di Pioggia		Gr. 54.$\frac{1}{10}$
Frà li due Fanali, che ſono alla bocca del Mar Nero.	4. Ago.	Gr. 56.$\frac{1}{4}$

alla

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Luoco.	*Meſe*	*Peſo*
A Spalatro in Dalmazia.	2. Ottob.	Gr. 91.$\frac{3}{4}$
Scoglietto Pelegrino in faccia à Parenzo in Iſtria.	16. Ottob.	Gr. 86.
Al lido di Venezia.		Gr. 75.$\frac{1}{2}$
I duoi ſuſſeguenti peſi moſtrano la differenza, che è frà l'acqua ſuperficiale, e profonda.		
A Biſectas dov'è il novo Serraglio del Rè, l'acqua ſuperficiale.	28. Giug.	Gr. 61.$\frac{3}{4}$
Nel medeſimo luogo, l'acqua profonda.	28. Giug.	Gr. 71.$\frac{3}{4}$

Con la detta Ampolla ermeticamente ſiggillata, con piombo dẽtro, di 1776. grani di peſo della Zecca Veneta, conobbi l'ordinata diminuzione de' peſi, (e li porto nella Tavola sẽza il peſo proprio dell'Ampolla) ſecondo che ſi accoſta al Mar Maggiore; e la differenza dell'acque dal-

K le

FIG. 3. Table of weights of sea water, from the middle of the Aegean Sea to the Black Sea, and at some other sites of the Adriatic, reproduced from Marsili (1681).

b. Measurement methodology

At all the stations where samples were collected, Marsili measured the specific gravity or "specific weight" of seawater, which in modern terminology is density normalized by a reference density. Marsili's initial scientific questions were concerned with salinity measurements since this was clearly a distinctive property of seawater with respect to other natural waters. However, he followed the 1674 recommendation of Boyle (reported in Hunter and Davis 1999):

> Wherefore I thought it would be more satisfactory to examine the sea-water by weight than by taste.

The laboratory measurement apparatus used by Marsili to analyze the collected water samples consisted of a hydrostatic ampoule, which was suspended in the fluid to be measured. Figure 5 shows examples of ampoules (also called "spherical aerometers") used at the time of Marsili, although we do not have records of the specific ones he used.

TABLE 1. Marsili (1681) stations and measurements translated from the original manuscript table of Fig. 3. Stations where reconstruction to modern units was not possible are not reproduced. Columns indicate, from left to right, locality of Marsili's measurement and the present-day name of location, Marsili sampling date, and weight in grains of the rings added to the ampoule.

Marsili name of location (and current name)	Marsili station date	Weight of rings (grains)
1) Aegean Sea, entrance of the Gulf of Smirne (İzmir)	8 Sep 1679	85.5
2) Aegean Sea, Lemnos, 80 miles from Dardanelles (Lemnos)	19 Sep 1679	81.5
3) Dardanelles, Sesto and Abido (Sestos and Abydos)	18 Oct 1679	71.5
4) Marmara Sea, Eracleo (Marmara Ereğlisi)	23 Oct 1679	69
5) Bosporus, Toppana (Tophane, north of the Golden Horn)	22 Feb 1680	64.5
6) Bosporus, Castelli novi (Rumeli Hisarı)	2 Feb 1680	64.5
7) Golden Horn, Terzana [Tersane (shipyard)]	10 Apr 1680	46.75
8) Golden Horn, Caragaz (Kara ağız)	10 Apr 1680	58.125
9) Golden Horn, Caragaz [Kara ağız (when it rains)]	10 Apr 1680	54.05
10) Bosporus, due Fanali alla bocca del Mar Nero [Rumeli Feneri (lighthouses)]	04 Aug 1680	56.25
11) Bosporus, Bisectas [Beşiktaş (surface)]	28 Jun 1680	61.75
12) Bosporus, Bisectas [Beşiktaş (deep)]	28 Jun 1680	71.75

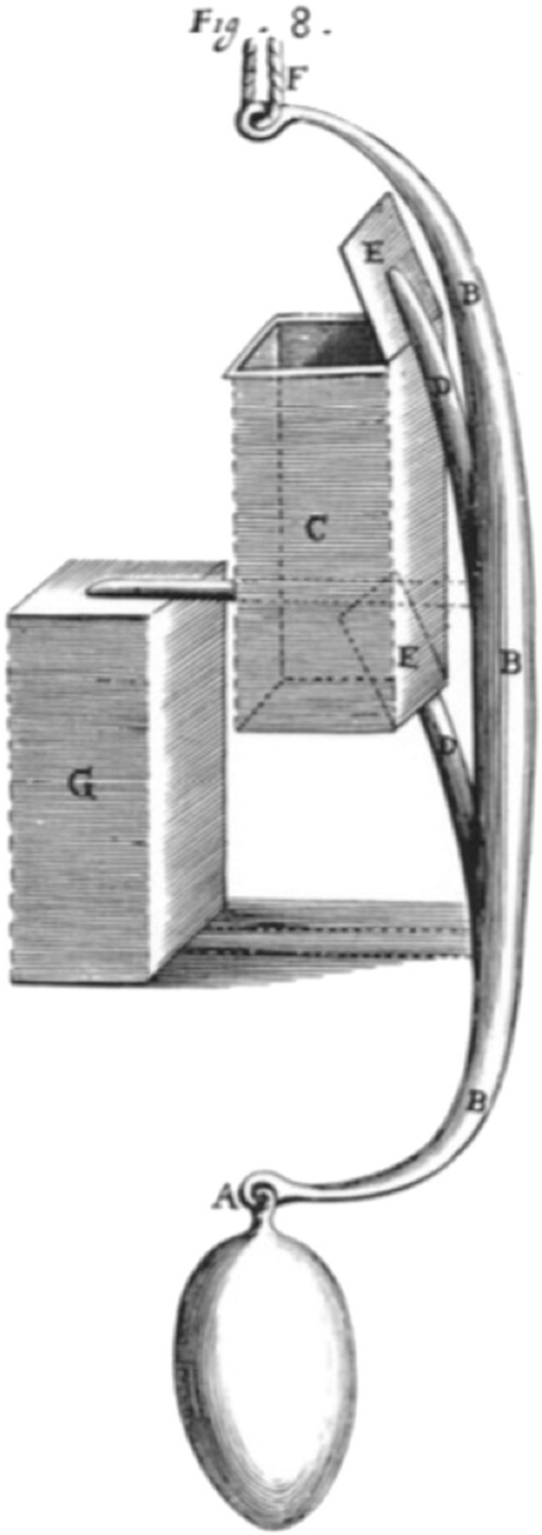

FIG. 4. Hooke's design of a water-sampling equipment (reproduced from Deacon 1971). Note the similarity of the instrument with the modern Niskin bottles.

The functioning principle of the hydrostatic ampoule is the Archimedes principle: a suspended object in a fluid will experience a force that is proportional to the weight of the fluid displaced. The ampoule measured this force using a different number of rings added to the ampoule neck until the ampoule was immersed in the fluid up to a certain level. The heavier the fluid, the more rings needed to be added.

The precision of the measurement depends on how accurately the weight of the different rings is measured and how accurately the ampoule can be submerged in the same way for the different waters. The instrument had been recommended by his teacher, the mathematician Geminiano Montanari (1633–87) of Padua University, as Marsili (1681) says in his treatise:

> The degree of saltiness I have determined experimentally with the Hydrostatic Ampoule according to the teachings of Doctor Montanari, renowned mathematician and my esteemed teacher, who showed me the principles of such studies, the foundations of the instrument, and the perfection that his noble spirit brought to it, in a letter that I have preserved.

A passage from Montanari, written in a posthumous essay published in the cultural journal *La Galeria di Minerva* (Montanari 1696), indicates the accuracy with which the sinking of the ampoule was recorded, and thus also the sensitivity with which the weight of the fluid was determined:

> These [rings] placed on the neck of the jar whilst it was immersed in a liquid little by little sunk it with their weight; operating this gradually, it was possible to see that just one thirty-second of a grain made it sink to the bottom, which weight being removed, it rose again to the surface. Thus, observing the quantity of grains, or rings, needed to sink it in one liquid as opposed to another [. . .] was far more precise observation.

It is believed that the letter that Marsili refers to in his treatise is the same as the one published in the posthumous essay. Montanari also uses a mathematical proportion to show that seawater was heavier than freshwater by 2% describing the following experiment (Montanari 1696):

> Let an hydrostatic ampoule have the weight of 300 grains in air and, when submerged in fresh water, require 50 more grains to sink to the bottom. The weight of the water displaced by the ampoule will be 350 grains. If we take again the same ampoule and put it in seawater it will require 357 grains to sink. Thus the seawater displaced by the ampoule will weight 357 grains. Thus the same ampoule will weight 350 and 357 in different waters, meaning that they are in the proportion of 2%. We will say then that the seawater is heavier than the fresh water by 2%.

FIG. 5. Hydrostatic ampoules (spherical aerometers) used to measure the specific gravity of fluids at the court of Ferdinando II de' Medici (1610–70), reproduced from the collection of Museo Galileo in Florence. The average diameter of the ampoules is about 4 cm and the maximum height is 8 cm. The functioning of such ampoules is described by Montanari (1696) and Davisi (1656).

Montanari probably discussed this extraordinary result with Marsili, who used exactly this methodology to carry out the specific weight measurements at the stations of Table 1.

To determine the specific weights of different water samples, Marsili had thus to measure the mass of the ampoule m submerged in the fluid with the rings, which can be written as follows:

$$m = m_a + m_{(\mathrm{rg})}, \tag{1}$$

where m_a is the mass of the ampoule in air and $m_{(\mathrm{rg})}$ is the mass of added rings. Measuring with the same ampoule a "reference" fluid mass, indicated by $m_R = m_a + m_{R(\mathrm{rg})}$, where now $m_{R(\mathrm{rg})}$ are the rings added to the ampoule when immersed in the reference fluid, we can estimate the proportion:

$$m/m_R = \rho/\rho_R. \tag{2}$$

The right-hand side of (2) is the specific weight that Marsili wanted to measure for different seawater samples.

The original measurements of Fig. 3 and Table 1 only report the "weights" of the rings added to the ampoule in units of "grains." Our aim is to reconstruct the density ρ in modern SI units using the following:

$$\rho = \rho_R m/m_R, \tag{3}$$

where ρ_R is the reference water density. We will estimate (3) using the values of m, m_R from Marsili's measurements in Table 1 and reconstructing the reference water density from the documentary evidence.

4. The 1679–80 density measurement reconstruction

In addition to the measurements in Fig. 3 three pieces of information are needed to determine the absolute density with (3): the weight of the ampoule in air, the reference water used by Marsili, and the conversion factors of "grains" into kilograms.

The weight in grains of the ampoule is given in the treatise: Marsili writes that it amounts to "1776 Venetian Mint grains." For the reference water Marsili probably thought of a type of water having constant characteristics at different times and locations so that its weighting with the hydrostatic ampoule would be reproducible.

Clearly freshwater is such "natural" reference water. In his treatise Marsili (1681) makes reference to rainwater, noting that a mass of rain water, considering it to be more uniform than that of any Country, and it was 23 Roman pounds and of an intrinsic weight, measured with the hydrostatic instrument, of 42 grains.

Unfortunately it is not possible from the treatise to ascertain whether the ampoule used to weight the rainwater was the same as the one used at the in situ stations. Searching through the *Oriental Manuscripts* we find mention of snow water: "to snow water I added 36½ grains." There are thus two possible reference waters and ring weights, 42 grains for rain and 36½ grains for snow water.

It is evident from the treatise that Marsili did not use the same grain units for the ampoule and the rings as for the seawater and the reference water. Marsili writes in the treatise about two other grain weight systems that were used at his time: the apothecary and commercial grain series of Bologna. Thus we need to assume that the weights measured by Marsili are transformed in modern units in the following way:

$$\tilde{m}_a = \alpha m_a, \quad \tilde{m}_{(\mathrm{rg})} = \beta m_{(\mathrm{rg})}, \quad \tilde{m}_{R(\mathrm{rg})} = \beta m_{R(\mathrm{rg})}, \tag{4}$$

where α and β are the conversion factors from grains to kilogram units that we supposed to be different for the rings and the ampoule. The conversion values for the different grain definitions are reported in Table 2, as defined by Zupko (1981).

Finally, the reconstructed absolute seawater density using (3) is given by

$$\rho = \rho_R \left[\frac{\alpha m_a + \beta m_{(\mathrm{rg})}}{\alpha m_a + \beta m_{R(\mathrm{rg})}} \right]. \tag{5}$$

We have used all possible combinations of the conversion factors and the different reference waters to estimate density with (5). Furthermore we assumed that either the rain or snow reference water has a present-day density of $\rho_R = 1000\,\mathrm{kg\,m^{-3}}$. Table 3 describes and shows eight different methods to combine the conversion factors and the two reference waters, keeping α fixed to the Venice mark series grain. Rainwater gives too small densities, irrespective of the combination of β values chosen. We thus conclude that the reference water was snow.

Figure 6 shows a plot of the reconstructed densities calculated using four possible combinations of unit conversions, keeping the snow water as the reference water and comparing them with the present-day density values. The latter were calculated from CTD profiles collected in April and October 2008, closest spatially and in time of the year to Marsili's measurements. The comparison with present-day values shows that method 8 (described in Table 3) gives the best agreement.

TABLE 2. Conversion factors of grains into kilograms from Zupko (1981).

Marsili measurement unit	Coefficients in (4)	Value of kg/grains
Venice apothecary pound series grain	α	5.23×10^{-5}
Venice mark series grain	α	5.17×10^{-5}
Bologna apothecary pound series grain	β	4.71×10^{-5}
Bologna commercial pound series grain	β	5.23×10^{-5}

The temperature, salinity, and density CTD profiles for a station close to the Beşiktaş site in three repeated surveys are compared with the Marsili converted values in Fig. 7, using methods 8 and 6, respectively. The comparison with present-day densities is striking: values are within 10%–20% of the modern-day surface measurements (Table 4). The measurements at depth have somewhat larger errors, but this could be due to the uncertainty regarding the depth of the historical measurement. Note that there are large seasonal variations in the Bosporus, as represented by the three profiles in Fig. 7, which could affect the comparison with the historical data. However, considering the methodology used, Marsili's measurements are considered to be remarkably accurate.

A further factor that could generate errors in the reconstructed density values is the temperature effect on the density, which was ignored by Marsili's experimental method. It is not clear how Marsili carried out his weighting measurements, if on land or on the ship. As explained in section 2, only four of the station samples were collected along the ship voyage while the remaining were collected during his stay in Istanbul and the return journey. If the weighting operation was done a certain amount of time after the collection, the samples could have changed their temperature, and therefore the density σ_t values would have been affected by a methodological error. Changes in temperature over the seasonal range (e.g., 5°–25°C) for a fixed surface salinity of 35 psu could change the σ_t by about 17% (UNESCO 1983). The percentage errors at each station (Table 4) show that temperature could be responsible for the differences between reconstructed densities and present-day values for some stations. In Boyle's essay, reported in Hunter and Davis (1999), the measurements of seawater specific gravity were certainly affected by large temperature errors since he tasked others to collect the samples far away from the laboratory.

TABLE 3. Conversion to density (kg m^{-3}) of the grain weights with (5) using different values of conversion coefficients from Table 2 for the 12 stations of Table 1. Method 1: rainwater as a reference and β equal to Bologna apothecary grain series conversion factor for numerator and denominator. Method 2: rainwater as a reference and β equal to Bologna apothecary grain series conversion factor for numerator and commercial grain series for the denominator. Method 3: as in method 1 but with snow water. Method 4: as in method 3 but with snow water. Method 5: rainwater as a reference and β equal to Bologna commercial grain series conversion factor for numerator and Bologna apothecaries conversion factor for the denominator. Method 6: rainwater as a reference and β equal to Bologna commercial grain series conversion factor for numerator and denominator. Method 7: as in method 5 but with snow water. Method 8: as in method 6 but with snow water.

		Density method							
Marsili station	Weight in grains	1	2	3	4	5	6	7	8
1	85.50	1019.8	1015.5	1022.4	1018.6	1028.6	1024.2	1031.2	1027.3
2	81.50	1018	1013.7	1020.6	1016.8	1026.4	1022	1029	1025.1
3	71.50	1013.5	1009.1	1016	1012.2	1020.8	1016.4	1023.4	1019.5
4	69.00	1012.3	1008	1014.9	1011.1	1019.4	1015	1022	1018.1
5	64.50	1010.3	1005.9	1012.8	1009	1016.9	1012.5	1019.4	1015.6
6	64.50	1010.3	1005.9	1012.8	1009	1016.9	1012.5	1019.4	1015.6
7	46.50	1002.1	997.8	1004.6	1000.8	1006.8	1002.5	1009.4	1005.6
8	58.13	1007.4	1003	1009.9	1006.1	1013.3	1009	1015.9	1012.1
9	54.10	1005.5	1001.2	1008	1004.3	1011.1	1006.7	1013.6	1009.8
10	56.25	1006.5	1002.2	1009	1005.3	1012.3	1007.9	1014.8	1011
11	61.25	1008.8	1004.5	1011.3	1007.5	1015.1	1010.7	1017.6	1013.8
12	71.25	1013.3	1009	1015.9	1012.1	1020.6	1016.3	1023.2	1019.4

Generally speaking, the comparison with modern density values highlights the fact that the experimental procedure reconstructed from the information contained in the documentary and bibliographical sources was indeed the one followed by Marsili. It also demonstrates Marsili's experimental ability as well as the reliability and robustness of his method. This proves that Marsili's experimental work should be considered as the first scientific oceanographic investigation carried out in the history of science aimed to collect in situ measurements of seawater density.

5. The reconstructed Bosporus Current inversion

In addition to the weight measurements, Marsili carried out the first direct current measurements in the Bosporus. Marsili refers to his interest in studying currents in the Bosporus as follows (Soffientino and Pilson 2009):

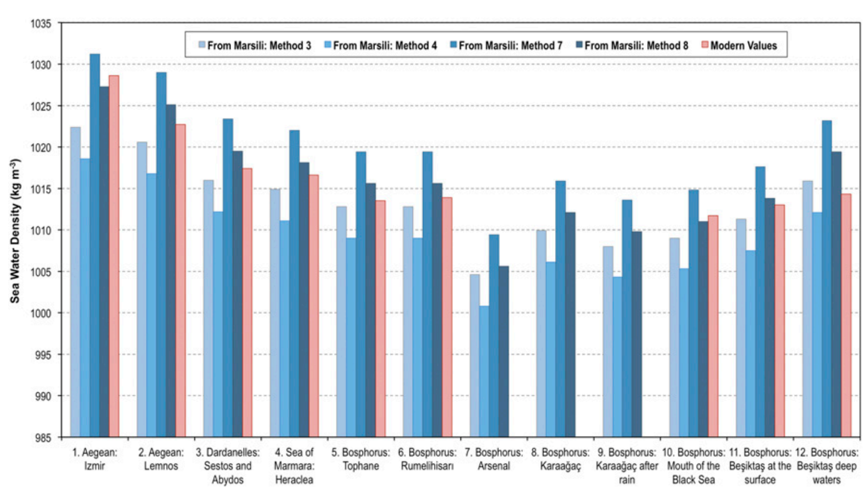

FIG. 6. Reconstructed density values as a function of the 12 Marsili stations (Table 1) with the reference density chosen as snow water and methods 3, 4, 7, and 8 (blue shades) and the corresponding values from modern measurements (red).

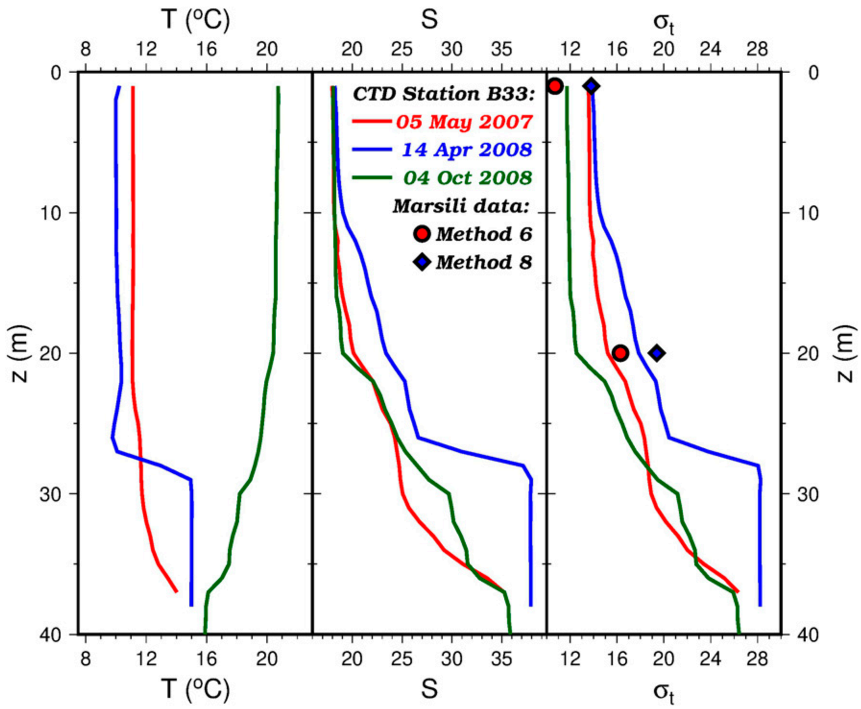

FIG. 7. Reconstructed surface and deep density values [method 6 (red dot) and method 8 (blue diamond)] for the Beşiktaş station (Tables 1 and 3). The profiles were taken in different months and years [May 2007 (red), April 2008 (blue), and October 2008 (green)] at a CTD station located at 41°02′N, 29°02′E, close to the Beşiktaş station of Marsili.

> In this great channel I found much to describe: its geographic location; its surface currents, and their velocities, their causes; the rise and fall of the mercury; the nature of the predominant winds; the flux and reflux; the current beneath that shall therefore call Sottana [...]; the difference in saltiness of the waters and its constituents.

The Bosporus Undercurrent was well known by the local inhabitants. Marsili had heard about the existence of an undercurrent from local fishermen (Deacon 1971), who had experienced the reversal of currents at depth with their nets submerged. The underflow was also referred to in the sixth-century note of Procopius of Ceasarea (Gill 1982; Deacon and Deacon 1982; Korfmann and Neumann 1985). However, nobody before Marsili had attempted to actually measure currents in the Bosporus.

Marsili constructed one of the first current meters, a wooden instrument with six paddles on an axle. Soffientino and Pilson (2005, 2009) reconstructed the size of the current meter paddles to be 33–43 cm long and 26–35 cm wide mounted on a 87–154-cm-long bar. The paddle rotation rate was counted by the number of revolutions per unit of time measured with the swings of a pendulum. Marsili counted 38 revolutions of the paddle in 100 swings of the pendulum. Soffientino and Pilson (2009) translated this measure into a current velocity of 0.97–1.2 m s^{-1}, which is very close to the surface current velocities found in the Bosporus.

In this paper we try to reconstruct the depth of the current inversion from a set of measurements described in the treatise. Marsili proceeded to obtain observational evidence of the expected current reversal at depth, using the technology shown in Fig. 8. He describes his instrument as follows:

TABLE 4. Estimated percentage errors between reconstructed density from Marsili ρ_M (method 8 in Table 3) and present-day densities ρ_T at the 12 stations of Table 2. The percentage error is computed by $\epsilon = |\rho_T - \rho_M|/(\rho_T - 1000)$.

Marsili station	Density error (%)
1	5
2	11
3	12
4	9
5	16
6	12
7	—
8	—
9	—
10	6
11	6
12	35

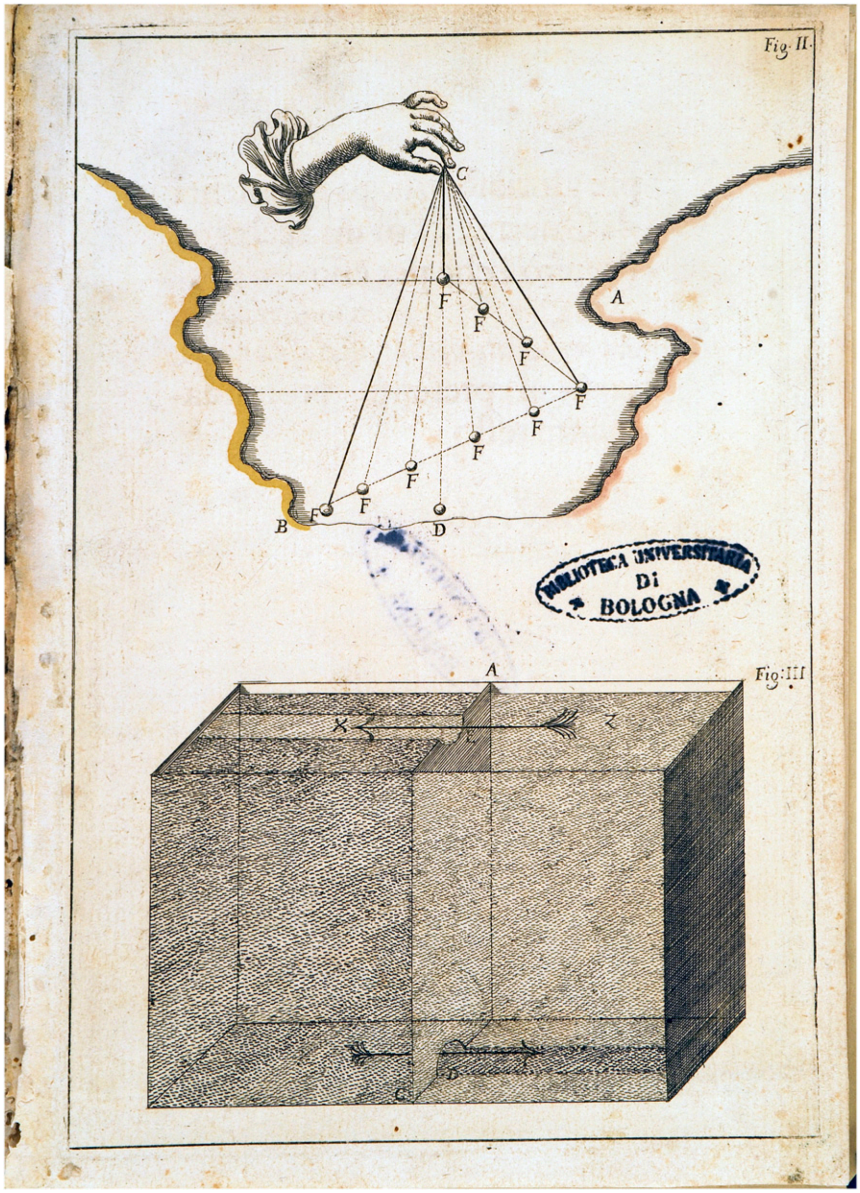

FIG. 8. The drawing, reproduced from Marsili's treatise, contains two frames: the first one is the demonstration of the principle for the measurement of inversion of the currents with white markers on a "rope," and the second is the description of the laboratory experiment carried out to explain the current inversion in the Bosporus.

> I began to investigate this phenomenon with instruments made of rope and pieces of cork painted white, so that they could be seen to an adequate depth and thus indicated the direction of the current by the way the rope bent.

By visually observing the relative horizontal displacements of white markers fixed on a rope lowered into the water, he found the depth of the reversal of the currents to be between 8 and 12 "Ottoman paces." We have tried to convert the Ottoman paces into modern units and then compare these with measurements from modern current profiles.

There are two ways to transform the length of the Ottoman pace into meters. The first is to find somewhere in what Marsili wrote a term in Ottoman Turkish that Marsili himself translates with pace. The second is based on the hypothesis that Marsili used the expression Ottoman pace to translate a correspondence between an Ottoman unit of measurement and a unit called a pace, which was in use in Italy at that time. The first conjecture is supported by a handwritten note in the *Oriental Manuscripts* that provides conversions of various Ottoman measures of length into lengths belonging to the systems in use in Bologna and Rome. In particular he writes the following:

> The Turkish architects measure [is] called Asin, pace, and they divide it into eight parts and call them [. . .]. This is precisely 6 Roman palms and 4 Bolognese feet.

The equivalence between lengths measured in Roman palms and Bolognese feet enabled us to calculate that the Arşın (the Asin in the treatise) was equal to 1.52 m. Arşın is typically the length of a footstep or pace (implied by the original Arabic word, meaning "the projection of a walker on Earth"), and local conversion from Ottoman measurement units specifies it as either 0.76 or 0.68 m, typical of a single human step. However, Marsili mentioning a similar unit of one eighth of an Arşın implies that the Arşın used at the time of Marsili may have been a pair of footsteps rather than a single one (i.e., 1.52 m).

The second hypothesis is based on the existence of the other Ottoman measurement unit, the Kulaç, which has comparable length values to certain values of the pace in use in Italy, particularly in Bologna, Rome, and Venice. The Kulaç is equal to 1.895 m, and it is translatable as "fathom" in Italian conversion charts. However, the Kulaç was a commonly used measure in Istanbul at the time of Marsili, so it is the value that we retained. Using both the Arşın and the Kulaç as the translation for pace, the current inversion depths measured are listed in Table 5. Comparing them with present-day measurements along the Bosporus (Özsoy et al. 2001; Gregg and Özsoy 2002), an example of which is shown in Fig. 9, we argue that the correct conversion unit is the Kulaç because it provides deeper values of the inversion, which appear closer to the present-day values of about 30 m near Beşiktaş (between 5- and 10-km distance along the cruise track in Fig. 9).

TABLE 5. Current inversion depth converted into meters using two possible units corresponding to the "Ottoman pace" reported by Marsili (1681).

Ottoman paces	Converted from the Arşın (meters)	Converted from the Kulaç (meters)
8	12	15
10	15	18
12	18	23

6. The laboratory experiment to verify the two-layer flow in the Bosporus

From the experimental evidence of the surface and deep seawater densities at Beşiktaş and the measured current inversion depth, Marsili provided a hypothesis on the cause of such currents. He postulates that "the cause for this phenomenon [two currents, opposite in direction, one above the other] is that what is heavy displaces that which is lighter, in fact I found that one of these two waters is lighter than the other."

From his observations of the water "specific gravity" at the surface and at depth, Marsili formulated a well-known physical principle of modern oceanography, which forms the basis of the two-layer exchange flow dynamics at the Bosporus (Gill 1982). To demonstrate the validity of the theory, with the philosopher Luc'Antonio Porzio (1639–1723) he organized the experiment illustrated in Fig. 8. This laboratory experiment—a total novelty for his day—confirmed the theory explaining the existence of two opposite currents in the Bosporus.

Marsili describes how, by filling the two sides of a water vessel separated by a partition, with water on one side taken from the undercurrent and on the other from the surface waters of the Bosporus, it was possible to show the dense water on one side flow toward the other side when the bottom hole on the separator plate was opened, while the surface waters flowed in the opposite direction through the surface opening in the plate, in compensation of the water volume carried by the deep flow. The result of the experiment irrefutably showed that the relative motion of the dense and less dense waters in opposite directions results from the pressure gradient derived from different densities of the waters on the two sides. The hypothesis Marsili had formulated based on the observations of weights of seawater that varied along the strait, combined with the observations of two-way exchange currents in the Bosporus, was thus definitively confirmed.

7. Discussion

In this paper we have reported on the first observations at sea carried out in the history of oceanography where precise reporting of location, time, and measurement values are given at stations along a cruise path and at fixed positions. Seawater samples were collected using a vessel submerged at different depths, and the water samples were analyzed in terms of specific gravity or relative density determined by high precision measurements. *Osservazioni intorno al Bosforo Tracio* (Marsili 1681) provides the first accurate, scientifically quantitative observations of ocean densities, current amplitude, and current inversion depth in the Bosporus. Marsili was the first to use the concept of a "reference" water, which enables density comparison of seawater at different locations at sea. The general concept of "universal measure" or "reference measure" was introduced in 1675 by T. L. Burattini (1617–80) in his treatise (Burattini 1675), but Marsili was the first one to implement

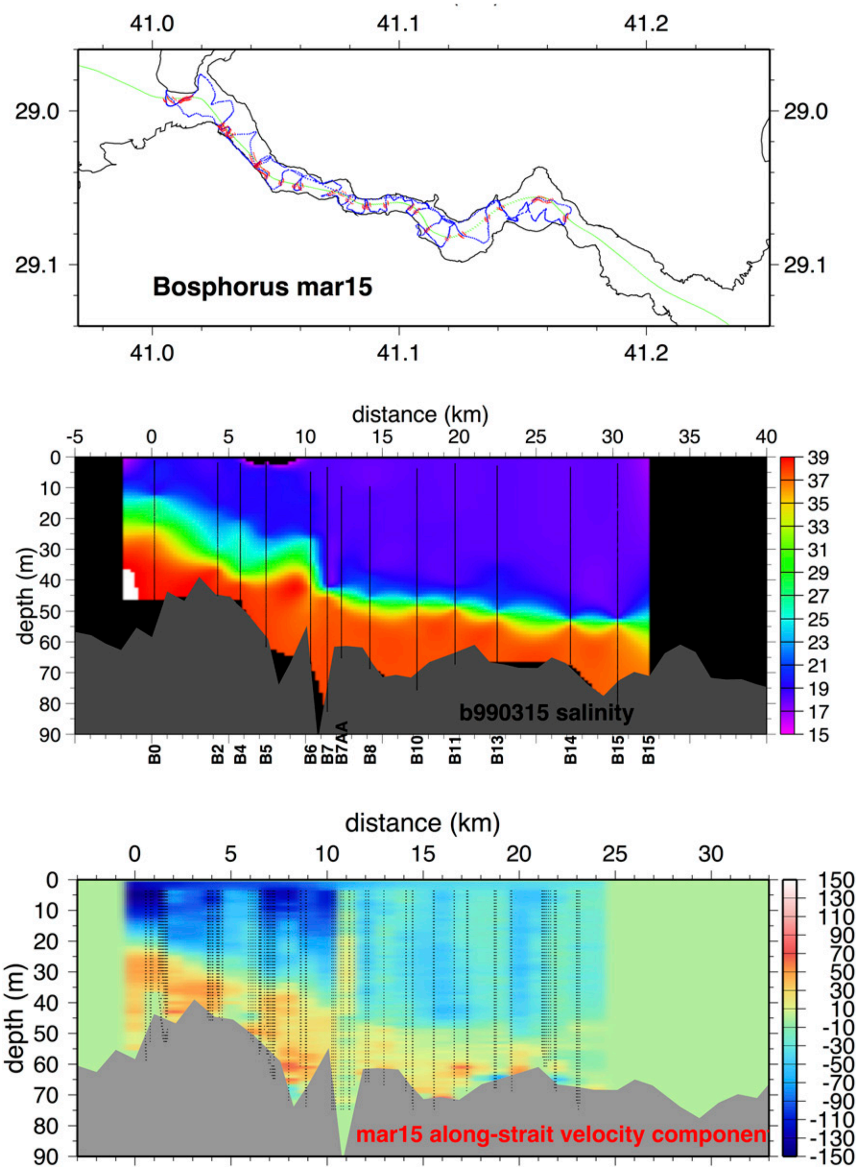

FIG. 9. Continuous measurements along the cruise track of Research Vessel (R/V) BILIM through the Bosporus on 15 Mar 1999. (top) Zigzag pattern of the ship trajectory (blue), the thalweg (green), and stations (red). (middle) Salinity (psu) along the thalweg. (bottom) Current components (cm s^{-1}) along the thalweg.

it in an oceanographic investigation. The use of snow water as a reference water allowed us to reconstruct absolute density at the stations and compare them with modern measurements.

Marsili established two important conceptual paradigms for the new field of oceanography. The first one was that accurate ocean measurements could enable conjectures to be made with confidence to explain underlying natural processes. The second was the need to conceive a theoretical model from basic physical principles and demonstrate the hypothesized mechanisms through a crucial experiment in the laboratory [nowadays carried out mainly by model simulations (e.g., Sözer and Özsoy 2017), in the case of the Bosporus].

It has been said that Marsili's personal encounter with the Bosporus played a central role in his discoveries, since in this relatively small but accessible channel, in situ measurements were easier to carry out than in any other parts of the world's oceans (Soffientino and Pilson 2005). On the contrary, the Gibraltar currents were not understood as a two-layer flow until the mid-nineteenth century, owing to the lack of reliable measurements. Despite the availability of Marsili's treatise in Europe, Captain Spratt (1811–89) found no evidence of undercurrents in the Bosporus and Dardanelles, and he insisted that the fast surface currents ran over static water below (Deacon 1978).

Marsili's work was not used to solve the paradox of an apparently continuous inflow of water through the Strait of Gibraltar into the Mediterranean. Many hypotheses were offered to explain the fact that the sea level was not increasing despite the inflow. If the inflow was to be balanced by the net water loss by evaporation, this would have subsequently caused an increase in water density. Since this was not observed, the only feasible solution at the time was the existence of subterranean links between seas, following the circulation schemes provided by the Jesuit Athanasius Kirker (1602–80) (Fletcher 2011).

Some of these myths and orthodox views were fed by the lack of new experimental evidence, and they survived at least until the end of the nineteenth century, despite Marsili's ingenious discoveries and experimental work in the seventeenth century. It is from the measurements carried out by Carpenter (1872) and Wharton (1886, 1899) that the stationary-lower-layer hypothesis of Spratt was challenged. Later observations extending into the early twentieth century by Nielsen (1910) provided again evidence of the Bosporus Undercurrent flowing toward the Black Sea. Experiments providing snapshots of water properties and currents for the whole of the Bosporus were carried out in 1918 and 1921 by Merz and Möller (1928), later interpreted by Defant (1961) as a confirmation of the age-old experiment of Marsili. Yet the earlier myth of Spratt was resuscitated by Pektaş (1953), who suggested that the Bosporus Undercurrent would occur only during part of the year, from August to March. Later studies by Çecen et al. (1981) failed to detect the outflow of the Mediterranean water into the Black Sea because of the insufficient sampling to locate the Mediterranean waters vein past the northern sill and into the narrow canyon on the Black Sea shelf (Latif et al. 1991; Özsoy et al. 2001).

Thus, it took more than two centuries to have a definitive evidence of the Bosporus Undercurrent after Marsili's exceptionally accurate measurements of density, current amplitude, and inversion depth.

Acknowledgments. This work is dedicated to our colleagues and friends who helped to start modern oceanography in the Mediterranean Sea, including our late colleagues Dr. Artur Hecht from IOLR, Haifa (Israel), Prof. Allan R. Robinson, Harvard University, Cambridge, and especially Prof. Ümit Ünlüata of IMS-METU, Erdemli (Turkey), to whom we owe the impetus for continued scientific studies of the Bosporus. Like Marsili, they too have been visionary scientists who contributed to internationally standardized and shared oceanographic data. The recent results presented for the Bosporus are only part of the voluminous archive of data collected on board the R/V BİLİM of the IMS-METU. The data presented here were collected in Investigations of Currents in the TSS (TURBO) carried out at the IMS-METU for the İstanbul Technical University Foundation and the Southern European Seas—Assessing and Modelling Ecosystem Changes (SESAME) research project.

APPENDIX

Short Biography of Luigi Ferdinando Marsili

Luigi Ferdinando Marsili was born in Bologna on 20 July 1658 into an aristocratic family and was the third of six children. His life can be divided into two parts, before and after 1682, when he started his military career. This article focuses on the most important work of the first part of his life, and thus these bibliographic notes focus on the period 1658–81.

His brother, Antonio Felice Marsili, erudite priest and man of letters, played a fundamental role in Luigi Ferdinando's cultural education, introducing him to the various scientific and literary academies that had been set up in the second half of the seventeenth century. Antonio Felice attempted to revitalize the University of Bologna by proposing the philosophical and scientific methods of Galileo and supporting various academies that were set up in 1660 in Bologna. Luigi Ferdinando Marsili's passion for natural history and scientific and mathematical methods can be traced back to the education he received from his brother.

Between 1660 and 1700, Bologna was a hotbed of reformist aspirations aimed at transforming the old systems of power and the way culture was managed. This was nourished by the work of key intellectuals of the Galilean school such as Marcello Malpighi (1628–94), Geminiano Montanari (1633–87), and Giovanni Domenico Cassini (1625–1712). Responsibility for Luigi Ferdinando's education was handed to Malpighi and Montanari, along with Lelio Trionferri, who was a professor of natural history. Thanks to their teaching, Luigi Ferdinando acquired a passion for science applied to solving concrete problems through field experiments and direct observations of natural phenomena. Between 1674, when he was sixteen, and 1677, Marsili traveled with his father to Venice, Padua, Rome, Naples, Pozzuoli, Livorno, and Lucca. He frequented intellectual circles in these cities, which gave him the opportunity to meet Giovanni Alfonso Borelli (1608–79), an outstanding scientist of this period. This long period of travel in his youth led Marsili to appreciate both the exchange of views between scientists and men of letters and the importance of directly observing natural phenomena.

Marsili returned to Bologna at the age of nineteen. Upon the death of his mother, he decided to go to Padua to study under Geminiano Montanari. He enrolled at the university there but never graduated. He returned once again to Bologna in 1679 and found it difficult to find any employment that satisfied him. In July 1679 he decided to accompany Pietro Civran, the Venetian ambassador to Constantinople. For 11 months he played the part of an erudite traveler, scientist, engineer, and military strategist, and he would remain in this role to the end of his life. During his time in Constantinople he set himself to learn Turkish and met physicians, geographers, and historians. He returned to Venice in 1680 after an adventurous overland journey through the plague-ridden Balkans. His father died at the end of 1680, and Marsili returned to Bologna only to move to Rome shortly afterward, where, in 1681, he and Luc'Antonio Porzio (1637–1715), the Neapolitan philosopher and naturalist, carried out a laboratory experiment to show the mechanism associated with the opposing currents in the Bosporus. Immediately afterward Marsili published the *Osservazioni intorno al Bosforo Tracio* in the form of a letter addressed to Queen Christina of Sweden (1626–89).

From 1682 to 1704 Marsili served the Holy Roman Emperor, Leopold I, as a soldier. He then returned to Bologna, where he continued to move in diplomatic circles and conduct scientific research in natural history, which led to him being invited to join the two most important scientific academies of the day: the French Academie des Sciences and the British Royal Society of London. He became a foreign member of the former in 1715 and a fellow of the latter in 1691, having been recommended by Newton (1642–1727). The time spent in Holland led to the publication of three works, *L'Histoire Physique de la Mer*, the *Danubius Pannonico-Mysicus*, and the *Stato Militare dell'Imperio Ottomano*, published in 1725, 1726, and 1732, respectively. The first two of these works, together with the *Osservazioni intorno al Bosforo Tracio*, laid the foundations of modern oceanography.

During the second period of his life, Marsili founded the Istituto delle Scienze, to which he donated all of his rich collection of scientific and learned material. The Istituto was inaugurated on 11 January 1712, and, in 1714, it was merged with the Accademia degli Inquieti (founded in 1690) to become the Accademia delle Scienze dell'Istituto di Bologna. Dedicated only to experimental sciences, medicine, and physics/mathematics, the Istituto delle Scienze and the Accademia delle Scienze led to an increasing awareness in Bologna of the theories of Malpighi, Descartes, and Newton and the doctrines of Copernicus, Galileo, and Bacon. The Institute's approach to the practical applications of research was also new and often groundbreaking. It soon created a new center of midwifery training and, following interest from Pope Benedict XIV (1675–1758), promoted surgery with the creation of a school specializing in the treatment of kidney stones. Luigi Ferdinando Marsili died in Bologna in 1730.

REFERENCES

Birch, T., 1756: *The History of the Royal Society of London, for Improving of Natural Knowledge from Its First Rise*. A. Millar, 534 pp.

Boschiero, L., 2007: *Experiment and Natural Philosophy in Seventeenth-Century Tuscany: The History of the Accademia del Cimento*. Studies in History and Philosophy of Science, Vol. 21, Springer, 251 pp.

Burattini, T., 1675: *Misura Universale*. Vilna, 32 pp.

Carpenter, W., 1872: Dardanelles and Bosphorus Undercurrent. *Nature*, **6**, 520–521, https://doi.org/10.1038/006520a0.

Castelli, B., 1660: *Della Misura dell'Acque Correnti*. Dozza, 61 pp.

Çecen, K., M. Beyazit, M. Sumer, S. Gucluer, M. Dogusal, and H. Yuce, 1981: Oceanographic and hydraulic investigations of the bosphorus: Section I, final report. Irrigation Unit of the Turkish Scientific and Technical Research Council Tech. Rep., 166 pp.

Davisi, U., 1656: *Trattato della Sfera di Galileo Galilei, con Alcune Pratticheinotrno a quella, e Modo di Fare la Figura Celeste, e i suoi Direttioni, Secondo la via Rationale.* Nicolo Angelo Tinassi, 297 pp.

Deacon, G. E. R., and M. Deacon, 1982: *Modern Concepts of Oceanography*. Hutchinson Ross Publishing Company, 416 pp.

Deacon, M., 1965: Founders of marine science in Britain: The work of the early fellows of the Royal Society. *Notes Rec. Roy. Soc. London*, **20**, 28–50, https://doi.org/10.1098/rsnr.1965.0003.

——, 1971: *Scientists and the Sea, 1650–1900: A Study of Marine Science*. Academic Press, 504 pp.

——, 1978: *Vice-Admiral TAB Spratt and the Development of Oceanography in the Mediterranean, 1841-1873*. National Maritime Museum, 74 pp.

Defant, A., 1961: *Physical Oceanography*. Vol. 2. Pergamon Press, 606 pp.

Fletcher, J. E., 2011: *A Study of the Life and Works of Athanasius Kircher,'Germanus Incredibilis': With a Selection of His Unpublished Correspondence and an Annotated Translation of His Autobiography*. Brill, 607 pp.

Galilei, G., P. Galluzzi, and M. Torrini, 1942: *Le Opere dei Discepoli di Galileo Galilei*. Barbera, 643 pp.

Gill, A. E., 1982: *Atmosphere-Ocean Dynamics*. Academic Press, 662 pp.

Gregg, M. C., and E. Özsoy, 2002: Flow, water mass changes, and hydraulics in the bosphorus. *J. Geophys. Res.*, **107**, 3016, https://doi.org/10.1029/2000JC000485.

Hunter, M., 2005: *Robert Boyle Project Occasional Papers*. Vol. 1. Robert Boyle Project, School of History, Classics and Archaeology, Birkbeck, University of London, 53 pp.

——, and E. B. Davis, 1999: *The Works of Robert Boyle*. Vol. 7. Pickering and Chatto, 638 pp.

Korfmann, M., and J. Neumann, 1985: Subsurface countercurrent in the Bosporus already known to 6th century A. D. Byzantine fishermen. *Ocean Dyn.*, **38**, 189–190, https://doi.org/10.1007/BF02328976.

Latif, M., E. Özsoy, T. Oguz, and Ü. Ünlüata, 1991: Observations of the Mediterranean inflow into the Black Sea. *Deep-Sea Res.*, **38A**, S711–S723, https://doi.org/10.1016/S0198-0149(10)80005-6.

Lovarini, E., 1930: *Autobiografia di Luigi Ferdinando Marsili Messa in Luce nel Secondo Centenario della Morte di lui dal Comitato Marsiliano*. Nicola Zanichelli, 264 pp.

Marsili, L. F., 1681: *Osservazioni intorno al Bosforo Tracio overo Canale di Costantinopoli, Rappresentate in Lettera alla Sacra Real Maestá Cristina Regina di Svezia da Luigi Ferdinando Marsili*. Nicoló Angelo Tinassi, 108 pp.

McConnell, A., 1982: *No Sea Too Deep: The History of Oceanographic Instruments*. Adam Hilger, 162 pp.

Merz, A., and L. Möller, 1928: *Hydrographische Untersuchungen in Bosporus und Dardanellen.* Mittler, 284 pp.

Montanari, G., 1696: Istruzione scritta gia' da tempo all'illustrissimo et eccellentissimo sig. Pietro Grimani dal Signor Geminiano Montanari, primo professore delle matematiche . . . sopra il modo di conoscere la differenza del peso de' fluidi fra loro. *La Galeria di Minerva overo Notizie Universali,* Girolamo Albrizzi, 213–225.

Nielsen, J. N., 1910: *Hydrography of the Mediterranean and Adjacent Waters*. A. F. Høst, 380 pp.

Özsoy, E., D. Di Iorio, M. C. Gregg, and J. O. Backhaus, 2001: Mixing in the Bosphorus Strait and the Black Sea continental shelf: Observations and a model of the dense water outflow. *J. Mar. Syst.*, **31**, 99–135, https://doi.org/10.1016/S0924-7963(01)00049-5.

Pektaş, H., 1953: Surface currents in the Bosphorus and the Sea of Marmara. *Hydrobiol. Res.*, **1**, 154–169.

Soffientino, B., and M. E. Q. Pilson, 2005: The Bosporus Strait: A special place in the history of oceanography. *Oceanography*, **18** (2), 16–23, https://doi.org/10.5670/oceanog.2005.38.

——, and ——, 2009: Osservazioni intorno al bosforo tracio overo canale di constantinopoli rappresentate in lettera alla sacra real maestá cristina regina di svezia da Luigi Ferdinando Marsilii. *Earth Sci. Hist.*, **28**, 57–63, https://doi.org/10.17704/eshi.28.1.m24qw2611176j35w.

Sözer, A., and E. Özsoy, 2017: Modeling of the Bosphorus exchange flow dynamics. *Ocean Dyn.*, **67**, 321–343, https://doi.org/10.1007/s10236-016-1026-z.

Stoye, J., 1994: *Marsigli's Europe, 1680–1730: The Life and Times of Luigi Ferdinando Marsigli, Soldier and Virtuoso.* Yale University Press, 368 pp.

UNESCO, 1983: Algorithms for the computation of fundamental properties of seawater. UNESCO Tech. Papers in Marine Sciences 44, 58 pp., http://unesdoc.unesco.org/images/0005/000598/059832eb.pdf.

Wharton, W. J. L., 1886: Report on the currents of the Dardanelles and Bosphorus. Admiralty Publ.

Wharton, W., 1899: Undercurrents. *Nature*, **60**, 316, https://doi.org/10.1038/060316b0.

Zupko, R. E., 1981: *Italian Weights and Measures from the Middle Ages to the Nineteenth Century*. American Philosophical Society, 339 pp.