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Review

Black Carbon and Other Air Pollutants in Italian Ports and Coastal Areas: Problems, Solutions and Implications for Policies

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Featured Application: The data and analysis can be applied to shipping emissions issues at five governmental levels: *local* (ports and port cities), *subnational regional* (port authorities), *national* (Italy and other countries), *international regional* (European Union and Mediterranean Sea coastal areas), and *global* (IMO).

Abstract: Ships' emissions of air pollutants pose problems for local and regional public health and agricultural production, as well as global climate change. The Italian government's endorsement in 2019 of the creation of a Mediterranean Emission Control Area is a reflection of increasing concern about the emissions. Also, ongoing developments in the International Maritime Organization and in the European Union add to the Italian government's maritime shipping agenda and increase its complexity and uncertainty. In that context, this review paper addresses two central questions: What are the consequences for human health and agricultural production of ships' emissions in Italian ports and coastal areas? How can their emissions be reduced? The approach to these questions is inter-disciplinary. It applies the results of studies in atmospheric chemistry and physics; maritime shipping engineering; public health; agriculture; economics; and international law and policymaking to assess current and prospective policy issues in Italy. The principal conclusions are that: (1) Black carbon emissions are threats to human health and agricultural production in Italy, as well as to the global climate. (2) It is important that black carbon emissions receive more serious attention in policymaking processes in order to reflect the significant analytic progress that has been made in terms of understanding the problems it poses and the technological and policy solutions. (3) There are cost-effective, emission-reducing measures that are readily available, as well as other measures needing more time before full-scale implementation. (4) Although existing multi-level governance systems pose complex analytic and policymaking challenges, they also offer opportunities to institute new policies with significant short-term and long-term co-benefits from reductions in emissions.

Keywords: ships' emissions; black carbon; Italy; ports; coastal areas; IMO; EU; Mediterranean ECA

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1. Introduction

Numerous scientific studies have found ample evidence that black carbon (BC) emissions, which are extremely small particles in soot from burning fossil fuels, including those of maritime shipping's diesel engines, pose significant threats to human health and agricultural production at local and regional levels, as well as to global climate change. However, the application of those findings in policymaking processes at many governmental levels has lagged behind progress in scientific research. Nevertheless, there are now BC-related emission-mitigating measures under active consideration in policymaking contexts at several levels of governance, and some have already been adopted for ports and coastal areas in several countries. This article reviews the scientific evidence, including the results of port case studies, and applies the evidence to a specific current agenda, namely maritime shipping emissions in Italian ports and coastal areas.

Ports and coastal areas in Italy are particularly appropriate subjects for research now because there is rising public concern about the effects of cruise ships' emissions on local air quality as well as other quality of life conditions (e.g., in Venice) and because of a wider national interest in air quality issues in other Italian ports and in the policymaking institutions of the European Union (EU) [1]. That agenda includes proposals for a regional Mediterranean Emission Control Area (Med ECA), which the Italian government has endorsed [2]. Black carbon emissions are on the agenda of the International Maritime Organization (IMO) at the global level [3]. A proposal to include international maritime shipping in the existing EU Emissions Trading System is on the agenda of the EU institutions in Brussels [4], and thus in European national capitals. Within Italy, maritime shipping issues are being addressed by the national government, of course, as well as regional port authorities and local port operators [5].

The paper addresses two central questions: What are the effects on human health and agricultural production of shipping's BC and other emissions in Italian ports and coastal areas? How can the emissions be reduced? The article analyzes current and prospective air pollution problems, and it assesses current policies as well as options for the future. The damage to public health and agricultural production is done by ships' as they pass along coastal areas and as they enter and leave ports. In addition, there are emissions while they are anchored or tied-up for loading and unloading, and there are also emissions from on-shore transportation systems and material-handling operations.

A common element of these emissions is that they are emitted by large diesel engines. The emissions thus include black carbon and other air pollutants, such as sulfur and nitrous oxides, which are known to cause human health [6–17] and agricultural production problems [7,8,18–21]. A challenge of the present study is thus to apply this knowledge to the activities of maritime shipping in Italian ports and coastal areas and to assess technologies and policies to reduce the emissions.

Shipowners and operators with headquarters and registrations in many countries have been changing their ships, their equipment, and their operations in order to reduce their emissions [9]. These changes are partly responses to changing technologies, and partly responses to changes in government policies at many levels of governance. In order to understand the air pollution policy issues and options facing Italian governmental authorities and shipping industry executives, the article therefore considers the core issues in the context of the Italian, Mediterranean, European and world shipping industry, and governmental policies at several levels of governance-local, intra-national regional, national, international regional and global.

The analytic approach of the article is inter-disciplinary, inclusive, eclectic, and integrative; it draws upon data and other materials from atmospheric chemistry and physics, public health, agricultural production and climate science, as well as maritime shipping engineering and economics, and international law and policymaking. These materials establish the basis for the analysis of maritime shipping's air pollution problems and their threats to Italian public health and agricultural production. There is also information about the technological opportunities to reduce emissions. In addition, the article draws upon information about issues and policy options at many levels of governance. The article thus seeks to transcend traditional analytic boundaries of scientific and policy studies to achieve a more encompassing and integrated understanding of problems and solutions.

Fortunately, there are detailed empirical case studies of emissions in Italian ports, and they are drawn upon to reach conclusions about ships' emissions as national issues in Italy. There are, in addition, closely related studies of other countries, regions, and global-level questions, which also provide relevant evidence while addressing Italian issues.

The analysis thus includes data and analyses of:

- the composition and volumes of ships' emissions and their effects on public health and agricultural production, as well as climate change;
- variations among 'classes' of ships in their emissions, equipment, and operations;

- ports, including the location of the ports in relation to human populations and agricultural production regions, as well as types and volumes of ship traffic;
- governmental policies in Italy, the European Union, the International Maritime Organization (IMO), and a proposed Mediterranean Emission Control Area (ECA) that is on the agenda in Italy and other Mediterranean countries.

It should be further noted that the article was being written in late 2020 during the coronavirus pandemic, which, of course, had significant consequences for maritime shipping activities in Italy. Fortunately for the present analysis, data for 2019 that were available for many of the analytic issues were not affected by the pandemic. The year 2020 was clearly a transitional year in many respects for international maritime shipping, including especially the cruise ship segment. As for 2021 and beyond, there are likely to be substantial increases in ship traffic, including in Italy, though it might take several years to resume its previous trajectories. Meanwhile, there continued to be progress in the development and adaptation of many marine technologies, and there was also continuing discussion about new regulatory policies at many levels of governance, including the EU in particular [4,22–24].

Despite these many changes and uncertainties, it is nevertheless feasible to address the two key questions: What are the effects on human health and agricultural production of shipping's BC and other emissions in Italian ports and coastal areas? How can they be reduced?

1.1. Maritime Emissions and Their Effects

Table 1 presents a summary of the kinds of maritime ships' emissions in terms of their chemical composition and their effects on climate change, human health, and food production [25–31].

Table 1. Maritime Ships' Emissions.

Emissions	Comments
Greenhouse *Gases* (GHGs)	
Carbon Dioxide (CO_2)	Principal contributor to global warming
Methane (CH_4)	Second leading global warming *gas* after carbon dioxide
Nitrous Oxide (N_2O)	Potent long-term greenhouse gas
Halogenated Hydrocarbons	Potent global warming gas per ton, but limited use in refrigeration
Other Gases	
SO_x	Contributes to sea and land acidification; damages human health, buildings, and other structures; is a global *coolant*
NO_x	Contributes to sea and land acidification and ozone formation; eutrophication; human health problems
Volatile Organic compounds	Contributes to formation of ozone
Particles	
Black Carbon (BC)	Second leading contributor, as particle matter, after carbon dioxide; also has detrimental effects on human health and food production
Organic Carbon (OC)	Global *coolant*, co-pollutant in soot with black carbon, consists of carbon combined with hydrogen, oxygen, sulphur or nitrogen
Elemental Carbon (EC)	Sometimes referred to as 'pure carbon', but earlier definitions were more complicated
Salt and various mineral particles	They have various health and environmental effects, but are not a direct concern of this paper

Black carbon is emphasized in the present article because BC emissions are:

- The second leading contributors to global warming, equaling about 55% of carbon dioxide's contribution, and more potent per ton than carbon dioxide by a factor on the order of thousands of times over a 20-year period [26,27].
- A principal contributor to the global public health impacts of air pollution and the most important component of particulate matter pollutants, and they are especially important in large urban areas [6–16].
- The greatest contributor per ton to the damages to food crops caused by climate change pollutants, and an especially threatening air pollutant for crops near coastal areas [7,8,18–21].

Two combinations of pollutants complicate the net effect of reducing some kinds of emissions. As noted in Table 1, one of the many types of emissions from maritime diesel engines is organic carbon (OC), which is a global *coolant*. The ratio of BC to OC in the ships plumes is therefore important because of ratio of BC to OC and because of different impacts. However, since the BC:OC ratio for large marine diesel engines is about 9:1, this particular combination is not a serious complication in maritime BC emissions analysis or policymaking [28]. See the paper Annex for further details about this issue.

Another complication of the multiplicity of maritime emissions is that sulfur dioxide is also a global *coolant*. Thus, reducing ships' emissions of sulfur dioxide emissions by reducing the sulfur content of their diesel fuel has the unintended consequence of reducing emissions of a global *coolant*. Moreover, reductions of the sulfur content of marine fuels may *increase* the black carbon content [27].

For more on the chemical and physical basics of BC, see Box 1.

1.1.1. Box 1. Black Carbon Basics

Black carbon (BC) is extremely small particles that result from burning fossil fuels and biofuels [7,8,17–21]. Diesel engines and coal-fired power plants are common sources of BC; so are wildfires and wood-burning cook stoves. BC is the second most important contributor to global warming; its share is equal to slightly over one-half of carbon dioxide's contribution. BC is also a major contributor to worldwide human health problems; it is a direct cause of several million deaths per year. BC emissions also destroy hundreds of millions of acres of grain crops each year [18–21].

BC is 'very fine particulate matter,' with a diameter 50 to 70 times smaller than a human hair. BC is classified as 'PM_1', because its diameter is equal to or less than one micron. (To mix metric and non-metric measures, there are about 25,000 microns in an inch.) BC is often only indirectly and implicitly measured as one of the components of $PM_{2.5}$, which is now often used as the standard unit of measurement in public health studies, and sometimes as one of the components of PM_{10}, which was previously the standard unit for public health studies. In any case, BC is present in measurements of PM_1, $PM_{2.5}$, and PM_{10}. Unfortunately, the precise amount of BC in each of these common measurement units varies; however, in each case, BC is the component that is the most damaging to human health. This feature of BC is particularly important in the discussion of the linkage of BC emissions to the incidence and severity of the coronavirus epidemic, as discussed in Box 2. As an 'aerosol,' BC can float through the air thousands of miles, or it can land on a surface within a few meters of the source. While in the air, particles of BC absorb solar energy and thus contribute to global warming. If BC falls to earth as a deposition on snow or ice, it reduces the capacity of snow and ice to reflect solar energy back into the atmosphere, that is, their 'albedo' effect. In short, BC poses local, regional, and global problems.

Black carbon is sometimes equated with 'soot,' but that is not accurate because soot contains other chemicals in addition to BC. However, since BC is an important component of soot, it is often necessary to clarify whether any particular reference to 'soot' either explicitly or implicitly includes BC in the scope of the analysis. Some studies of 'soot' report results separately for BC along with soot's other components.

Finally, note that black carbon is not carbon black. Searches on the internet or elsewhere for 'black carbon' may produce results for 'carbon black.' If so, ignore them because carbon black is a manufactured product used to make things like vehicle tires black; carbon black is not BC. (A formal definition and measurement issues are discussed further in the Annex.)

1.1.2. Air Pollution in Italy

As for $PM_{2.5}$ and thus implicitly BC, Italy has had an air pollution problem relative to most other European countries for at least two decades (see Table 2) [32]. Over the period from 2000–2017, Italy's national average PM2.5 levels were consistently 20% to 30% above the EU average, and consistently higher than the levels of the other large population European countries. Yet, its absolute levels did decline by 2017 to 84% of what they had been in 2000. Finally, in terms of the most important comparison, namely the Italian average compared with the recommended maximum of the WHO, Italy has improved from 2.0 in 2000 to 1.7 in 2017, but, of course, that is still 70% above the WTO guideline. Italy's air pollution problem, therefore, is surely less than it was two decades ago, but it is still substantially worse than most European countries and significantly worse than the internationally recognized standard for 'safe' levels.

Table 2. Italy's Levels of $PM_{2.5}$ over the Period 2000–2017 Compared with Other European Countries.

	2000	2005	2010	2015	2016	2017
Italy	19.69	19.42	19.00	17.68	16.34	16.50
France	14.78	14.78	14.84	12.83	11.98	11.96
Germany	15.05	14.58	15.38	12.98	12.09	12.09
Spain	12.11	11.96	11.73	10.67	9.90	9.91
European Union EU-28 pre-UK departure	16.18	15.99	16.00	13.97	13.08	13.09
Italy						
cf. EU	1.2	1.2	1.2	1.3	1.2	1.3
cf. WTO guidelines	2.0	1.9	1.9	1.8	1.6	1.7
cf. Italy 2000		99%	96%	90%	83%	84%

Compared with the rest of the world, an extensive analysis [33] of 180 countries' levels and growth rates in their air quality and emissions of BC and six other air pollutants found that Italy's rankings across the seven pollutants ranged from 24th to 65th in the world, down from the best scoring countries. More than 20 European countries fared better than Italy, and many tied for number 1. In contrast, Italy's 2005–2014 growth rates in emissions of BC, N_2O and NOx put it among the three worst countries in the world. Although maritime shipping's contributions to the national total were not itemized, they were substantial, and they were concentrated in densely populated port and coastal areas, as discussed below in more detail.

In addition to these decadal trends in air pollutants prior to 2020, the threat to human health from such air pollutants has been further highlighted by the coronavirus pandemic in 2020. Although the findings of early studies during the pandemic have been treated as preliminary, there are nevertheless clear consistencies in the patterns found in Italy and other countries. See Box 2.

1.1.3. Box 2. Links between Black Carbon Emissions and the Coronavirus Pandemic in Italy

There were already many studies in 2020 exploring links between levels of air pollution, including black carbon (BC) emissions in Italy, and the incidence and outcomes of cases of the coronavirus [34–41]. Evidence from initial studies indicates that black carbon (BC) increased the severity of the coronavirus pandemic in three ways: (1) BC makes people more susceptible to getting the virus because of their weakened underlying health conditions caused by BC air pollution. Specifically, when BC particles are taken into the body through routine breathing of BC-polluted air, the extremely small size of the BC particles facilitates their penetration into lungs. The lung damage thus becomes a pre-condition that increases the likelihood of the person contracting the coronavirus. (2) Among people who get the virus-from whatever source-BC exacerbates the seriousness of the damage to patients' lungs because their lungs are already weakened by breathing BC-polluted air. This effect on lungs, in turn, affects coronavirus patients' prospects for short-term and long-term recovery. (3) Airborne particles of BC transport the virus beyond localized outbreaks and thus increase the geographic extent of the pandemic.

Many studies have focused on Italy because of its relatively high rate of deaths per 100,000 population (the rate was 59.02 as of 19 September 2020) and because of the role of cases early in the public phase of the pandemic in Europe.

As research continues to progress in Italy and other countries in the coming months and years, the results should explicitly be brought to bear on the central issues of the present article, including how much of a problem ships' emissions are for public health. Inference from the preliminary evidence thus far suggests that ships' emissions, including their black carbon emissions in particular, have contributed to the extent and severity of the coronavirus pandemic and can reasonably be expected to do so again in the future.

In any case, it is useful to be aware of the global context of the problems addressed here for Italy. Accordingly, a report by the World Health Organization [17] summarizes the evidence about the effects of fine particulate matter ($PM_{2.5}$) including black carbon on health as follows:

The WHO 'estimates that around 7 million people die every year from exposure to fine particles in polluted air that penetrate deep into the lungs and cardiovascular system, causing diseases including stroke, heart disease, lung cancer, chronic obstructive pulmonary diseases, and respiratory infections, including pneumonia. Ambient air pollution alone caused some 4.2 million deaths in 2016. WHO recognizes that air pollution is a critical risk factor for noncommunicable diseases (NCDs), causing an estimated one-quarter (24%) of all adult deaths from heart disease, 25% from stroke, 43% from chronic obstructive pulmonary disease, and 29% from lung cancer. $PM_{2.5}$ includes pollutants, such as sulfate, nitrates and black carbon, which pose the greatest risks to human health.'

The relatively high levels of $PM_{2.5}$ emissions in Italy are notable in an analysis by the European Environment Agency [42], which found that Italy was in the second most deadly category of European countries, with an estimate of 854–1110 deaths per 100,000 population in 2015 attributable to $PM_{2.5}$. Although most countries in eastern Europe were higher, Italy's death rate was higher than the levels in France, Germany, Spain and other countries in western Europe.

1.1.4. Italian Ports

Data about ship activity and emissions in Italy's ports are available from a variety of sources, but the lists of ports in each data set vary considerably. Thus, although it is possible to develop summaries of the overall system of ports and detailed data about maritime activity and emissions in many individual ports, it is not possible to present a single comprehensive table with data for all indicators for all of the ports. What follows, then, is a series of tables from a variety of sources, which altogether add up to a compilation that allows observations about the ports in relation to the focal concerns of the paper [43–54].

The principal international ports of Italy are organized into 15 regions, each with a core network port and most of the regions with one or more of 18 additional ports. Altogether, the study focuses on the 33 international ports in the formally organized Italian national port system, with their highly varying sizes and mixes of types of ships.

In terms of the aggregate indicator of 'vessels in main ports,' each year over the period from 2013 through 2018, Italy had the second largest number in Europe after Greece; Italy has been the leading 'seaborne passenger' country in Europe for several years. In 2018 Italian ports processed nearly 85 million passengers on cruise ships and ferries combined. Most of these were ferry passengers [55].

Cruise ship traffic is, of course, economically significant to the ports and is experiencing increasing political attention because of its conspicuous physical presence in ports and along coasts. Cruise ship ports in Italy are particularly noteworthy for the volume of activity in them, especially in the context of the Mediterranean Sea.

Italian ports' cruise activity equaled about 40% of all Mediterranean cruise traffic in 2019; altogether, Italian ports processed 23.8 million cruise passengers and 8959 port calls in 2019 [56]. Four of the Italian ports were among the top ten in the Mediterranean area as measured by number of passengers and port calls. Civitavecchia, which serves Rome, was second in the Mediterranean, after number 1, Barcelona, Spain. The specifics for the top four Italian ports are in Table 3, where large increases from the previous year are evident.

Table 3. Cruise Port Activity in Italy's Top Four Cruise Ports.

Port	Number of Passengers Millions (2019)	Change from 2018 to 2019	Number of Port Calls	Percent Change from 2018 to 2019	Rank among Top Ten Mediterranean Ports
Civitavecchia	2.56	+4.9	827	+8.8	2nd
Venice	1.55	['stable']	500	['stable']	5th
Genoa	1.35	+33.5	268	+17.0	6th
Napoli	1.23	+14.6	456	+20.3	7th

Note that a confusing feature of 'passenger' counts is that passengers are usually counted twice on each trip, first when embarking and then when debarking, as in Tables 3 and 4 [32,55]. However, there are also data sets where this 'double counting' is avoided. Thus, while some data sets report on the order of 20 million cruise passengers per year in Italy, others report about half as many.

Table 4. Cruise Ship Emissions.

Port	Number of Ships (2017)	No. of Ships (Rank)	Port Call Time (Hours)	Port Call Time (Rank)	(PM_{10}) [a] (kg)	(PM_{10}) [a] (Rank)	NOx (kg)	NOx (Rank)
Cagliari	45	5–6	2592	7	1468	9	144,070	7
Civitavecchia	76	1	5466	2	8898	2	500,326	2
Genoa	31	9	3376	4	4946	5	261,550	5
La Spetzia	43	6	3278	5	3721	6	194,646	6
Livorno	63	3	4720	3	6497	3	378,129	3
Messina	45	5–6	2296	9	2296	8	130,777	8
Napoli	52	4	2968	6	5138	4	303,708	4
Palermo	33	8	2393	8	2393	7	130,054	9
Venice	68	2	7988	1	10,961 [c]	1	600,337 [c]	1
Total	[456 [b]]		35,077		46,318		2,643,597	

[a] BC included in PM_{10}. [b] Includes multiple visits. [c] 3rd highest in Europe.

There was significant growth in the cruise traffic from 2018 to 2019 before the coronavirus hit Italy in early 2020. In 2018, Italy was first in Europe in the number of cruise passengers passing through its ports, ahead of Spain and Germany [32]. The economic significance of the cruise ship industry in Italy is further indicated by the fact that Italian cruise shipbuilder Fincantieri is the largest in Europe. As of late 2020, the previously planned merger with French cruise shipbuilder Chantiers de l'Atlantique seemed destined to be discontinued because of EU Commission doubts about competition policy issues and French government hesitations about other issues [43].

However, shipping traffic in Italian ports is dominated by non-specialized cargo, as indicated by numbers of vessels and by gross tonnage [32]. Container ship activity in three Italian ports put them in the top 20 in Europe in recent years during 2008–2018, Gioia Taro (8th), with 4.0 million TEUs in 2018, Genoa (13th) with 2.6 million, and La Spezia (19th) with 1.7 million. As for total freight handled in Italian ports over the period 2013–2018, only Trieste (12th) and Genoa (17th) ranked in the top 20 in Europe. At the top among European ports were Rotterdam, Antwerp, and Hamburg with 14, 11, and 9 million TEUs, respectively.

The importance of maritime BC emissions has been noted in many studies of Italian ports [43–54]. One is a case study of Civitavecchia, which is the port for Rome [45]. It distinguishes among three levels of measurement of particulate matter: PM_{10}, $PM_{2.5}$ and black carbon, which is PM_1. The distinction is important for policymaking because PM_{10} and $PM_{2.5}$ are covered by current EU and local regulations. However, maritime black carbon is not explicitly covered by regulations even though it is a serious health threat and a significant component of ships' air polluting emissions. An implication is that studies of ships' emissions need to be explicit about the types of emissions that are and are not included in the study and in detailed discussions of the results and implications. (See the Annex for additional definitional and measurement issues.)

In Table 4, in terms of the volume of cruise ship emissions, Venice was not only first in Italy, it was third among all European countries [55]. Some other Italian ports, such as Messina, were ranked relatively high in the number of ships but not in their time in port or their emissions. Genoa, on the other hand, ranked low in the number of ships but high in time in port and their emissions.

In sum, Italian port emission levels of PM (including black carbon), as well as sulfur dioxide and nitrogen oxides, are relatively high compared with other large European ports. They are high in absolute terms, such as total tons per year, and also high in relative terms, such as tons per vessel-visit. The emissions are particularly high for cruise ships, but they are also high for container ships and other kinds of vessels. On the other hand, there are also ports elsewhere in Europe with higher levels of air pollutants by several measures.

1.1.5. Human Populations in Italian Port and Coastal Areas

There are about 5 million people living in the cities of the 33 ports in the Italian port system, with three of the cities (Genoa, Napoli and Palermo) accounting for about 2 million. The photo below of Genoa (Figure 1) illustrates the close proximity of large residential areas to port operations. Further, as is often the case, ports have coastal hills that constrain emissions' more widespread dispersal and thus routinely increase the level of local pollutants. Genoa is one of Italy's largest ports in terms of local population, as Table 5 indicates more precisely [56].

Figure 1. Aerial View of the Port of Genoa.

Exposure to maritime emissions is not limited to ports, of course; it also includes coastal residents, and tourists, within the dispersion ranges of the emissions [57]. Of Italy's coastal population, a third live within only 5 km of a coast, slightly more than half live within 15 km, and more than 90% live within 50 km.

Table 5. Human populations in Italy's Ports.

Core Network Ports (15)/ Other Network Ports in the Regional Authority (18)	Population-2020 (000)
Genoa	*574*
Savona	60
Valdo Ligure	[a]
La Spezia	*93*
Marina di Carrara	[a]
Livorno	*157*
Piombino	[a]
Civitavecchia	*53*
Gaeta	[a]
Napoli	*959*
Salerno	133
Castellamare di Stabia	65
Gioia Tauro	[a]
Messina	230
Cagliari	*153*
Arbatax-Tottoli	[a]
Golfo Aranci	[a]
Olbia	61
Oristano	[a]
Torres Castellamare di Stabia	65
Palermo	*658*
Augusta	[a]
Catania	311
Bari	322
Brindisi	86
Manfredonia	56
Taranto	*195*
Ancona	*100*
Pesaro	95
Pescara	120
Ravenna	*158*
Venezia	*259*
Trieste	*203*
Subtotal: Core Network Ports	*3884*
Subtotal: Other Network Ports	1052
Total	4936

[a] Some port populations are not in the original source.

In addition to the major metropolitan areas of northern Italy, the concentrations of people in the coastal areas are evident. These coastal concentrations include, of course, many port cities, for instance, Napoli on the west coast, Cagliari on the south coast of Sardinia, Palermo on the north coast of Sicily, Bari and Brindisi on the east coast, and Venice in the northeast. In sum, millions of Italians live in port cities and nearby coasts. These millions are obviously the most vulnerable to the detrimental health effects of ship's emissions. In addition, many millions of tourists experience short-term exposure as coastal visitors. Although their exposure to air pollutants is much shorter, compared with year-round residents, it is nevertheless true that even relatively short-term exposures to black carbon, in particular, have been found to be damaging to lungs.

1.1.6. Coastal Agricultural Production Exposure

Agricultural production in Italy is concentrated along the seacoasts as well as in the Po valley. Although the precise proportions cannot be determined, it is clear from Figure 2 that nearly all of the coastal regions, except in the far northwest, are croplands [58].

Figure 2. Map of Cropland Areas in Italy.

The diversity and the quantities of agricultural products are evident in Table 6 [59]. Although grapes and olives are, of course, conspicuous, there are many other crops that are also important. Among them, wheat, maize, rice, and soybean crops have all been found to be damaged by BC and ozone emissions in other countries [21]. The damage is caused by a combination of factors: changes in the local and regional patterns of precipitation as a result of climate change; pollution of water supplies by depositions of emissions; and BC falling directly on the leaves of plants [21].

Table 6. Italy's Agricultural Commodity Production.

Commodity	Tons, in Descending Order, 2018
Grapes	8,513,643
Wheat	6,932,943
Maize	6,179,035
Tomatoes	5,798,103
Apples	2,414,921
Olives	1,877,222
Oranges	1,522,213
Rice	1,512,241
Soybeans	1,138,993
Peaches and nectarines	1,090,678
Barley	1,010,328

Although it is not feasible systematically and precisely to allocate each type of agricultural production to particular areas, it is possible to highlight some of the specialized regions and thereby gain a preliminary understanding of the exposure of agricultural production to the damaging effects of ships' emissions of black carbon [60]. See Figure 3.

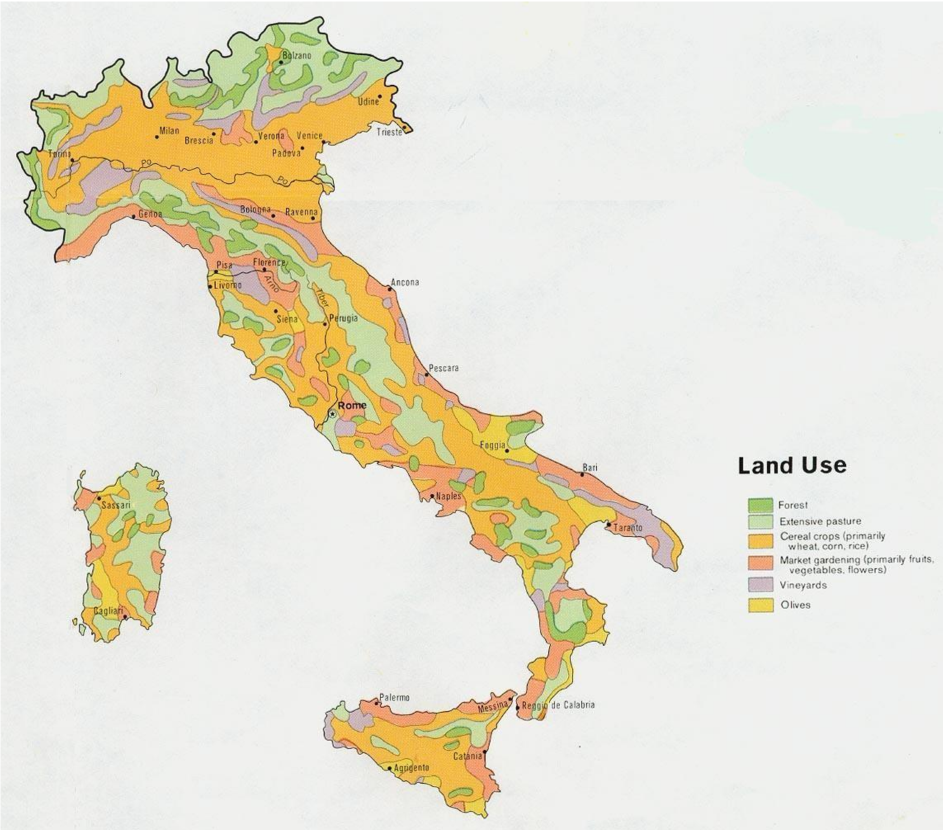

Figure 3. Map of Geographic Distribution of Types of Crops in Italy.

In sum, nearly all the coastal areas of Italy's 7500 km of coasts are important agricultural areas, and for many types of crops.

2. Technological and Policy Solutions

2.1. Technologies

There is an increasingly wide range of technologies that could reduce shipping's air emissions. Some are already in use, others are in use in smaller numbers but are available for more widespread use, and yet others are in various stages of development. The list in Table 7 is suggestive of the range of possibilities [3,61–65]. It is organized into groups: energy efficiency, alternative propulsion systems and fuels, machinery systems, and new information technologies, as well as operational measures.

Table 7. Illustrative Technologies and Operations that Have Been Proposed by Various Sources for Reducing Shipping's Emissions.

Energy Efficiency
Hull form
Efficient propellers
Lightweight construction
Reduce ballast
Ducktail waterline extensions
Propulsion Systems and Fuels
Wind
Solar
Towing kite
Hydrogen fuel cells
CRP Propulsion
Liquified natural gas fuel
Distillate fuel
Biodiesel fuel
Methanol fuel
Battery electric
Machinery Systems
Harbor-side auxiliary electricity (shore power)
Power storage
Waste heat recovery
Main engine tuning
Exhaust gas recirculation (with scrubbers)
Diesel particulate filters (DPF, various types)
Electrostatic precipitators (ESP)
Scrubbers (SOx, with exhaust gas cleaning systems)
Selective catalytic reduction
Hybrid electric storage
Engine tuning with selective catalytic reduction/exhaust gas recirculation
Diesel oxidation catalyst (DOC)
Information Technologies
Artificial intelligence: machine learning
Big data
Engine control technologies
Operational Measures
Propeller brushing
Hull brushing
Weather routing
Slow steaming

These and other possibilities have been the subject of a wide-ranging assessment process of several years' duration, which have thus far been formally centered in the IMO. Meanwhile, there have been many other developments at the IMO over the past many years.

2.2. Policymaking Arenas

2.2.1. IMO

The relevant IMO agreements that are currently in effect are the Energy Efficiency Design Index (EEDI) adopted in 2011 and the related Ship Energy Efficiency Management Plan (SEEMP) and the Energy Efficiency Operational Indicator (EEOI), and sulfur fuel content limitations, which were initially adopted in 2005 and then lowered in January 2020.

The EEDI [66] and its related agreements are intended to improve energy efficiency and thereby reduce carbon dioxide emissions. The agreements are complex, include many technical requirements for calculations and verifications, distinguish among 13 types of ships, and differentiate the applicability of the specific requirements for individual ships according to weight, engine type, and time-of-construction. The EEDI implementation period is divided into four phases with phase 0 beginning in 2013 and phase 4 beginning in 2025, with each phase being defined in terms of varying combinations of the dates of contract-signing, keel-laying and delivery. To the extent that they make the world's international maritime shipping fleet of about 70,000 vessels more fuel efficient, they also reduce black carbon emissions, though only indirectly and without specific monitoring of those indirect effects.

New sulphur regulations that entered into effect in January 2020 [67] have been a preoccupation of maritime industry participants and observers for several years. The new limit is that the sulphur content of fuel may not exceed 0.05%. However, ships with exhaust gas cleaning systems, i.e., 'scrubbers', can still use high-sulphur fuel oil (HSFO). Some types of scrubbers, i.e., those with 'open-loop systems' that could discharge water into port areas, are banned by some ports. Another issue about the reduction of sulphur emissions was noted above in the discussion of the chemical composition of shipping's emissions, namely that sulphur oxide emissions are global *coolants*. This unintended consequence of the IMO emission regulation has not been a central concern at the IMO, but there is increasing awareness of the issue.

There are also two emission regulatory policymaking tracks in progress at the IMO: the Initial Greenhouse Gas Strategy and the black carbon emission control track. In April 2018, IMO members adopted an Initial Greenhouse Strategy with a 2050 target of reducing maritime shipping's total GHG emissions by at least 50% compared to 2008 [68–70]. It also includes energy intensity targets of a 40% reduction by 2030 and 70% by 2050, compared with 2008. The targets represent significant reductions from business as usual projections, and there are other targets of an aspirational nature. There will be reviews/revisions in 2023 and 2028. In the context of the present article, a key question is whether black carbon will be included in the specifics of the strategy as it progresses through IMO processes.

As for black carbon at the IMO to date, its Maritime Environment Protection Committee (MEPC) took up black carbon issues in 2011, when it instructed what has since become the subcommittee concerning Pollution Prevention and Response (PPR) to develop a definition, identify appropriate measurement methods and investigate control measures. [71] These tasks have been the focal topics of a series of expert workshops organized by the International Council on Clean Transportation (ICCT) beginning in 2014 [72]. The workshop participants included government officials, maritime industry representatives, NGO staff experts, and academic specialists. The expert group agreed on a definition, as reproduced above at the end of this paper's Annex, which was accepted by the IMO's MEPC. A workshop in 2015 approved a measurement-reporting protocol, which was accepted by the IMO's PPR in 2016 [73]. The expert workshops in 2016 and 2017 agreed that there were three appropriate measurement methods: filter smoke number (FSN), photo-acoustic spectroscopy (PAS) and laser-induced incandescence (LII), and those were accepted by the IMO PPR in 2018 [74]. At the expert workshop in 2018 [3], there was agreement on a list of 13 appropriate control technologies, and the IMO PPR agreed with that list (see Table 8). These are thus an agreed subset of the possibilities noted above in Table 7.

Table 8. Appropriate BC Emission Control Measures [a].

Types of Measures
Fuel Type
LNG
Distillate
Biodiesel
Methanol
Exhaust Gas Treatment
DPF paired with marine fuels with low S and ash content (e.g., distillates)
DPF w/SCR, paired with marine fuels with low S and ash content (e.g., distillates)
ESP
Engine and Propulsion System Design
Engine tuning to low BC (NOx reduced with EGR/SCR)
Engine control technologies
Hybrid/energy storage
Full BEV
Hydrogen fuel cells
Other Measures
Shore power

[a] These are BC control measures that the group agreed were appropriate for international shipping after evaluating them against six 'considerations': [Effectiveness, Feasibility, Availability, Applicability, Co-emitted pollutants, Other]. The order in the list does not imply priority.

In 2018, the IMO MEPC decided that it would make a policy decision in 2021—on the basis of the work over several years by the workshops and PPR meetings. (As of this writing in late 2020, many IMO meetings were being delayed or canceled during the coronavirus pandemic.)

2.2.2. ECAs

International regional Emission Control Areas (ECAs) have been established in four areas, and they are all recognized by the IMO, specifically in the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI. Two of the five are particularly noteworthy because they are international agreements that limit ships' black carbon emissions (as $PM_{2.5}$). One is the large North American ECA, which covers the Atlantic and Pacific coasts [75]. The North Atlantic ECA was signed by Canada, the United States, and France, which has two territories (Saint Pierre and Miquelon off the Newfoundland Atlantic coast of Canada) and adopted by the IMO in 2010. The second ECA with $PM_{2.5}$ /black carbon limits is the US Caribbean ECA, which includes Puerto Rico and the US Virgin Islands, and which was recognized by the IMO in 2011 [76].

There are two ECAs in northern Europe—one for the Baltic Sea and the other for the North Sea and part of the English Channel. However, these were only created as SECA's, i.e., Sulphur ECAs. They are scheduled also to be NECAs (Nitrogen ECAs) beginning in 2021. Whether either or both will add particulate matter, including black carbon, remains to be seen [77].

2.2.3. Gothenburg Protocol

The Gothenburg Protocol [78], with an amendment that was agreed in 2012 and entered into force in 2019, explicitly includes emission reductions in BC as a component of $PM_{2.5.}$ The protocol also includes emission reductions in sulfur dioxide (SO_2), nitrogen oxides (NOx), ammonia (NH_3), and volatile organic compounds (VOCs), in addition to fine particulate matter $PM_{2.5.}$ It has been ratified by the EU and 25 countries in Europe and North America. Although it does not cover international maritime shipping, it does cover electricity-producing plants and vehicles in and around ports. The Protocol has been especially important in Europe where the EU has used it as a legal framework for its National Emissions Ceilings Directive, which was revised in 2016 and which includes monitoring and reporting procedures. The Protocol is itself embedded in the Convention on Long-range Transboundary Air

Pollution (CLRTAP), which was negotiated in the context of the UN Economic Commission for Europe (ECE). The ECE oversees the administration of the Gothenburg Protocol and serves as a forum for efforts to expand its geographic scope to include additional European countries.

2.2.4. EU

Because Italy is a member of the EU, regional EU policies are obviously relevant. The strong interest in more action on a wide range of environmental issues, including air pollution in the transportation sector, is clearly an important element in the policymaking context in Brussels [79,80]. As of late 2020, the most important specific issue for the international maritime shipping industry, and therefore the Italian government, is the Commission's proposal to include international shipping traffic in the EU Emission Trading System (ETS). There is substantial support for the proposal in Brussels and in many EU countries, but there are technical and legal issues as well as political and economic issues. The stakes are obviously high for maritime shipping, but it is too early as of October 2020 to be prognosticating about its fate.

2.2.5. Mediterranean

Proposals for the creation of a regional Mediterranean Emission Control Area (Med ECA) have been endorsed by the Italian, French and Spanish governments. The emission coverage of such an ECA has not been agreed, nor have other design issues, such as how to enforce compliance. There have been meetings of the 22 Mediterranean coastal countries in the context of the Barcelona Convention, so there is an existing international legal framework where such issues can be addressed. However, it seems likely that the discussions will include consideration of the experiences of the existing ECAs, as noted above, those covering the Baltic Sea, North Sea-English Channel, North American Atlantic and Pacific coasts, and the US-Caribbean Islands. An advantage of regional agreements is that they can reduce incentives for an individual port to adopt unilateral measures that are designed to increase the port's competitive advantage over other ports in the region. Given the large number of Mediterranean ports, some in close proximity to one another, this is a particularly relevant consideration for the Italian Port System Authorities as well as the Italian government.

2.2.6. Italy

It has been noted by a 2019–2020 study of the Civitavecchia port [45] that although EU-regulated emissions of NO_2, PM_{10}, and SO_2 met EU standards, there were also unregulated emissions that were problems, in particular, black carbon and ultrafine-to-coarse particles. The data indicated that such non-regulated pollutants showed 'the in-port, high polluting potential of some ship categories' including Ro-Ro passenger ships.' This finding underscores the potential significance of including emissions limits on black carbon and other particulate matter not currently covered by IMO or EU or Italian policies. It also suggests that Ro-Ro passenger ships should be a high-priority 'class' of ships for intensive emissions monitoring.

That finding is also a useful point of departure for an analysis of Italy's policy issues, for it suggests that the status quo is not acceptable because of the impact of maritime shipping's emissions. Despite existing IMO limitations on the sulfur content of maritime fuel and despite EU limitations on some emissions, ships and their ports are nevertheless emitting gases and particulate matter that are damaging to human health and agricultural production. Maritime emissions are a threat to public health, especially near ports and coasts, and they are a threat to many kinds of agricultural crops [7,8,17–20].

In Italy, Venice is receiving the most attention among environmentalists, urban planners and policymakers as well as journalists, because of the damage done by large cruise ships to the area's physical, cultural, and economic sustainability [47]. In addition to the impact of the ships in the damage done by their wakes to the foundations of the buildings and thus the future existence of the city, there are also serious air pollution issues, including the damage done by the ships' emissions to public health. As indicated by the emissions of both particulate matter (PM) and nitrogen oxides (NOx) in 2017, Venice had the third highest emission level among Italian ports [47].

The mix of impacts on public health and agricultural production is different in different regions and ports. In large northern and cruise-intensive ports everywhere, there is relatively more impact on the health of millions of nearby residents, while in smaller ports and where there are major agricultural areas nearby there is more impact on olives, grapes and other crops. Of course, there are both kinds of concerns, but the focus and results of technical effectiveness analyses and economic cost–benefit analyses of mitigation alternatives are quite different depending on the profiles of the ports and the volume and types of ships passing through them.

Table 9 displays the list of 33 ports in the Italian system [81]. The 33 individual ports are subject to the authority of the regional authorities, which are in turn subject to national laws. The system thus has elements of both decentralization and centralization.

Table 9. Current Administrative Organization of the Italian Port System.

Port System Authorities	Core Network Ports	Other Network Ports
1-Western Ligurian Sea	Genova	Savona Valdo Ligure
2-Eastern Ligurian Sea	La Spezia	Marina di Carrara
3-Northern Tyrrhenian Sea	Livorno	Piombino
4-Central-Northern Tyrrhenian Sea	Civitavecchia (Rome)	Gaeta
5-Central Tyrrhenian Sea	Napoli	Salerno Castellamare di Stabia
6-Central-Southern Sea and Strait	Gioia Tauro	Messina
7-Sea of Sardinia	Gagliari	Arbatax-Tottoli Golfo Aranci Olbia Oristano Torres Castellamare di Stabia
8-Western Sicilian Sea	Palermo	
9- Eastern Sicilian Sea	Augusta	Catania
10-Southern Adriatic Sea	Bari	Brindisi Manfredonia
11-Ionian Sea	Taranto	
12-Central Adriatic Sea	Ancona	Pesaro Pescara
13-Central-Northern Adriatic Sea	Ravenna	
14-Northern Adriatic Sea	Venezia	
15- Eastern Adriatic Sea	Trieste	

3. Monitoring, Reviewing, Verifying and Enforcing (MRV&E)

Regulatory standards for maritime emissions, whatever they are and whoever is responsible for implementing them, need systems for monitoring, reporting, and verifying compliance (MRV), and there are many of those in place at all levels of governance [82]. They involve a combination of well-established procedures and evolving technologies. In addition, unless the standards are only expected to result in voluntary compliance, enforcement procedures are also needed, thus suggesting a new acronym 'MRV&E' [83].

Italy is a signatory to the Paris Memorandum of Understanding (MoU) on Port State Control along with 26 other mostly European countries to cooperate on enforcement of international maritime regulations [84]. There are a total of nine such regional MoUs in the world. Since the Paris MoU has a cooperation agreement with the Mediterranean MoU, Italy is indirectly involved in Mediterranean cooperation efforts, as well as its direct involvement in European cooperation. An objective of the MoUs is to reduce incentives for ports to engage in lax enforcement of international agreements in order to entice business away from competitive ports. A detailed analysis of the Paris MoU and Mediterranean MoU annual reports over time might reveal patterns of compliance or non-compliance, but that is beyond the scope of this paper.

4. Conclusions

Maritime shipping's emissions are significant air pollutants that cause public health and food production problems, in addition to climate change. In Italy, as elsewhere, the emissions vary among industry segments and among locations. Until the coronavirus pandemic of 2020, cruise ships were a major air polluter in Italian ports and along its coasts. By late 2020, there were signs that the cruise segment of maritime shipping was beginning to resume operations on a small scale, though with doubts about how many years it would be before it regained much of its lost business.

In ports, it is not only the ships' emissions that contribute to the problem, it is also the emissions of the port loading and unloading equipment, as well as the truck and rail traffic that connects to the marine traffic in the port areas. Diesel engines are the common element in all of these sources of emissions, whether in ports, along coasts or on the high seas.

Because of black carbon's three kinds of impacts (climate, health and food), reductions of BC emissions offer three kinds of corresponding benefits. The potential resulting co-benefits of one emission reduction measure make such measures economically and politically attractive. In addition, the effects of mitigating BC emissions are evident virtually immediately as visible black smoke plumes diminish with the implementation of the emission control measures. The time scale of a matter of days for the effects of BC reductions to occur contrasts with the decades and centuries for the effects of carbon dioxide emission reductions. Further, the reductions of shipping's BC emissions occur locally and regionally as well as globally. The local and regional benefits to human health and food production are direct consequences of the emission reductions, and the local and regional health and food production benefits are enjoyed by local and regional inhabitants. The 'free rider' problem of reducing global warming forcing agents is thus largely circumvented by localized and regionalized emission reductions, though there is still some free-riding because of the global benefits of reducing global warming emissions.

There are diverse operational and technological solutions that can reduce BC and other emissions, and there are governmental policies that can create incentives for industry participants to change their operational and technological choices. Italian shipbuilders, owners, and operators are all therefore encountering expanding options to address maritime emissions issues. Their choices will of course be influenced by technological and economic factors. As this paper and others' analyses have been suggesting for the past several years, the maritime shipping industry is in the midst of overlapping technological revolutions, including, in particular, propulsion technologies and information processing technologies. As technologies change, so also do the economic cost–benefit calculations of industry participants and governmental policymakers.

Those industry options and decisions are also influenced by policymaking processes at all levels of governance. Potential governmental policy changes are on the active agendas of the International Maritime Organization, the 22 countries that are signatories of the Convention for the Protection of the Mediterranean Sea against Pollution (i.e., the Barcelona Convention), and the 27 countries of the European Union, as well as other European countries such as Norway and the UK with significant stakes in international maritime shipping. The Italian national government is of course a participant in all these fora. It has already taken a leadership position, along with France and Italy, on the creation of a Mediterranean Emission Control Area (Med ECA).

However, in order to address the maritime black carbon emission problem in Italy and the other Mediterranean coastal countries, black carbon needs to be covered in a Med ECA. Italy can draw upon the experiences of the existing ECAs in North America and the Caribbean, where black carbon is covered, and in the North Sea and Baltic Sea regions, where black carbon is not covered, but where nitrogen oxide is being added to sulphur oxide. Given the regional sensitivities to the levels of ships' black carbon emissions in the North and Baltic seas, black carbon may soon be on the agenda for another expansion of the limits on maritime emissions in these ECAs.

The Italian national government oversees and coordinates a network of more than 30 local ports through its own domestic regionalized system. As the Italian national government and its regional and local port authorities contemplate the expanding policy agenda, it is important to note the mixture of common and distinctive features of the shipping industry's various 'segments'. There are two important features they all have in common: (1) diesel engines are still the predominant engines for ships' propulsion systems and auxiliary electric generators, and (2) significant levels of their emissions occur near coastal population agglomerations and agricultural zones as well as port areas. Such emissions are particularly problematic because of Italy's geographical configuration with so much coastline relative to its territory and population.

One simple, effective, and available measure is to require slow steaming everywhere within Italian waters. This could be the beginning of an incremental process of increasing limits on black carbon emissions in Italy's coastal zones. As for ports, harbor-side electric hookups can be installed where electricity from sustainable sources is available. Since the energy policy reforms of 2013, wind, solar, and biofuels have been increasing and coal decreasing. However, because oil and natural gas remain major sources, it will be necessary to assess the sustainable electricity capacity, if any, that is available for each individual port. Such an assessment could draw upon the experience and expertise of other ports and specialized international organizations, particularly the International Ports and Harbors Association, the Climate and Clean Air Coalition, the International Energy Agency the EU and the International Transport Forum (ITF) at the OECD [85]. The Italian government could thus coordinate international and local resources for an Italian port assessment.

More generally, the Italian government should update its 2013 policy revisions with a 2021 assessment and plan for the next decade. This could be integrated into Italy's participation in the EU energy and climate plans under development in late 2020. Italy could ensure that maritime black carbon emissions are on the EU agenda for more attention and action.

As Italy contemplates its policy options, it is participating in several quite different policymaking arenas. One is the virtually globalized IMO that has two active policy tracks focused on emissions limitations, one concerning the Initial GHG Strategy, with an interim review in 2023, and the other concerning black carbon, with a meeting to decide key issues scheduled for 2021. Since each EU member is separately represented at the IMO, with the EU having 'observer' status, Italy's role as a major shipping country, especially in cruise shipping, puts it in a prominent position. As an EU member, it is in a favorable situation for working with other major EU shipping countries including, France, Spain, the Netherlands, Belgium, Germany, Denmark, Finland and Sweden, plus non-EU Norway and the UK. Collectively, they are powerful proponents of more extensive IMO limitations on shorter schedules. In any case, the two active policymaking tracks at the IMO will require Italy to take positions on emissions regulations in coming months and years, and probably for many years to follow. The agenda will include not only rules about levels of emissions, but also rules and administrative processes about monitoring, reporting, verifying, and enforcing the rules, i.e., MRV&E. In any event, black carbon is likely to be on the IMO agenda for many years.

At the same time, as a member of the EU, Italy is already obligated to adhere to regional rules concerning emissions in ports and nearby cities. Again, black carbon is already on the EU agenda, though mostly through studies rather than as an explicit item on a formal institutional agenda. It seems likely, however, that the current Commission and the current Parliament, and perhaps their successors, will include black carbon in their ambitious efforts to expand regulations of the international maritime shipping industry via the EU and/or the IMO.

In addition to its involvement in the IMO and EU, Italy is already engaged in the development of a Mediterranean Emission Control Area (Med ECA). Because of its position as a principal participant in the passenger cruise services sector of the maritime industry, including significant cruise ship traffic between Italian and several North African ports, it has much at stake in the design of the Med ECA. Thus far, it has positioned itself as a Med ECA proponent with France and Spain, both of whom are major participants in Mediterranean cruise business. Since all three are on record for favoring a Med ECA, the logical next steps include addressing important design issues such as the kinds of emissions to be covered and related MRV&E policies and processes. The existing ECAs in the Baltic and North Seas, the Atlantic and Pacific Oceans, and the Caribbean Sea all provide experience and many studies that can be drawn upon in the development of a Med ECA. Including black carbon among the regulated air pollutants, along with sulfur and nitrogen emissions, is an obvious and forward-looking option.

Of course, in addition to these three internationalized policymaking arenas, Italy has its own domestic policymaking arenas. The existing regionalized system, including 15 ports as regional network centers and a further 18 as participants in the network, provides a policymaking and administrative framework for considering Italian national policy options. Regardless of its internal governmental structural arrangements, however, Italy will be obliged to follow the increasingly elaborate array of international laws and administrative processes by adhering to them and by enforcing them. Thus, in response to the theme of this special journal issue, Italy already has many opportunities for 'improving the environmental performances of maritime transport and ports.'

As always, there are significant needs for further research. Although the paper focuses on the immediate public health and agricultural production consequences of ships' emissions, there is also an urgent need to address the climate change implications, and those implications, of course, extend to the rest of the world beyond Italy and far into the future.

5. Annex: Black Carbon Definition and Measurement Issues

A landmark study [26] of black carbon notes that 'The strong absorption of visible light at all visible wave lengths by black carbon is the distinguishing characteristic that has raised interest in studies of atmospheric radiative transfer. No other substance with such strong light absorption per unit mass is present in the atmosphere in significant quantities.'

Black carbon (BC) is sometimes equated to soot, but that is not accurate. Black carbon is one component of soot, which is the black smoke that appears when fossil fuels and biofuels burn. The other components of soot, as co-pollutants with BC, include organic carbon (OC), sulphur oxide (SOx), nitrous oxide NOx), and ozone. A secondary emission ozone occurs as a result of interactions of elements in the soot, including black carbon.

The amount of BC in diesel exhaust is especially notable in the context of the present article because the ratio of BC to OC is centrally important to an understanding of the effects on climate change of emissions of these co-pollutants in ships' emissions. The reason is that OC is a global *coolant*. The BC:OC ratio varies across sources. At one extreme, heavy duty diesel engines have a relatively high BC:OC ratio and are thus potent global warming agents. Since not all diesel engines are the same, it is necessary to consider the type of application in order to obtain a precise indication of the BC:OC ratio. Large marine engines have been reported to have a BC:OC ratio as high as 9 [28]. In studies of elemental carbon (EC), which is highly correlated with BC though not chemically quite the same, for US on-road heavy-duty diesel vehicles, the EC:OC ratio was found to be 4.4 [86]. In the same study, the ratio for on-road light-duty vehicles the ratio was 1.5. The consistent core finding is that the net of warming over cooling agents was greater than 1, and usually much greater. Similar patterns have been found for non-road diesel and locomotive diesel engines in the US [86].

Commonly used numbers about the levels of emissions of GHGs and/or BC are not indicative of the full extent of the consequences of BC emissions for climate change, human health, or food production. (1) Numbers that indicate levels of greenhouse gas emissions singly or as a collective CO2e do not include BC. (2) BC numbers for global emissions do not reflect three important regional facts about the emissions: (a) BC emissions are disproportionately concentrated in densely populated urban areas in Italy and other countries and thus affect human health more than global numbers imply. (b) Shipping's emissions are particularly damaging to human health and food production along coastal shipping routes. (c) BC emissions in the Arctic region are more impactful than carbon dioxide emissions and thus contribute disproportionately to the Arctic's temperature increase, which is more than twice as much as the global average as a result of BC, CO_2, and other greenhouse gasses.

A formal definition of black carbon follows [24]: 'Black carbon is a distinct type of carbonaceous material, formed only in flames during combustion of carbon-based fuels. It is distinguishable from other forms of carbon and carbon compounds contained in atmospheric aerosol because it has a unique combination of the following physical properties: 1. It strongly absorbs visible light with a mass absorption cross-section of at least 5 $m^2 g^{-1}$ at a wavelength of 550 nm. 2. It is refractory; that is, it retains its basic format at very high temperatures, with a vaporization temperature near 4000K. 3. It is insoluble in water, in organic solvents including methanol and acetone, and in other components of atmospheric aerosol. 4. It exists as an aggregate of small carbon spherules.

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