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Giovanni Solari

Wind Science and Engineering

Origins, Developments, Fundamentals and Advancements

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To my Family

Preface

I have been studying the wind and its effects on construction, environment and territory for over 40 years. In the course of these years, I have mainly carried out research on wind engineering, trying to keep as broad a vision as possible; this research has led me to publish many scientific papers in international journals. In parallel, starting from wind and structural engineering, I have studied and followed, mainly for passion, the aspects more properly related to the evolution of knowledge, culture and science; I have written a limited number of papers in this field, but I have given many talks at universities, academies and cultural associations of all kinds.

For a long time, I have considered these two visions distinct, as if the first were my job and the second a hobby that allowed me to fly higher, to overcome the analytical, numerical, experimental and technological conception of scientific research, projecting myself into a wider and more charming world. Under this point of view, I have often lived two parallel lives. Until I started to think, it was a pity and a limitation to keep two such visions distinct because, if integrated together, they could offer mutual insights and interpretations able to raise both.

From this stems the conception and writing of a book that tries to translate and harmonise these two visions through a historical reconstruction and a synthetic perspective of distant worlds that pursue and attract one another: on the one hand, the wind as a source of life and comfort and as a cause of injury and death; on the other hand, the wind as a focal topic of scientific and humanistic cultures, exceptionally branched into microworlds at different scales, which over the centuries have been ignored or inspired by each other.

In this spirit, the book goes through scientific sections full of equations, sections dominated by technological issues described by means of technical drawings, sections where the history of the development of the wind science and technology prevails in a discursive form, narrative sections that collect often curious facts and discoveries related to wind, sections with a humanistic and sometimes philosophical matrix. Everything is intertwined and joined in order to recognise and provide the links, motivations and intersections that have given rise to the Wind Science and Engineering.

The result is a complex and articulated text that alternates easy and hopefully pleasant passages with demanding parts, searching for a viewpoint wider than the usual scientific approach, which is often aiming to investigate ever more deeply and in detail increasingly circumscribed problems.

During this process, I have found it fascinating to research into ancient thinkers' speculations which are the core of scientific theories. I have met great human stories behind great scientific discoveries. I have understood how the most sophisticated equipment is often the evolution of bizarre instrumentations. I have reached the awareness that several fundamental equations are the result of endless coarse attempts, that many basic concepts were born independently by sectors that have long been ignored each other, and that great ideas attributed to famous scientists were actually developed or conceived by others who have not been lucky enough to be recognized for their own merits. I have also found it fascinating to study and try to communicate the concept that what was developed in our own field is often the result of visions accrued at a larger scale. Or it was already known in areas which, if studied in depth, would have avoided rediscovering already known aspects or would have enabled us to start from knowledge bases from which it would have been possible to reach higher levels.

Just towards the end of this work, I realized it gave me the opportunity of making a long journey through time and space, and above all through my life, which made me rediscover the texts where I studied, the people I attended along my career or I wanted to know, the difficulty of getting into sectors little known or unknown, the curiosity to understand and the fear of making mistakes, the effort to seek, the joy of finding and the suffering of failing.

As the publication of this book draws near, I feel the concern for the judgement of those who will read individual chapters, or even worse individual sections, with a specific knowledge of their topics greater than that of the author. I ask them to get into the whole of the wind science and engineering, or at least to recognise the effort made to treat this matter altogether, without resorting to the simplest collection of contributions from different specialists with different and uneven views and approaches. Perhaps, ideas and reflections on the vast spaces that still exist towards the creation of a truly interdisciplinary view of the wind can emerge just out of the shortcomings exhibited by the author in the treatment of individual parts, deliberately not entrusted to the review of experts.

Now, I just have to thank those who contributed directly and indirectly to this book, hoping not to forget anyone.

I thank the University of Genova, the Polytechnic School (formerly the Faculty of Engineering) and the Department of Civil, Chemical and Environmental Engineering (DICCA, formerly DICAT, DISEG and ISC), who put me in the position to express myself as much as I could and to do what I aspired to. I thank Margherita Capelletti, and before her Sonia Russo, who assisted me in the drafting of the text, Promoest, Susanna Marrella and Carlo Lagomarsino, who edited the translation and the revision of my writings, Rita Soffientino, who provided me with

hard-to-find books and papers, Springer and Pier Paolo Riva, who accepted and implemented this editorial proposal. Any error remains my sole responsibility.

I thank all the students who have followed my lessons, my many graduates, doctoral scholars, postdoc researchers and visiting scientists, in particular Stefano Brusco, Ileana Calotescu, Federico Canepa, Michela Damele, Luca Roncallo, Stefano Torre, Andi Xhelaj, Shi Zhang and Josip Zuzul. I thank my friends and colleagues who over the years have been part of the WinDyn Research Group, primarily Giuseppe Piccardo, with whom I shared a life of friendship and work, then Maria Pia Repetto and Massimiliano Burlando, with and thanks to whom, I crowned the dream of an Advanced Grant of the European Research Council for the THUNDERR Project. Its support for this book is acknowledged.

I thank all those with whom I spent wonderful hours at conferences, universities and institutions all over the world; by virtue of the personal relationships I established with them, wherever I was, in space and time, I felt surrounded by friends and part of a large family. Among them, I express special thanks to my great friends and outstanding colleagues Ahsan Kareem and Yukio Tamura, with whom I shared the most significant moments of my career and of my personal life.

I thank Genova and Liguria, where I was born and lived, to which I am deeply attached. From the beauty and familiarity of my lands, I have always drawn peace and inspiration.

Finally, I thank my whole Family for what I received from them and to them I dedicate this book. I am grateful to my wife Simonetta for the beautiful moments we spent together. I entrust my commitment to the memory of my sons Davide and Matteo.

Genoa, Italy Giovanni Solari

Contents

About the Author

Giovanni Solari is a professor of Structural and Wind Engineering at the University of Genoa, senior adviser at the Beijing Jiaotong University, guest professor at the University of Western Ontario, Canada, and formerly at the *Universidad de la República*, Uruguay, honorary professor at the Shijiazhuang Tiedao University and at the South Central University, Changsha, China, and honorary doctor honoris causa at the Technical University of Civil Engineering, Bucharest.

He was awarded the Scanlan Medal 2017 (EMI-ASCE), the Reese Research Prize 2014 (SEI-ASCE), the Flachsbart Medal 2013 (WTG), the Davenport Medal 2011 (IAWE) and the Cermak Medal 2006 (EMI-ASCE).

He was a president of the International Association for Wind Engineering (IAWE), founding co-editor of Wind and Structures, series editor of Springer Tracts in Civil Engineering, scientific responsible of the European Projects "Wind and Ports" and "Wind, Ports and Sea". The European Research Council awarded him an Advanced Grant 2016 for the THUNDERR Project.

He is a member of the Liguria Academy of Science and Letters and author of nearly 400 papers, almost 150 of which appeared in peer-reviewed journals.

He carried out the wind loading and response analysis of several signature structures, including the Leaning Tower of Pisa, the Messina Strait Bridge and the Brancusi Endless Column. He currently serves as the designated president of the Italian Institute of Welding.

Chapter 1
Introduction

Abstract This chapter provides an overview of the four periods in which knowledge of the wind and mankind's ability to exploit its beneficial aspects and protect itself from the harmful ones develops. In the first period, from the dawn of history to the Renaissance, the origins of wind knowledge were manifested through varied and disjoint contributions. In the second period, from the Renaissance to the end of the nineteenth century, the new form of knowledge based on experience, science, produced substantial evolutions in the culture of the wind and its effects. In the third period, from the late nineteenth to the mid-twentieth century, the foundations of the individual disciplines destined to give life to wind engineering were born and the first links between different sectors were manifested. In the fourth and last period, from the mid-twentieth century to the third millennium, the many strands of the wind culture show substantial advancements that first lead to the foundation of wind engineering and then to the enlarged view of wind science and engineering.

Few natural phenomena are as ethereal, indefinable and mysterious as the wind. Few natural phenomena produce so visible, tangible and varied effects as the wind does. Few natural phenomena, throughout the centuries, have been the object of speculation, observations, experiences and research as abundant as those carried out on the wind.

These aspects are mostly due to the rare property of dualism possessed by the wind: the wind is evil when it destroys buildings and anthropogenic areas, producing more fatalities and damage than any other natural event; when it whips men, houses and settlements with air that is either too cold or too hot; when it makes urban spaces uncomfortable; when it destroys crops and exposes transport to risks; when it erodes the soil to the point of making whole lands deserts; when it drifts snow, burying buildings and roads; and when it is a tool for air pollution and for aggression on our monumental heritage. On the other hand, the wind is good because, as the engine of atmospheric motions, life on Earth would not exist without it. The wind is good when it powers windmills and wind turbines, producing clean renewable energy; when it favours the circulation of fresh air inside buildings or along the arteries of the urban fabric; when it offers breath to the populations that live in deserts or on lands dried up

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by the sun; when it disperses the emissions of pollutant sources away from populated areas; and when it carries smog clouds away from heated urban islands.

The evolution of knowledge of the wind and mankind's ability to exploit its beneficial aspects and protect itself from the harmful ones has developed through four periods [1].

The first period, from the dawn of history to the Renaissance (Chap. 2), was dominated first by a mythological vision, then by a speculative approach in part inspired by observation and finally by the beginnings of a scientific method based on experience. The first weather forecasts appeared, partly dictated by astrological practice. Man used the energy of the wind to sail, to support the flying of kites and to drive the blades of the first windmills. He also developed the first experiences aiming at guaranteeing his settlements and homes a bioclimatic environment, so as to improve living conditions. He noted, however, usually with feelings of resignation and inevitability, the destruction caused by windstorms.

In the second period, from the Renaissance to the end of the nineteenth century, a form of knowledge based on experience developed, science, supplanting the role of speculation and observation. The wind availed itself of this progress drawing on concepts and principles from the basic disciplines that were born and developed in this period, especially in physics, mathematics and probability theory, mechanics, fluid dynamics and thermodynamics, structural mechanics and vibration (Chap. 3). Thanks to these disciplines and the progress made in the field of navigation and flight, meteorological knowledge was accrued, a new culture arose on the resistance of bodies immersed in the wind, and the exploitation of wind energy progressed; man also became aware of the risks faced by the boldest constructions seeing their collapse, due to the wind, especially of many bridges that were the pride of the engineering of this time (Chap. 4).

In the third period, from the late nineteenth to the mid-twentieth century, the maturation of the basic disciplines is completed, especially fluid mechanics and probability theory, from which wind science draws; it is also worth noting the advent of the computer and its fundamental link with meteorological forecasts (Chap. 5). At the same time, new lines of research were developed concerning meteorology, aerodynamics, wind actions and effects on environment and construction, wind hazard, vulnerability and risk. Knowledge of the wind phenomena took maximum impetus from the progress of ground instruments and remote monitoring, from the evolution of meteorology and from the advent of micrometeorology, the theory of turbulence and climatology (Chap. 6). Aerodynamics made enormous progress in the experimental field thanks to the dissemination of full-scale measurements and above all of wind tunnels; this greatly contributed to the new culture that pervaded the fields of aeronautics, shipping, and road and rail transport (Chap. 7). Environmental wind actions and effects were fertile fields of study with regard to wind turbines, supplanting the old mills, the atmospheric dispersion of pollutants, soil erosion and snowdrift, the protection of crops, the urban and architectural design inspired by bioclimatic principles (Chap. 8). The study of wind actions and effects on buildings was strengthened by the realisation of long and light bridges, tall and slender towers and skyscrapers, and, more generally, a new generation of structures increasingly susceptible to wind loading; a new

culture also matured of the static, dynamic and aeroelastic wind actions on structures (Chap. 9). Thanks to new knowledge in the fields of meteorology and construction, man understood that wind-induced disasters can be contrasted and mitigated by manifold interventions to which he devoted efforts and enthusiasm (Chap. 10).

In the fourth and last period, from the mid-twentieth century to the third millennium, the many strands of wind culture, until then generally cultivated as independent subjects, have come to be configured according to an autonomous and uniform scientific framework (Chap. 11).

In 1961, Alan Garnett Davenport (1932–2009) laid the foundations of this transition, creating the namesake chain [2]: it links together the fundamentals of wind, aerodynamics and mechanics, originating the first unitary procedure to analyse wind actions and effects on structures; this gave rise to four international conferences on this subject, from 1963 to 1975, outlining the stages of the first phase of the new course.

During the last of these conferences, the community involved took note of the new form of knowledge. In the meanwhile, it realised that this view was narrow and restrictive. Hence, the will arose to establish a wider scientific community that deals, in its entirety, with the various issues related to wind actions and effects not only on constructions but also on environment and territory. This remark gave rise to the advent of Wind Engineering, defined by Jack Edward Cermak (1922–2012) in 1975 as "the rational treatment of the interactions between wind in the atmospheric boundary layer and man and his works on the surface of earth". With it, the International Association for Wind Engineering was also born, aimed at co-ordinating the activities of this new sector, and a series of six namesake conferences, from 1979 to 1999, outlining the stages of the second phase of the new course.

In the last of these conferences, the conviction and the awareness matured that the role of the wind was now crucial to many areas of science and technology and the number of those studying and working in this sector, increasingly wide and varied, had become absolutely huge. Hence, the idea and the will arose to give the association born just 24 years before a more modern and efficient organisation, which is able to play a stronger and more proactive role with regard to the needs of society and humanity towards the wind. In this new perspective, the awareness is essential that the wind is the cause of about 75% of the damage and deaths caused by nature on the Earth every year. The conferences that took place in the following years offered testimony of the third phase of the new course, pointing out such a broad and complex framework as to make "Wind engineering" an almost reductive definition. Hence, a wider viewpoint has been emerging that goes beyond the engineering world and projects this discipline into a higher and more general scenario well-embraced by the new definition "Wind science and engineering". This is also the title of the present book.

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Part I
Origins: From the Dawn of History to the Renaissance

Chapter 2
The Wind in Antiquity

Abstract This chapter addresses the will of men, which took place in the period that goes from the beginning of history to the Renaissance, to know the wind, to exploit its beneficial aspects and to protect themselves from its harmful effects. Accordingly, it describes a mythological view that emphasises the dualism between the wind as a source of life and as a means of death, the advent of a naturalistic speculation inspired by observation and the first scientific concepts, prodromes of experience, mainly focused on mathematical, mechanical and astronomical problems, as well as the innate interest of man for weather knowledge and forecasting. At the same time, it describes the first man's attempts to exploit the wind power as an energy source, equipping boats with sails, using atmospheric currents to support kites, taking advantage of wind power to operate mill blades for multiple forms of work. In the same spirit of profound dualism, the development of architectural principles inspired by local climate is described as well as the mechanical role of wind actions and effects on buildings. The chapter ends dealing with the outstanding interest of Leonardo da Vinci towards wind and his studies on fluid and solid mechanics, meteorological instrumentation, aerodynamics and human flight.

The period that goes from the beginnings of history to the Renaissance was dominated by the will of man to know the wind, to exploit its beneficial aspects and protect themselves from its harmful effects.

At first, man related to the culture of wind by elaborating a mythological view that emphasised the dualism between the wind as a source of life and the wind as a means of death (Sect. 2.1). Later, with the advent of Greek civilisation, a naturalistic speculation was born inspired by observation (Sect. 2.2). At the same time, although at a sporadic level, the first scientific concepts and prodromes of experience, mainly related to mathematical, mechanical and astronomical problems established themselves (Sect. 2.3). From the background of this reality, the innate interest of man emerged for weather knowledge and forecasting: it found answers in two disciplines, meteorology and astrology, destined to attract and repel throughout history (Sect. 2.4).

At the same time, man learnt to exploit the wind power as an energy source, equipping his boats with sails (Sect. 2.5). Later, he began to hover in the sky using

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just as unlikely as dangerous wings or exploited atmospheric currents to support his kites (Sect. 2.6). Lastly, he used wind power to operate mill blades for multiple forms of work (Sect. 2.7). In any case, he understood that the wind, so generous in vital potential, frequently and suddenly can change into a fierce enemy.

In the same spirit of profound dualism between the wind that is good and the wind that is bad, man has tried to improve his living conditions by blocking the path to the coldest winds or creating pleasant streams of air where the heat is more oppressive; in this way, he has developed, from ancient times, architectural and urban principles inspired by the local climate (Sect. 2.8). On the other hand, he has observed, generally with a sense of resignation and ineluctability, the destruction caused to the territory by windstorms; he has also sought to understand the mechanical role of wind actions on buildings, delaying the study of remedies to guard against their consequences (Sect. 2.9).

With the advent of the Renaissance, the world was pervaded by a fervour of activity and innovation that affected all fields of knowledge, including that of the wind. Leonardo da Vinci anticipated and inspired this transformation, providing extraordinary contributions to many scientific areas including fluid and solid mechanics, meteorological instrumentation, aerodynamics and human flight (Sect. 2.10). Some of his ideas still retain unchanged relevance to today's world.

There emerged a picture of a reality where the study of wind struggled to take on clear contours and autonomy of thought and discussion. The culture of this phenomenon remained an integral and in some cases hidden part of broader and more general themes. These themes cannot be ignored, if we want to capture and highlight the first moments in which the relationship between man and wind manifested itself at its embryonic level.

2.1 The Wind in Mythology

Ancient peoples regarded natural phenomena as direct or indirect manifestations of divine power. The wind, in its many manifestations, was of all the natural phenomena, the one which probably captured the imagination of man more and inspired him to combinations and allegories related to religious ideas and to the concept of genesis. In many primitive societies and cultures, the wind was personified and divinised by appearances that reproduced its prerogatives [1, 2]. One of the most fascinating aspects of the wind mythology was that peoples of every place and age autonomously matured similar beliefs and striking coincidences around such an intangible and immaterial phenomenon.

Many of the oldest myths made the wind rise from holes or caves hidden in the ground or in the sky. The Bakitara of Uganda believed in the existence of four holes in the sacred hill of Kahola, the home of the winds, from which they flew. Yukon Inuit narrated of a wooden doll made by a couple without children; it acquired life and reached the hem of the world, where it found a hole in the sky covered with skin; it cut through it, and released the wind with a herd of caribou. The Iroquois believed that

the winds were held captive by Gaoh in the cave of a mountain called Kahola, "the house of the winds". Similarly, Batek Negrito of Malaysia argued that the winds were kept in a cave of Batu Balok and carried out by ropes pulled by Gobar, the Supreme Being. Sarawak's Dusus believed in the existence of Kinorohingan, a blacksmith who forged the seven parts of each man's soul; when they wore out, he turned them into twisted winds and kept them in a cave. The Maori of New Zealand told the legend of Mani, a hero who captured the winds to confine them to caves. In the Cook Islands, the wind was enclosed in the sky, represented by a pumpkin dotted with holes closed by stoppers that were placed or raised, depending on circumstances, by the "great priest". In the Hawaii, "the perennial wind pumpkin" was guarded by "kahuna", who handed down the names and secrets of the winds from fathers to sons. In Polynesia, it was believed that there were holes on the horizon through which Raka, the god of the winds, and his sons blew out.

At the beginning of the first millennium BC, a rich mythology flourished in Greece. Aeolus, son of Poseidon, god of the sea, was the guardian of winds that he kept chained in a cave of the Island of Eolia. Legend has it that, as time went by, he lost control of them. So, when Odysseus arrived with his crew, he closed them in a bag of ox skin and released them with satisfaction. His sailors opened it believing that the sack contained a treasure and was overwhelmed by the impetus of the freed winds. The sack that enclosed the winds was a cornerstone of many other myths and ancient legends. In the Chinese tradition, the wind god is Feng Po, an old man with a white beard and a blue cap; he had a yellow sack called "the mother of the winds"; orienting the opening of the sack, he determined their direction. Fujin, the Japanese wind demon, was depicted as a horrible being who pulled the winds from a bag carried over his shoulder; their intensity depended on the opening of the mouth of this bag.

Caves, pumpkins and sacks were clear symbols of a maternal womb from which the wind flows to come to light. In this regard, there was a deep bond with other myths where the wind was associated with the life that was born. The Sermat people in Indonesia believed that only the sky was originally inhabited; from the sky, along a palm tree that is still venerated, descended a woman made pregnant by the south wind as she slept; all the people of our planet are her descendants. The Sulawesi people believed that they came from a girl who was made pregnant by Western winds. Hiawatha, the Algonquin hero, was born after his mother Wenonah received the visit of an astute wind. The ancient Finns told us that the virgin Ilmater, mother of the witch Vainamoinen, was inseminated by the east wind. The goddess Hera conceived Hephaestus, one of the gods, after inhaling an errant wind. The Babylonian goddess Tiamat was born when her mother's womb was filled with furious winds. The Arunta women in Australia hid themselves in their huts when the storm came from the north; it brought the seeds of the devil, responsible for twins being born.

The vision of the wind that brings life was linked to two other very common images in the mythology of the wind: birds and creation. The Harpies of Greek mythology—Aello (storm), Celaeno (obscure, with reference to storm clouds), Podarge (quickest) and Ocypete (she who flies fast)—were demonic beings with the head, the chest and the arms of a woman, the rest of the body of a bird of prey; in the

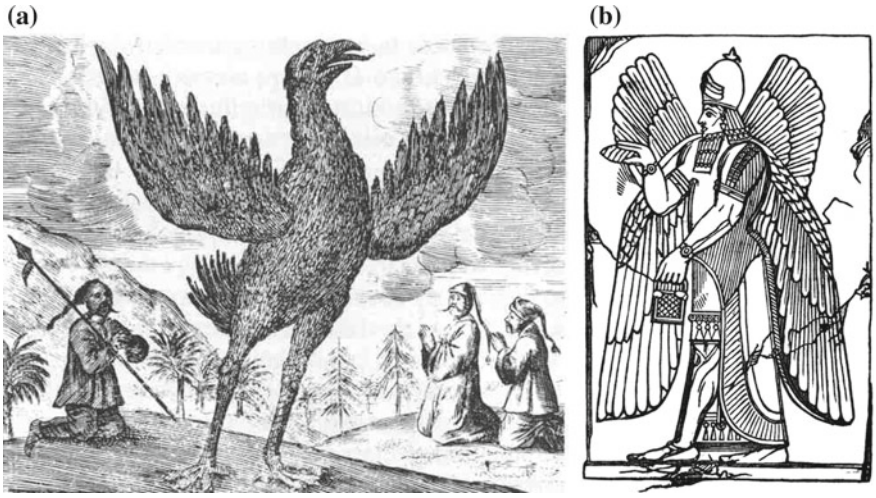

Fig. 2.1 **a** Hung Kong [3]; **b** Enlil

Greek popular belief, they carried divine revenge in the form of storms. Taiwanese people considered Hung Kong, a bird with monstrous wings, the cause of typhoons scourging the China Sea (Fig. 2.1a). In the Norwegian myth, Hraesvelgr was an eagle that devours corpses; sat on the edge of the world and distributed the wind by beating its wings. Similarly, New Mexico's Indians told of a crow that flew over the sea and brought it to life thanks to the wind caused by its wings. The Inuit on the shores of the Bering Sea worshiped Tulukauguk, the father crow and creator of the world. Brama, the creator, freed himself in the air on the back of Hamsa, the duck that personified the wind. According to the Melanesians, the world at the beginning was chaos; it remained so until Tabuerik, the god-bird, pounded over the turmoil and gave it a full form of thanks to the wind produced by beating his wings. The Aztecs of Mexico honoured the god of the Quetzalcoatl wind; his son Ehecatonatiuh allegorically represented the second historical age of mankind, the one destroyed by the wind; the gods then transformed men into monkeys to help them cling to the branches of trees, avoiding being grabbed by storms.

A relationship between wind and man emerged based on a dualism between good and evil [1, 3]. In the early days of the Assyrian Babylonian civilisation, around 3000 BC, Enlil was worshipped as the god of hurricanes (Fig. 2.1b); from 2000 BC, he was replaced by Teshup, god of lightning and storms and wind-maker; he was also honoured as the God of the wind's beneficial rainfall, an indispensable element for crops. Rudra, the Hindu god of the storms, is cited in the Vedas, the four sacred texts of Indian tradition; he is described as a god sometimes benevolent sometimes destructive, the divine healer and at the same time the demon who kills men and animals. For the Hurons and Iroquois of Canada, the Lord of the Winds was the father of Ioskeha, the creator, and of Tawiscara, the evil power. Amon, ancient Egyptian god of wind and fertility, with the passing of time took on the role of the king of the

gods; later, he acquired the qualities of Ra, the god of sun and spring of life, taking the name Amon-Ra. At Uxmal, temple of the Maya culture, storms were depicted with sigma, double sigma and swastika symbols, representing the devastating power of nature; yet they were coupled with the phallus and snake, typical emblems of fertility and life; it was symptomatic that Mexico saw in the hurricane an essential source of irrigation for its sun-scorched lands (Sect. 10.1).

The role of the wind is still characterised, even in modern terms, by the same dualism between good and evil. The wind is good when it fills the sails of boats, when it feeds mills producing energy, when it favours fresh air circulation inside homes or along the arteries of the urban fabric, when it takes away the fumes of polluting sources or brings the rain to the most arid areas. The wind is bad when it lashes men, houses and settlements with freezing or too hot air, when it devastates crops and makes transport dangerous, when it erodes soil or builds snow drifts, when it becomes a source of pollution, when it damages or even destroys buildings and territory.

This dualism does not comprise an ancient myth, which was to play an important role in the development of scientific knowledge in the twentieth century: the Aeolian harp [1, 2]. It is to be found in some of the oldest tales, not as a musical instrument in the strict sense, but as a magical item or concept, inspired and brought to life by the wind. Its sound is described as being soporific and lulling, or ethereal and spectral, adding to the mysterious aura surrounding the harp. The Jewish tradition has it that, at night King David hung the harp over his bed, so that he could be soothed by the sounds of the wind. Aeolus is the divine harpist, under calm, balmy conditions. During the monsoon, the first kite builders (Sect. 2.6) created sound orchestras over the villages of Malaysia. In England, during the Middle Ages, the Archbishop of Canterbury Saint Dunstan (925–988) reinstated the dictates of monastic life, making use of the sound of harps strummed by wind, raising suspicions of witchcraft. Athanasius Kircher (1602–1680) described the Aeolian harp he realised in *Misurgia universalis, sive ars magna dissoni et consoni*[1] (1650). It comprised a rectangular box in which 12 catgut strings of various thicknesses were tensioned (Fig. 2.2). More than two centuries had to pass before Strouhal, Reynolds and Karman provided a scientific explanation of the physical phenomenon that causes the harp's cords to vibrate (Sect. 5.1).

2.2 Speculation and Observation

Philosophy, which in Greek means "love for wisdom", is the study of the general principles common to the various disciplines of wisdom and knowledge. According to the philosophers of ancient Greece, to whom foundation of this discipline is normally attributed at around 600 BC, it is the totality of all the sciences. Interpreting the terms

[1] A description of the harp is contained in Liber IX, *Magia Phonotactica*, *Machinamentum X, Aliam Machinam harmonicam Automatam concinnare, quae nullo rotarum, follium, vel Cilindri phonotactici ministerio, sed solo vento & aerte perpetuum quondam harmoniosum sonum excitet*.

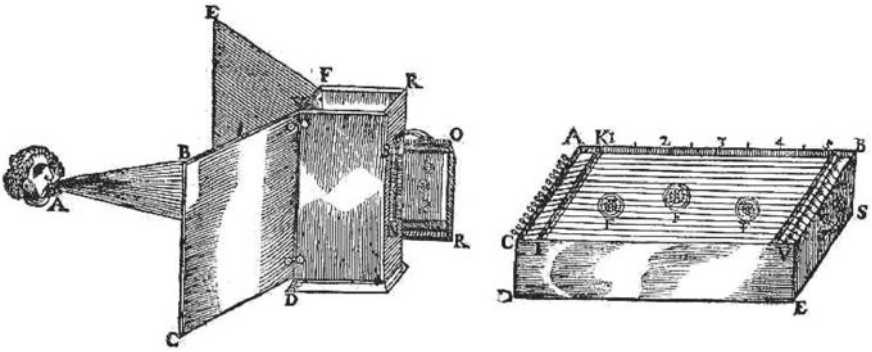

Fig. 2.2 Athanasius Kircher's Aeolian harp (from *Misurgia universalis*)

science and philosophy in a modern key, the science of the Greeks is what is now called philosophy.

The first Greek philosophers, the Presocratics, developed a cosmogonic and cosmological conception where nature, and therefore wind, played a central role. Using observation, the mythological interpretation was flanked and progressively overcome by the speculative vision [4–11]. With rare exceptions, the experience was absent.

The Ionian School, along the coasts of Asia Minor, was the first Greek philosophical school. Founded by Thales, it included, among its exponents, Anaximandros and Anaximenes.

Thales of Miletos (about 624–546 BC), considered by tradition one of the seven sages, was the first philosopher who tried to explain the world and cosmos according to the principles of nature, rather than as a consequence of divine forces. He argued that water, or humidity, is the "principle of all and has created everything". He rejected the existence of void. He supported the concept, albeit at the embryonic level, that man lives at the bottom of a sort of ocean formed by the atmosphere [9]. He also promoted the idea that the study of nature requires direct observations [5]. He is considered the founder of geometry (Sect. 2.3).

Anaximandros of Miletos (about 611–547 BC) was the author of *On nature*, a work in which he claims that everything is born from "ápeiron", the infinite, ingenerated, indestructible and indefinite principle. It was associated with the concept of water as a generator principle and that of fire, which, by joining with solid bodies, made them liquid, and joining with liquid elements transformed them into air [11]. Within this vision, that represents the first speculation on the origin of the wind, it was described as a movement of air masses produced by forces associated, in some way, to the sun [6]. Thanks to this statement, Anaximandros preceded by over two millennia some basic concepts of modern meteorology [9]. He was also the first to argue that the earth is in the centre of the universe.

Unlike Anaximandros, Anaximenes of Miletos (about 586–528 BC) stated that the air is the primordial principle from which "everything comes, everything returns"; thanks to its perennial motion, it penetrates everywhere and constitutes the universal

bond of nature. From air, the four basic elements of life are formed: air itself, fire, water and earth; water and earth originate from the air through condensation, fire forms due to rarefaction. He noted also that air cools moving upward due to the progressive reduction of intensity of sunlight reflected from the earth's surface [7].

The second Greek philosophical school was the Pythagorean School founded by Pythagoras of Samos (around 570–495 BC) in Crotone around 530 BC. By attributing to mathematics the role of the principal form of knowledge, and by interpreting the number as the principle of proportion and perfect harmony of the universe (Sect. 2.3), he identified five regular solids: cube, octahedron, tetrahedron, icosahedron and dodecahedron. The first four depicted the elements that form matter, in the order earth, water, fire and air; in turn, they derived from the combination of pairs of four basic qualities: cold, hot, wet and dry (for example, water is cold and humid; fire is hot and dry). The fifth solid was identified with ether. On such bases, Pythagoras argued that the study of "mundanae" figures was equivalent to the analysis of the five elementary particles.[2]

The Pythagorean School also offered remarkable contributions to astronomy and music. Philolaus of Croton (born around 430 BC) laid the foundations of heliocentric theory proposing a cosmological model that denied geocentricism. Aristarchus of Samos (about 310–250 BC) conceived the Earth as a rotating sphere, with other planets, around a central fire. Animated by these principles, Pythagoreans explained the order of the universe as a musical harmony of heavenly bodies that produced sounds; separated by intervals corresponding to the harmonic lengths of sound strings (Sect. 2.3), they formed the harmony of the spheres. They also introduced the concept, persisting in medieval times that geometry, arithmetic, music and astronomy constitute the "quadrivium" of education.

Parallel to the Pythagorean School, two philosophical orientations developed in Hellas and Magna Graecia that dealt with the problem of origin in an opposing way.

The first of these, the Eleatic School, was born in Elea in Magna Graecia thanks to Xenophanes of Colophon (about 565–470 BC). Doubting every affirmation, he professed the negation of science. This doctrine was to have devastating consequences on the development of thought and knowledge.

His most important pupil, Parmenides (born around 540 BC), wrote *On nature*, a work where he stated that the absolute and original being cannot be identified either with matter or with a concept that has immediate relations with the sensitive world, being an "immobile and eternal one". He also extended the concepts of uniqueness and immutability to earthly things, denying the existence of not being and of its real manifestations such as movement, becoming, void and nothingness.

Zeno of Elea (about 492–425 BC), the principal follower of Parmenides, founded dialectics, which is the art of arguing. To uphold the principles of his master, he refuted the concepts of continuity and movement making use, among other things, of Achille's famous paradoxes of the tortoise and of the arrow pointed in the direction of the tree. He instilled a lively aversion to science in the young Socrates.

[2]Orientals argue that five-element theory ("pentchatouan") was born in India thanks to Kanada. From this conception, comes the atomistic theory.

Opposed to this doctrine was the orientation founded by Heraclitus of Ephesus (about 536–470 BC). In his work *On nature*, he manifested contempt for the materialistic theories of Anaximandros and Anaximenes, arguing that reality is a "becoming" that stems from a generating fire in continuous transformation, a kind of material soul of which everything is made and to which everything returns. Around this thought, various philosophical lines developed that counteract the movement to immobility.

Empedocles of Agrigentum (around 482–423 BC) explained the reasons for the movement by asserting that the four elements of Anaximenes—air, water, earth and fire—are the origin of all beings. He also worked on Pythagorean ideas by establishing a parallelism with the most general concepts of solid, liquid, gaseous and "more rarefied than gaseous". Continuously agitated, these elements combine in the universe in different proportions, under the influence of two opposing divine powers: love, or attraction, that tends to unite them, and hatred, or repulsion, that tends to divide them. Within this conception, Empedocles provided a justification for the material texture of the wind; discussing the subject in an aura of mysticism and allegory, he also professed to be able to dominate the forces of nature. For this reason, he was called the "tamer of the winds".

Closer to the spirit of Heraclitus was the thought of Democritus of Abdera (about 460–370 BC), the founder of atomism. A disciple of Leucippus of Miletos (about 450–370 BC) but soon more famous than his master, he interpreted the universe and the wind, as a set of infinite indivisible and impenetrable particles, atoms, all equal in their quality but different in weight and size; they move continuously in the void and, colliding, aggregate and disintegrate, forming matter. The wind picks up when many atoms concentrate in a small space; it calms when large portions of space contain few atoms. According to Democritus, everything is material, including soul, and is regulated by forces acting mechanically.

Partially, similar concepts were developed by Anaxagoras of Clazomenae (about 499–428 BC). He argued that the universe is made up of infinite particles, "omeomeríe" or "seeds" of equal weight and size but of different quality; they are grouped by a sorting mind called "Nous" or"intellect". According to Anaxagoras, heat determines ascent of the air. He also understood that the air is warm near the ground and cold in the upper air. Clouds are formed when hot air, rising, comes into contact with the coldest air.

In the fifth century BC, in the face of the problem of origin, Greek thought was then faced with two alternative solutions. One imagined reality as absolute, immutable and eternal. The other saw it pervaded by an energy that pushed it to become continuous. From this contrast, the Sophist movement was born, namely the dialectical development of philosophy inspired by practical purposes. The greatest exponents were Gorgias of Lentini (about 485–380 BC), in the Eleatic spirit, and Protagoras of Abdera (about 480–411 BC) in the line of Heraclitus.

Socrates (470/469–399 BC), animated by a deep concept of absolute justice, reacted to Sophist thought by challenging the search for the useful to the benefit of the universal and eternal truth. Deeply influenced by Zeno, he denied the role of science in speculative problems and claimed that its use should be limited to

practical issues. He conveyed this form of aversion, at least in part, to Plato and Aristotle, conditioning the evolution of scientific thought for many centuries.

Plato (428/427–348/347 BC), the disciple favoured by Socrates, animated the thought of the master of religious afflatus, posing it in a sphere of sublime values; he formulated the doctrine of ideas, according to which there are two worlds, one superior and spiritual, immutable and eternal, the other inferior and material, changing and temporary. Between the spiritual world and the material world, he placed the soul, which participated in the essence of the first and in the materiality of the second. In Athens, Plato founded the "Akademia", where he promoted mathematics, astronomy, natural sciences and humanities. Like Thales, he proclaimed the importance of observation. He loved the Pythagorean bent for mathematics. More than the study of nature, he dedicated himself to physics and metaphysics.

Aristotle (384–322 BC), Plato's principal student, developed a partially different vision from that of his master. While Plato loved ideas, Aristotle loved facts.[3] While Plato was a speculative mathematician, Aristotle was a contemplative naturalist scientist [5]. Founder of the Peripatetic School, also called Lyceum, he gave life to a new doctrine that spanned vast horizons (Sect. 2.3), embracing the learning of his time. In this way, he realised a system of ideas that were to remain, for the whole of the Middle Ages and beyond, the official conception of the world, considered insurmountable and blindly accepted.

Aristotle shared the two basic principles of Plato's theory, calling the immaterial world "form" and the material world "matter". Unlike Plato, the two worlds were not independent but necessary for each other. Moreover, while Plato fixed the order of the universe, inspired by a mythology full of charm, Aristotle solved the problem by establishing a rigorous cosmology. According to Aristotle, the universe was divided into two concentric worlds: one celestial or supernatural the other terrestrial or sublunar. The celestial world was made up of ether, an incorruptible element called the fifth essence; it was composed of eight concentric balls to which the stars and planets belong; the last of them, the closest to earth is the moon. The terrestrial world was identified with our planet, the immobile centre of the universe, the site of continuous transformation of generation and destruction. Aristotle dealt with these concepts in *On the heavens*, where he argued that earth's transformations are caused by the opposing principles of heat and cold, humidity and dryness; acting in pairs, they produce the four fundamental elements: fire, air, water and earth; the first two tend to ascend, the others tend to fall. Aristotle considered heat, emanation of fire, a quality or an accident that brought together homogeneous substances and decreased or separated heterogeneous ones. Outside the universe, beyond the last sky, there was God, "motionless motor" and "thought of thought".

Aristotle tackled the topic of wind in *Meteorologica*, the discourse on celestial phenomena. It is the first meteorological treatise and consists of four books [10]. The first summarises the previous works on natural sciences, defines the object and

[3] Someone described Aristotle as a proponent of the experimental method for his sentence: "Experience must give its own matter to be elaborated and converted into general principles; logic is not the instrument that must provide the form of science."

the extension of meteorology, distinguishes the four elements of nature, describes comets, wind, rain, clouds, rivers, springs, dew, hail and climate and dwells on the previous misconceptions. In the second book, Aristotle formulates the general theory of wind by saying that "from the warming of the earth by the sun a non-simple exhalation is necessarily generated, but rather of two types: one more like vapour, the other is more like the breath": the humid exhalation is at the base of the formation mechanism of clouds, rain, snow, springs, rivers, dew and frost; the dry exhalation, highly flammable, produces comets, falling stars, winds, earthquakes, lightning strikes, whirlwinds and typhoons [3]. In the same book, he introduced a classification and definition of winds depending on their oncoming direction. He also proved the non-existence of empty space (the famous theory of "horror vacui", "nature abhors the void") that was to be a brake on the progress of knowledge for almost two millennia. In his third book, Aristotle formulated a theory of thunder and lightning, placing these phenomena in relation to fire, whirlwinds and typhoons. In his fourth book, he deepened the theory of the four elements, separating the active ones, heat and cold, from the passive ones, dryness and humidity.

Inspired by observation, Aristotle also refined the classification of the winds according to their origin in a peripatetic treatise, *Ventorum situs et appellationes*, where he identified twelve principal winds associated with as many directions[4] (Fig. 2.3) [12]: Thraskias and Argestes bring calm; Argestes and Euros, initially associated with a dry climate, cause a progressive increase in humidity; Meses and Boreas are cold winds; Notos, Zephyros and Euros are warm winds; Kaikias and Lips make the sky cloudy; the wind does not blow from the south-southwest [7]. He applied these concepts to formulate a number of urban principles of great interest (Sect. 2.8).

Theophrastus of Eresus (371–286 BC) was a pupil of Aristotle famous for his meteorological predictions (Sect. 2.4), and the author of a treatise, *On winds*, where he affirmed the existence of various types of winds, each accompanied by peculiar forces and conditions. He defined Greek winds, characterised by recurrence and cyclic forms, monsoons; among them, there were the twenty Etesian winds; they blow from the north in summer, for a definite number of days, ceasing in the evening, never happening at night. He also argued that air movement is caused by snow melting.

With Aristotle, the intense creative movement of Greek philosophy ended. The philosophical schools that developed after him reflected the sense of bitterness pervading the spirits and reflected the rampant dejection in the Greek–Roman world; so, they called upon previous experience, to come to conceptions that help overcome the daily drama of existence. It is a strange fact that the behaviour of the beaten population, the Greeks, spread to the victors, the Romans. They shied away from the abstract speculations of Plato and Aristotle to follow new philosophies more adherent to practical life.

[4]Throughout the classical era, there were two wind roses in the Mediterranean, one referring to twelve directions, the other to eight. According to some researchers, the wind rose of twelve winds originated from the Mesopotamian Zodiac, namely of 12 signs. Moving the Zodiac from heaven to earth organises the territory in the image of heaven, attracting the favour of gods. It is possible that Aristotle was influenced by this conception.

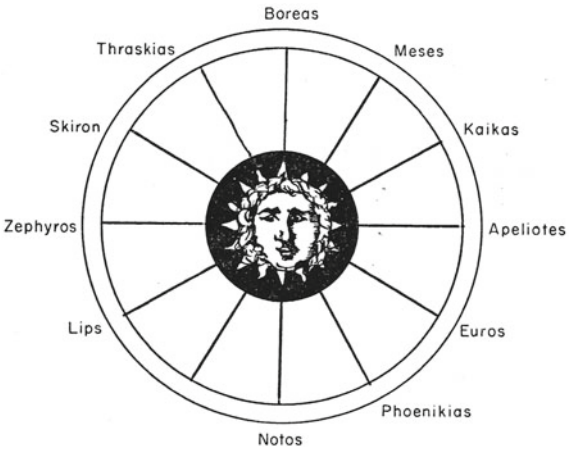

Fig. 2.3 Aristotle's wind rose [12]

On the basis of this assumption, the Romans developed four lines of thought: epicureanism, stoicism, scepticism and eclecticism. Epicureanism, founded by Epicurus of Samos (341–270 BC) and spread to Rome by Titus Lucretius Carus (98–54 BC), resumed the atomic doctrine of Leucippus and Democritus, arguing that the universe lives on the unstoppable motion of atoms which aggregate and disintegrate, giving rise to an infinite succession of worlds and composite materials; in the *De rerum natura* (60 BC) Lucretius stated that heat is a fluid substance emitted by burning bodies, he noted that sound takes some time to pass from source to the receiver and identified the energy source of the tornado in the electric forces present in the air (Sect. 10.2). Stoicism, founded by Zeno of Citium (334–262 BC) in the footsteps of Heraclitus, and advocated by Emperor Marcus Aurelius (121–180 AD), dealt with the world as a great living organism with a body of water and earth and a soul, or "pneuma", of air and fire. Scepticism, founded by Pyrrho of Elis (360–270 BC), criticised previous philosophies, arguing that man cannot reach the truth because of the subjectivism of his state of mind. Eclecticism, of which Cicero (106–43 BC) was the greatest exponent, was the typical Roman philosophical orientation, collected the principles of the various philosophies, aligning them with the "common sense" possessed by all men.

Against this background, the naturalistic and speculative interest in the wind, born in ancient Greece, continued with the Romans thanks to Virgil, Ovid, Seneca and Pliny the Elder. Their writings offered a clear testimony of a still deeply rooted mythological vision.

Publius Vergilius Maro (70–19 BC) recounted some stories of Homer (IX–VIII century BC) in the *Odissey*, presenting the Harpies (Sect. 2.1) as creatures heralding storms. In *Georgics,* he dealt with weather forecasts (Sect. 2.4). In *Aeneid,* he provided numerous descriptions of the Mediterranean winds, highlighting a nomenclature often different from the Greek one.

The masterpiece of Publius Ovidius Naso (43 BC–17 AD), *Metamorphoses*, consists of 15 books that narrate the transformations from original chaos to the divinisation of Caesar (100–44 BC) through about 200 fairy tales from which the legend of Daedalus and Icarus (Sect. 2.6) stands out. In this poem, Ovid reordered Greek and Roman myths, exhibiting them in a widely renewed narrative form. Most of the wind representations in medieval and Renaissance art, in Elizabethan and Romantic literature, and in modern thought, are still anchored to his descriptions.

Lucius Annaeus Seneca (2–65 AD) was the author of *Naturales quaestiones*, a four-volume treatise inspired by the Greek opera [7]. The first three volumes were dedicated to rainbows, dawn, thunder, lightning and wind. The fourth dealt with clouds, rain, dew, hail, frost, snow and ice. Seneca also explored astronomy, earthquakes and comets, interposing moral reflections and lively stories. He had cleared the concept that temperature decreases as the height increases.

Pliny the Elder (23–79 AD) was the greatest representative of Roman scientific excellence in the imperial age. He wrote the first encyclopaedia of natural sciences, *Naturalis historia*, a reference document on science in the ancient world. The work, in 37 volumes, contains a synthesis of over 2000 works by Greek and Latin authors centred on nature and largely on the wind. This provides a vision where mythology and observation coexist. On the one hand, Pliny interpreted genesis explaining that there are "certain caverns and holes that generate winds continuously and without rest" (Sect. 2.1). On the other hand, he came to describe the complex circulatory phenomena that occur in the Mediterranean area referring, unlike Aristotle, to a rose of eight winds: Septentrio (N), Aquilo (NE), Subsolanus (E), Volturnus (SE), Auster (S), Africus (SO), Favonius) and Corus (NO).

With the advent of the vulgar era, two new philosophical orientations emerged: Neoplatonism and Christianity. Neoplatonism, established by the Greek Plotinus (204–270), spread to Rome from 245 AD, when Plotinus himself founded a school that introduced two profound innovations: the conception of a supreme truth that unlike the Aristotelian divinity was unthinkable and unrecognisable by reason, and the affirmation of a form of non-rational knowledge. Christianity developed through two successive periods, Patristic (first–eighth century) and Scholastic (ninth–fourteenth century), which ferried humanity from Aristotelian truth to Galilean reason.

Patristics pursued a dual objective: to fix the peculiar elements of Christianity and to establish a path of reconciliation between Christian philosophy and pagan philosophy. Saint Augustine (354–430), the most creative figure of the early period of Patristics, recognised the contribution of Neoplatonism to Christianity in the *Confessions* (397), where he noted the deep influence exerted by this philosophical school on his religious thought.

With the spread of these doctrines, the influence of the great pagan thinkers—Aristotle, Lucretius and Pliny—began to decline, and the interpretation of atmospheric phenomena returned to ethics and theology. The discovery and dissemination of passages as "the Lord struts in the whirlwind and in the storm", from the first chapter of the *Book of Nahum*, stifled what remained of the ancient naturalist philosophy.

Isidore of Seville and Bede the Venerable partially moved away from this conception. Isidore of Seville (560–636) was the author of a monumental work in 20