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What causes winds was regarded as one of the most difficult questions of early modern natural philosophy. Vitruvius, the ancient Roman architectural author, put forth an alternative to Aristotle's theory by likening the generation of wind to the actions of the aeolipile, which he believed made artificial winds. As Vitruvius's work proliferated during the sixteenth and seventeenth centuries, numerous natural philosophers, including Descartes, used the aeolipile as a model for nature. Yet, interpretations of Vitruvius's text and of the relation of the aeolipile to natural winds varied according to definitions and conceptions of air, wind, rarefaction, condensation, and vapor.

1. Introduction

Numerous early modern natural philosophers, Aristotelians as well as their detractors, invoked the workings of the aeolipile to explain the origin and matter of winds. An aeolipile, in its simplest form, is a hollow metal ball or vessel that has one or two small openings. An external fire, or other source of heat, warms water placed within the ball until jets of steam and air shoot forth from the aperture or apertures. From antiquity to the seventeenth century, natural philosophers referred to this artificial device as evidence for specific theories of the wind. These writings typically cited Vitruvius, the ancient Roman author of *De architectura*, who gave the earliest

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extant identification of the generation of winds with the functioning of the aeolipile.

Although the example of the aeolipile was routinely called an experience or experiment, it was neither an example of quotidian experience, being a relatively uncommon device, nor an example of a contrived test or crucial experiment that could resolve a particular issue. It is even unclear, and perhaps irrelevant, whether many natural philosophers who referred to the aeolipile had even seen or used one since the transmission of knowledge of Vitruvius's apparatus was largely textual. Nevertheless, the aeolipile was a potential experiential model for the workings of nature. As an attempted artificial reproduction or imitation of nature its meaning was ambiguous. Natural philosophers read the apparatus in different ways. Many recognized limitations of the model, although they did not agree on what those limitations were or on how the model related to natural winds. Readings of this device changed according to varied definitions of air and wind, according to differing conceptions of condensation and rarefaction, and according to new understandings of the weight of air. Descartes' presentation of this device as an artificial replication of winds bolstered his conviction that artificial and natural bodies are moved by the same causes. Most of those, such as the Englishmen Ralph Bohun and Robert Boyle, who rejected his account, did so because they thought that the effects of the aeolipile were not similar to the way certain winds are generated. For the most part, Descartes' (and Vitruvius') critics partially accepted the analogy while rejecting it as a universal model for natural winds.

2. Ancient Background

Vitruvius, despite believing that the aeolipile replicated natural winds, failed to put forth a coherent theory of their nature. As a result, interpretations of his text on the relation of the aeolipile to natural winds varied. Natural philosophers and scholars easily adapted his work to different theories of winds. For example, some early modern thinkers believed that the aeolipile provided evidence, against Aristotle, that winds were moving air, while others, contended that it demonstrated that wind was composed of aqueous vapors.

Aristotle's understanding of the winds offered a frequent starting place for early modern theories, for those that contested, altered, or accepted Peripatetic frameworks. Aristotle's determination of the cause of wind derived from his understanding of the dual exhalations, the vaporous and terrestrial, as being responsible for most meteorological phenomena. Aristotle explained that wind is not simply moving air, just as motion does not make water a river. Instead winds are regular or semi-regular flows of the terrestrial exhalation. Aristotle understood wind to be in opposition to rain, just as he believed that their underlying matter were contraries: rainy weather derives from the vaporous exhalation, while windy conditions result from what is called the dry, terrestrial, or smoky exhalation. Although Aristotle did not think elemental air was the matter of winds, his language at times was ambiguous; he described air as the matter of the region between the earth and the moon, although this air is conceived as being made up of both exhalations (360a21–27).

For Aristotle, heat, deriving from either the sun or the earth's interior, is an efficient cause. The sun's heat draws up vaporous exhalations into the middle region of the sublunary region where they fall after being affected by the cold (359b34–360a16). Aristotle described this process as constant: "the exhalation continually increases and decreases, expands and contracts, clouds and winds are constantly being produced" (360a34–b3). In *De caelo*, he described the transformation of water into vapor. The newly created air has "finer" (*leptomeresteron*) parts and therefore takes up more room, citing as evidence that water turned to steam can break its container because of lack of space (305b12–16). In this manner Aristotle associated the qualitative causes of hot and cold with changes in the size and quantity of exhalations.

Aristotle's position that wind is not merely moving air met opposition throughout antiquity, beginning with his followers. The *Problemata* described wind as moving air, following Theophrastus's *De ventis* (940b5–8; 944a26–27). The Hippocratic *De flatibus* also indicated that the wind was a moving mass of air (3,1). In the *Natural Questions*, Seneca, maintaining that wind is air that moves in one direction, offered an alternative to Aristotle's efficient cause as well (*NQ* V,1,1). He held that the sun's morning light not only heats but also strikes (*concutit*) with blows (*ictus*) the air, driving it in a lateral direction (*NQ*, V,9,3). Other evening winds come from swamps and rivers that emit exhalations that collect in areas closed by mountains. As the area becomes filled, the exhalation is pressed out (*exprimitur*) through an open space, thereby creating wind (*NQ,* V,8,1).

Vitruvius gave an account similar to Seneca's of morning winds by which the sun's "twisting beats (*pulsat*) the air's moisture (*humor*) that rises forward with force (*impetus*) and presses (*exprimit*) the flows of gales with its predawn exhalation (*spiritus*)" (1,6,11). This poetic description describes the generation of all winds, not just matutinal ones. Vitruvius wrote: "Wind is a wave of flowing air with irregular overflows of motion. Wind comes to be when heat hits (*offendit*) moisture (*humor*) and the resulting force (*impetus*) presses (*exprimit*) the power (*vis*) of the exhalation (*spiritus*)" (1,6,2). Vitruvius's explanation is a two-step process: heat moves the moisture, which in turn drives air into motion.

As support, Vitruvius cited the aeolipile. He believed these devices allow us to "know and judge … the explanations for the winds" (1,6,2). For

Vitruvius, this artificial device mimics the workings of nature, indicating that wind is air laterally moved by moisture that has been impelled by heat or the sun's force. The strength of this demonstration is that the aeolipile expels vapor horizontally. The wind's lateral motion puzzled Aristotelians, who held that the terrestrial elements naturally moved away or toward the earth's center. Oblique flows of the winds suggested a violent motion, yet their constancy pointed to an unyielding cause. Winds defied simple explanations to the extent that Jean Bodin declared that there was no natural cause and looked to the divine, proclaiming angels to be the cause of this seemingly unnatural motion (Bodin [1596] 1597, pp. 159–63).

Vitruvius emphasized the importance of using natural philosophical principles and elements as starting points for architecture and other endeavors. These principles, despite having some kinship to Stoicism, were left undefined, allowing his examples, often more practical than speculative, to fit with multiple visions of nature (Berryman 2009, pp. 130–43). Consequently, interpretations of his text varied. Natural philosophers and scholars easily adapted his work to different theories of nature or winds.

3. Late-Renaissance Reception

References to the aeolipile were relatively infrequent until the middle of the sixteenth century. Before then, few cited it as a model for nature. Without linking the device to natural winds, Hero of Alexandria described a rotating version with two jets, which was also known during the Renaissance (Hero 1575, p. 52; Boas 1949). Archeological research has uncovered numerous medieval and early modern examples, some in the shape of humans and some that appear to have been used in mining or alchemical operations for raising the temperature of fires (Hildburgh 1951; MacGregor 2007, pp. 289–90). When steam from an aeolipile is sprayed on hot coals it separates into hydrogen and oxygen, which combines with the carbon of the charcoal to form carbon monoxide, both of which are then burned by the fire. In perhaps the earliest philosophical reference to the apparatus in the Middle Ages, Albertus Magnus described a "sufflator" that was often anthropomorphic in shape. Instead of considering winds, Albertus thought the device offered an analogy to the expulsion of water from the earth during earthquakes and volcanic eruptions (Albertus Magnus 2003, pp. 146–47).

During the fifteenth century, the aeolipile appears to have been an object of courtly luxury, judging by Filarete's description of one, the extant example found in the British Museum, and the fact that one was presented to King René of Anjou in 1448 (Filarete 1972 vol.1, p. 268; Hildburgh 1951, p. 48; Warren 2004, p. 36). Prominent sixteenth-century authors, including Ambroise Paré, Bernard Palissy, Girolamo Cardano, and Georgius Agricola, described aeolipiles or similar devices (Hildburgh 1951, pp. 28–9, 31). At that point, new translations and editions of Vitruvius's *De architectura* proliferated (Ciapponi 1976). During this same period mining and chymical workshops seemingly used the device with greater regularity than before. By 1648, John Wilkins characterized their use for heating metal and glass as common (Wilkins 1648, p. 149; MacGregor 2007, p. 291). Knowledge of these devices was widespread enough that Rabelais likened a particular strong case of flatulence to not just the actions of an aeolipile but also to blowing wind in book four of *Pantagruel* (Rabelais [1552] 1991, p. 532). Although many medieval manuscripts of *De architectura* circulated, by Rabelais' time, it was even more widely available, having been translated into German, Italian, and French and released in numerous Latin editions (Krinsky 1967; Rowland 1998).

De architectura, the subject of numerous commentaries, was highly influential among architects and engineers, for whom it became a model for architectural treatises and a prominent source for knowledge of ancient building practices and styles (Payne 1999). Those interested in natural philosophy and mechanics also valued its contents. The professor of medicine Gabriele Falloppio praised Vitruvius's understanding of subterranean heat, a topic at least tangentially related to winds (Falloppio 1569, p. 14r–v). Several erudites occupied with mechanics acknowledged Vitruvius's conception of the subject. For example, Alessandro Piccolomini, author of a famed treatise on mechanics had read Vitruvius (Vilain 2008, p. 155). Giuseppe Moletti in his lectures on the Aristotelian *Mechanica* in the 1580s tried to confer dignity to the field by approvingly citing Vitruvius's statement that "all the machinery of things is born of nature" (Laird 2008, p. 177).

The two earliest sixteenth-century commentaries on Vitruvius show little concern with natural philosophy in their discussion of the aeolipile. Cesare Cesariano's lavishly illustrated and architecturally sophisticated commentary distinguished so few differences between Vitruvius's and Aristotle's theories that it directed the reader to Aristotle's *Meteorology* should the discussion of winds in *De architectura* prove to be unsatisfactorily short (Cesariano 1521, p. 23r). Cesariano, however, affirmed the importance of Vitruvius's experiment with the aeolipile because it showed how "human ingenuity through human works can obtain accurate knowledge of the truth of the divine secrets that operate similarly" (Cesariano 1521, p. 23r). Shortly thereafter, Guillaume Philandrier, a philologist who also commented on Quintillian's *Institutes*, explained only the etymology of aeolipile in his Vitruvian commentary, without considering the relevance to investigations into nature (Philandrier 1552, p. 30).

In contrast to these earlier accounts, Daniele Barbaro considered the experimental ramifications of the aeolipile in his 1567 translation and commentary on *De architectura*. Barbaro, a Venetian patrician, gained his natural philosophical training while studying medicine at Padua, where he eventually oversaw the construction of its botanical garden (Cellauro 2004, pp. 293–94). His Aristotelianism colored his reading of Vitruvius, notably with respect to theories relating to aesthetics but also in his comments on the section on winds (Mitrovic 1998).

Barbaro doubted the significance of the aeolipile for proving that winds are moving air. He wrote that Vitruvius, despite demonstrating the power of heat in the formation of winds, "did not clearly explain its effects." Barbaro asserted that "the wind is the exhalation of the earth, which rises up into the air, and, having been crushed by the cold, which is in that [upper] part of the sky, strikes the air with violence." In his view, the sun's heat lifts these terrestrial humors, "making them the most rarefied bodies" (Barbaro 1567, p. 55). Barbaro explained that the aeolipile converts water into air, which has greater volume than water since it is more rare. The water having been transformed into air then escapes through the small opening. A stronger effect could be achieved, according to Barbaro, by converting the water into fire, which is even more rarefied. In this manner, he explained the action of gunpowder in artillery. Despite explaining the mechanics behind the aeolipile, Barbaro rejected it as a model for wind as a wave of air, maintaining that the air moves with the terrestrial humor rather than being set in motion by the wet exhalation (Barbaro 1567, pp. 55–6).

Barbaro's use of the concept of rarefaction is significant since much of the substance of later debates was whether rarefaction could create wind, with a number of Aristotelians rejecting the possibility. In Vitruvius's text there is no mention of rarefaction. His understanding of the functioning of the aeolipile, and consequently of the generation of winds, is based solely on motion imparted to water's humor that in turn strikes the air, expelling it from the ball. Aristotelians, however, relied greatly on the concepts of rarefaction and condensation, which for them, were accidental qualities caused by heat or coldness that confer heaviness and lightness and at times are related to space and extension. For example, Pietro Pomponazzi, professor at Padua and then Bologna, in his commentary on *Meteorology* 4 wrote that heat's essential and *per se* power is to heat; and its secondary power is to rarefy (*rarefacere*) (Pomponazzi 1563, p. 3). Pomponazzi understood rarefaction in spatial terms closely related to dissolution (*disgregare*) and extension (*extendere*), associating this view with physicians who hold that the "operation of heat is to rarefy (*rarefacere*) and extend (*extendere*)" (Pomponazzi 1563, p. 2).

At least one sixteenth-century physician described a device similar to an aeolipile in precisely these terms. In a work first printed in 1551, Ambroise Paré described the internal workings of an aeolipile-like device used by German troops as a bomb in his famous treatise on firearm wounds. For this device, the copper ball does not have an opening and the heated vapor causes an explosion. In Paré's account, the water, "because it occupies more space in the form of air in which it has been changed," violently creates an opening in its container. According to Paré, this bomb confirms what natural philosophers know, that "one part water, [is] ten of air" (Paré 1633, p. 315).

Paré's ratio of the expansion of water into air derived from interpretations of *De generatione et corruptione* 2.6, where during the discussion of the transmutation of the four primary elements, earth, water, air, and fire, Aristotle responded to Empedocles' claim that the elements are incommensurable and therefore cannot transform into each other. Aristotle quoted Empedocles as writing "since these [elements] are all not equal" (333a20). Aristotle explored the possible meanings of this utterance, including whether this supposed inequality is with respect to quantity or power. In his discussion of quantity he suggested the possibility that "one measure of water is equivalent to ten of air" (333a23). These words became the basis for the belief that air occupies ten times the amount of space as water. An example of this contention is found in Gaetano of Thiene's commentary on the *Meteorology*. He stated "air is ten times as much as water, as is fire to air and water to earth" (Gaetano of Thiene 1476, A1r). This ratio of water to air, or water to aqueous vapor, limited the power of rarefaction, as it had for Paré. This limitation meant that many accepted the reality of rarefaction and condensation in nature yet rejected that it was powerful enough to drive winds.

During the first part of the sixteenth century, prominent commentaries on Aristotle's *Meteorology*, such as those by Francesco Vimercati and Agostino Nifo, did not refer to Vitruvius's aeolipile, preferring a hermeneutical approach that followed closely the ancient Greek commentators (Nifo [1523] 1560; Vimercati [1556] 1565). Yet they used rarefaction and condensation to explain meteorological phenomena besides winds. Nifo used rarity and density of the exhalations to explain lightning and Vimercati for thunder (Martin 2011, pp. 93–94).

By the end of the 1500s, references to Vitruvius's aeolipile appear frequently in natural philosophical works, reflecting the growing influence of Vitruvius as well as greater engagement among natural philosophers with practical endeavors that used aeolipiles as fire-blowers. For example, several Aristotelians referred to this ancient device, which they associated with Vitruvius. Francesco Piccolomini, a professor of philosophy at Padua, doubted that Vitruvius's example provided a general explanation for the wind, holding that wind is composed of the dry exhalation. He wrote that "various exhalations can be moved and agitated but not all, however, are wind" (Piccolomini 1597, p. 923). Vitruvius's "experiment" (*experientia*) shows that heat and the water's humor move air, while "Aristotle considered what happens for most of the time because, for most of the time wind is a rare and dry spirit (*spiritus*) roused up by heat" (Piccolomini 1597, p. 923). Piccolomini conceded that a few winds might arise by Vitruvius's model, but he held that his general conclusion was unwarranted because winds that are made by the wet humor are always mixed with this rare and dry spirit (Piccolomini 1597, p. 923). In this manner, Piccolomini hesitatingly accepted that the aeolipile could be a model for some winds while rejecting the conclusion that winds are moving air.

Piccolomini's disagreement lay partly in different understandings of the definition of air and exhalation. To maintain that wind is merely moving air went against the Aristotelian understanding that the elements do not exist in pure form as well as contradicting quotidian experience that recognizes qualitative differences in winds. Even those who were ready to follow Vitruvius, along with Hippocrates, the *Problemata*, and Theophrastus, thought that winds, even if mainly air, contained vapors. Girolamo Cardano, after going through a lengthy argument in favor of the proposition that wind is moving air in his commentary on the Hippocratic *Airs, Waters, Places*, conceded that winds could not be only air because it is the various exhalations contained within the winds that is the source of their salubrious or noxious characteristics (Cardano [1570] 1663b, p. 7). Nevertheless, in *De rerum varietate*, which Cardano maintained he wrote after abandoning a commentary on Vitruvius, he described the aeolipile as emitting wind (Cardano [1557] 1663a, p. 245; Ciapponi 1976, p. 409). Some Aristotelians were also willing to deviate from Aristotle's view that winds were made up of the dry exhalation. The Coimbran commentary, for example, maintained that some winds consisted of the wet exhalation, or vapor, as well as the dry exhalation (Collegium [1592] 1631, col. 55). The Franciscan Scotists Mastri and Belluti contended that wind could be composed of "simple air, or exhalations and vapors" (Mastri and Belluti 1640, p. 253).

It is unclear whether Piccolomini, or Barbaro, had ever used or seen an aeolipile. Their accounts do not indicate any acquaintance with the device beyond textual. Others, such as Cardano, however, perhaps had hands-on experience, although it is not clear whether use of this device affected interpretations of its significance. Daniel Sennert, a man well versed in chymical practice, which he applied to his understanding of meteorology, perhaps used aeolipiles (Martin 2011, pp. 109–12). Sennert, like the Coimbrans and other late-Renaissance Aristotelians, did not hold that all winds were made up of the terrestrial exhalation. Rather, he contended that there were various kinds of winds, composed of different mixtures of both the wet and dry exhalations. Winds that are purely made up of the dry exhalation are uncommon. Each wind takes on the qualities from the place where it originated, so winds potentially are hot and dry or cold and wet (Sennert 1618, p. 288).

Sennert accepted that wind comes not just from the middle region of the sky but that it was "very probable" that vapors arise from caves and other places closed within the earth (Sennert 1618, p. 290). He held that there is a "subterranean heat," below the earth as well as the sea, theorizing that the force of this heat underneath the sea gives rise to tempests. As evidence that the subterranean heat might be a cause of winds, Sennert referred to "the instrument that Chymists use in place of bellows." He described how chymists use fire-blowers with an aperture or an external tube to stoke fires, suggesting that this offers an analogy for how maritime storms arise (Sennert 1618, p. 291). Yet, for Sennert, the aeolipile did not offer a universal parallel to winds, since he maintained that many are generated by the motion and position of stars, planets, and sun.

A few Aristotelians rejected Vitruvius's theory of the winds outright. Libert Froidmont, a professor at Louvain best known for polemical exchanges with Descartes, associated Vitruvius's theory with Seneca, as well as that of Giovanni Battista Benedetti, namely that wind was caused by rarefaction and condensation. Benedetti, like Barbaro a Venetian noble, complained that none of Aristotle's followers used condensation and rarefaction to explain the winds (Benedetti 1585, p. 192; Borrelli 2008, pp. 73–75). Analyzing numerous kinds of condensation and rarefaction, he linked these phenomena to the powers of heat and cold, just as Aristotelians did, holding that the sun's heat rarifies vapors and humors, which in turn causes them to rise (Benedetti 1585, p. 194). Without referring to Vitruvius, he described an experiment in which air heated in a vase rarifies and expands (*dilatatur*), causing it to leave the vessel (Benedetti 1585, pp. 193–94).

Benedetti's explanation influenced Giovan Battista Della Porta and Cornelis Drebbel, who used inverted-glass or calendar glass experiments to demonstrate the ability of air to expand and contract (Borrelli 2008, pp. 88–93). Unlike Benedetti and Drebbel, Della Porta referred to Vitruvius's aeolipile in his *De aeris transmutationibus*, which is not surprising considering Della Porta's erudition and elaborate citation practices. Using vocabulary distinct yet nearly equivalent from his Aristotelian colleagues, Della Porta held that "air is thinned out (*extenuatur*) and scattered (*disiicitur*) by heat" so that "one part changes into many released parts" (Della Porta [1617] 2000, p. 43). Accordingly, if air that is thick (*concretus*) "warms by the glowing sun, it flows more freely and spreads into a wider region, from where it overflows violently and more forceful winds arise" (Della Porta [1617] 2000, p. 43). This transformation, according to Della Porta, is made clear by Vitruvius's "experimentum" (Della Porta [1617] 2000, p. 45). In this manner, Della Porta explained that winds are made of flowing of air and it is the heat's power of thinning out and dispersing aerial particles that causes these flows.

Rarefaction and condensation were not completely alien from Aristotelian meteorology, and the text of the *Meteorology* points to the quantity of vapors and exhalations in its explanation of winds. Accordingly, Froidmont accepted that air and vapors condense but did not believe that rarefaction and condensation were sufficiently powerful to create wind. Moreover, he asserted that many winds do not rise in conjunction with excessive rarefaction and condensation of air and vapor. Froidmont contended that strong winds are present in the summer, when the air is very rare, in winter, when it is very condensed, and in spring and autumn, when the air is neither. Other examples of quotidian experience supported his arguments: condensation of the air is an effect, not a cause, of icy winter winds; the air of his native Brabant is often cold and condensed, which should, under Benedetti's theory, cause winds to flow into Louvain from all directions, a hypothetical phenomenon that runs counter to experience (Froidmont [1627] 1656, p. 182).

Other Aristotelians accepted that rarefaction (or dilation) and condensation (or contraction) of the air could cause at least some winds. Niccolò Cabeo, the Jesuit author of a commentary of the *Meteorology* that endorsed chymical practices and a corpuscularian reading of Aristotle, maintained that some underestimate the powers of rarefaction and condensation (Cabeo 1646 vol.2:172). Cabeo criticized Froidmont for what he considered an inaccurate and uncharitable reading of Bodin, so it is plausible he also had Froidmont in mind in this instance as well (Cabeo 1646, 2:170). Cabeo argued that rarefaction and condensation are not universal causes of wind. He wrote that "it seems clear that rarefaction and condensation of air by itself can excite a motion in the air by which air moves, and by common agreement and sense, is called wind" (Cabeo 1646, 2:171). Yet, this is not the only cause of winds, for Cabeo. In partial agreement with Froidmont, he cited the many violent effects of winds that tear down trees and buildings. For these winds, rarefaction of the air is not sufficient, but, having drawn a parallel to gunpowder, Cabeo concluded that many winds must be caused by spirits similar to salnitre (Cabeo 1646, 2:172).

Francis Bacon seemingly cited Drebbel's experiments and described a variation of the aeolipile experiment (Colie 1955; Keller 2010, p. 48). In the *Historia ventorum*, he described heating air with fire in an enclosed tower. The heat caused the air to exit a small window, although apparently not steadily in the fashion of strong winds (Bacon [1622] 2007, pp. 70–72). Bacon concluded that some winds, notably weak ones, are caused by the dilation of air but winds are made of vapors and exhalations changed into impure air (Bacon 2007, p. 73). According to Bacon, vapor when "dissolved into air" increases its volume significantly, at least one hundred times more, causing it to rise to middle region of the sky where it creates wind by "overloading the air and making tumult" (Bacon 2007, pp. 62–4). Bacon, unlike Cabeo, was less drawn to using explosives as an analogy for strong winds, in part because he believed that many overestimated the strength of wind. Bacon thought that winds uproot trees only by using the trees' size and weight (Bacon 2007, pp. 52–4). Bacon, fitting in with Cabeo and Sennert, rejected that rarefaction and condensation were universal causes of the moving air that forms wind. Reports from travelers, medical knowledge, and new natural histories, such as José de Acosta's confirmed that winds varied in their matter, qualities, and origins (Acosta [1590] 1890, 1:169–212). The aeolipile might prove that air can be moved as the result of rarefaction but it did not provide knowledge of a general cause.

4. Descartes and Cartesians

Descartes invoked the aeolipile seemingly to counter Froidmont's doubts about the ability of rarefaction and condensation to cause winds. According to Claus Zittel, Descartes' "experiment attempts to demonstrate how even a small quantity of water can engender quite a strong wind" (Zittel 2008, p. 364). There were also broader ramifications, since Descartes made the aeolipile a general model for wind. Consideration of the device served the additional goal of demonstrating the plausibility that explanations for the motions of natural and artificial bodies are identical, which he contended in the *Principia* and in later correspondence (AT 5:546; AT 8,1:326; Manning 2013, p. 239). Descartes also used an aeolipile as an analogy for the heart's role in the circulation of blood (Beverwyck 1644, p. 133).

Descartes' theory of winds resembles Seneca's and Benedetti's but his presentation was innovative in several respects. Where Descartes learned about aeolipiles is unknown, although he was probably familiar with Salomon de Caus' description (Zittel 2009, p. 213). He likely read about the aeolipile in the *Récréation mathématicque*, a work, which Descartes and Mersenne knew, derived from Jesuit lectures at Pont-à-Mousson, widely attributed to Jean Leurechon (Heeffer 2013, pp. 437–39). The *Récréation mathématicque* described the functioning of Vitruvius's aeolipile as depending on rarefaction and condensation, estimating that water occupies 1000 times more space after it has become vapor (Leurechon [1624] 1627, pp. 128–29). Descartes also read among contemporary medical authors, including most

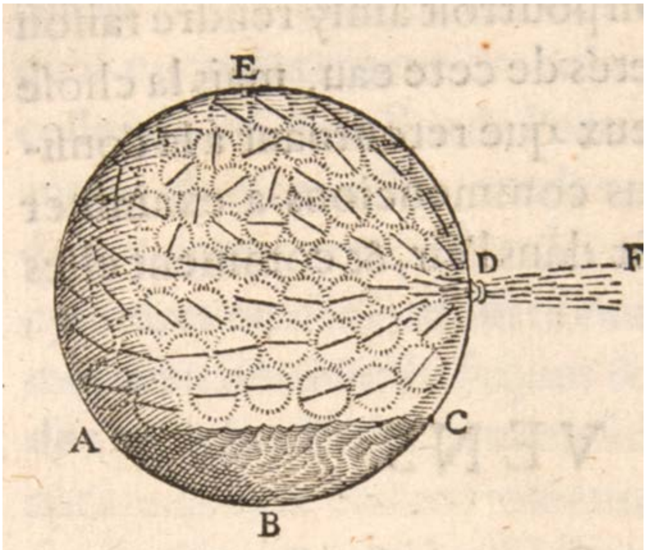

Illustration 1. (Descartes 1637, 190. By permission of History of Science Collections, University of Oklahoma Libraries)

probably Paré, so he potentially knew his description of the aeolipile-like bomb (AT 10:90; Manning 2013, p. 241–p. 42n21). Unlike Caus and Paré, Descartes referred to the device as an aeolipile, indicating he knew its ancient provenance.

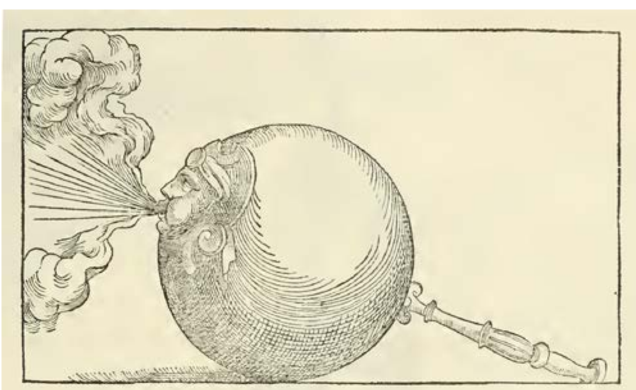

Illustration 2. (Vitruvius 1547, 11r. By permission of The Getty Research Institute, Los Angeles (87-B7748))

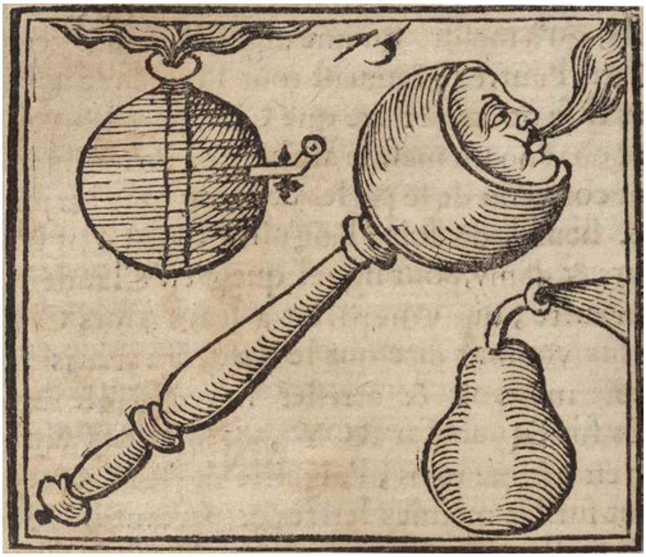

Illustration 3. ([Leurechon] [1624] 1680, 116. By permission of The Folger Shakespeare Library)

Descartes' aeolipile [see illustration 1] differs from earlier woodcuts, such as that made by Jean Goujon in the 1547 French translation of Vitruvius, which shows the device, in the form of Aeolus, the mythical ruler of the winds, expelling puffs of steam [see illustration 2]. The *Récréation mathématicque* portrayed three different kinds, one similiar to Goujon's, and others more like ones used in artisanal settings [see illustration 3]. In metallurgical works, such as Lazarus Ercker's, the device functions as a fire-blower attached to a furnace [see illustration 4]. Caus' *Les raison des forces mouvantes* depicts an aeolipile resembling that described by Sennert [see illustration 5]. It has two openings and reveals the outline of an internal tube, without depicting the water and air inside. Descartes' aeolipile corresponds more in design to Goujon's woodcut than to Caus' or Ercker's. Much like in the Vitruvian woodcut, the aeolipile is shown as a simple ball with a single hole at the midpoint not functioning in relation to a specific setting. Unlike in Goujon's illustration, in *Les Météores* the aeolipile's anthropomorphic features have been removed. More significantly, aiming to show how the aeolipile functions, Descartes revealed the interior in an attempt to render the unseen visible.

Key to Descartes' explanation were his definitions of wind and air. For him, all agitations of the air are wind; and all invisible and impalpable bodies are air (AT 6:265). This definition of air means that "when water

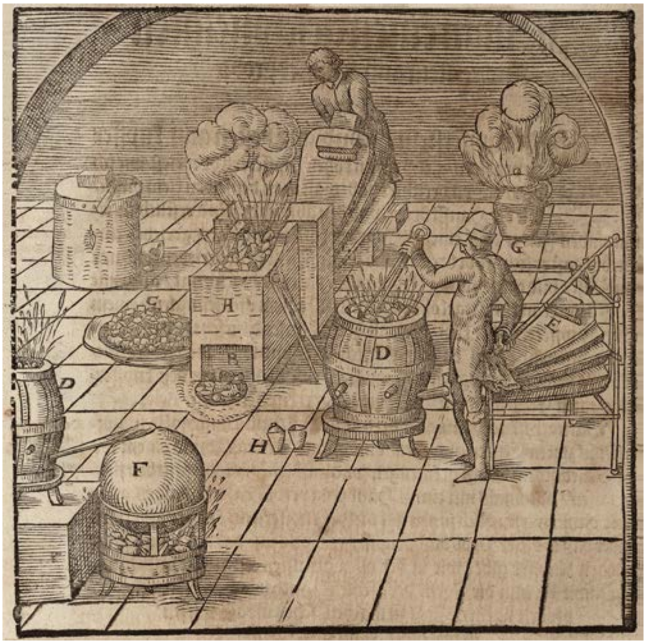

Illustration 4. (Ercker [1574] 1629, 98v. By permission of the Folger Shakespeare Library)

is greatly rarified and changed into a very subtle vapor, it can be said that is has been converted into air," even if strictly speaking corpuscles of different shapes and size make up what others would define as elemental air and water (AT 6:265). The drawing of the aeolipile depicts how "heat, agitating the particles of water, lifts many of them above the water's surface" (AT 6:266). Archeological remnants and early modern descriptions suggest that most aeolipiles were metal or clay, meaning that unlike Drebbel's weather glass, the actions of the vapor and air within aeolipiles remained hidden, although Marin Mersenne described experimenting with a glass one, seven years after *Les Météores* was published (Mersenne 1644, 1:141). In any case, Descartes aimed to show how air particles take up more space as their rotating bodies form circles, thereby illustrating why the heated vapor, extended and dilated, pushes the air out in a lateral direction that mirrors the motion of natural winds. The aeolipile suggests that artificial winds have the same causes as natural ones and that rarefaction or dilation of water vapor can create powerful flows of air. As an analogy it relies on allowing the reader to move from the understanding of the cause of an effect (that of the aeolipile) to knowing the previously

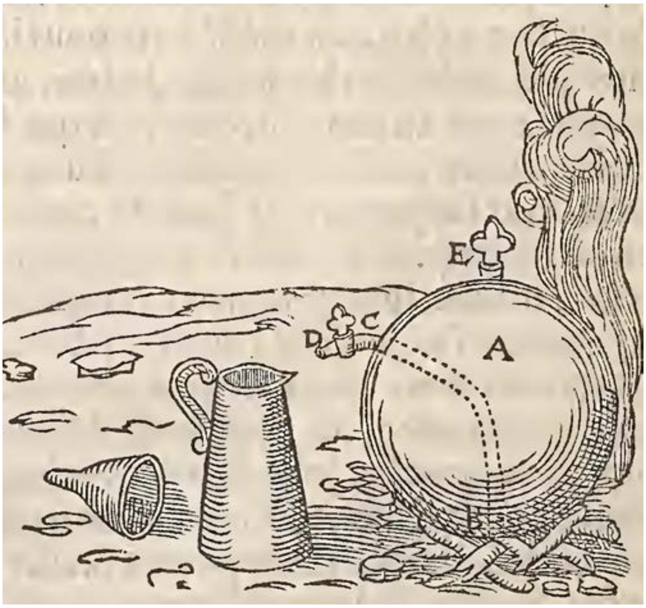

Illustration 5. (Caus 1615, 2v. By permission of The Getty Research Institute, Los Angeles (85-B12429))

unknown cause of an analogous effect (that of the winds) (Manning 2012, p. 402).

To bolster his case, Descartes relied on an estimation of the amount of space that water vapor occupies relative to water. Doubling what is found in the *Récréation mathématicque,* he estimated that it occupies 2000 or 3000 times more space, rather than the tenfold of the Aristotelians. He added that rarefied air only increases its volume by two or three times (AT, 6:268). Thus, the transformation, or dilation, of water into vapor must drive powerful winds. By increasing the magnitude of order of the change in volume of water vapor, he more convincingly argued that winds could originate from rarefaction, dilation, and condensation, in opposition to the views of Froidmont. Descartes did not explain how he arrived at his estimate. Visualizing the aeolipile's interior cannot confirm the exact ratio of the volume of space, but it suggests the change in volume by depicting the vapor particles' hypothetical motion and transformation.

Descartes recognized limitations of the analogy for natural winds, conceding two primary differences. The first is that vapors arise not only from bodies of water but also from earth, snow, and clouds. The second difference is that vapors are not enclosed in the uniform fashion of the aeolipile. Rather, thicker vapors, clouds, mountains, and other geographical formations retain recently heated vapors in an irregular manner, since some vapors expand or condense into rain and snow, often leaving the natural container in a state of flux (AT 1:266–68). Despite recognizing these limitations, Descartes thought the aeolipile provided a general model for all winds. Froidmont objected to his use of this device as an analogy for a general (*universim*) explanation of the wind (AT 1:408). Froidmont, leaving behind his criticism of the power of rarefaction that he leveled earlier, contended that winds could only rarely be compressed between clouds or between mountains and clouds in such a manner to create a force (*impetus*) as strong as that in an aeolipile; Descartes curtly replied that Froidmont had not paid enough attention to the laws of mechanics (AT 1:430).

A number of Descartes' followers accepted the aeolipile as a general model of the winds, appealing to similarities between the artificial and natural. Jean-Baptiste Du Hamel described winds as deriving from the dilation of water vapor, "no differently than in an aeolipile" (Du Hamel 1660, pp. 55–6). Jacques Rohault in his *Traité de physique* placed a representation of an aeolipile nearly identical to that found in *Les Météores* (Rohault 1671, 3:262). Holding, as did Descartes, that wind comes from the dilation of aqueous vapors that agitate the air, he wrote that this general theory of the winds "is confirmed by the experience (*experience*) of the aeolipile" (Rohault 1671, 3:262). The French Jesuit Georges Fournier argued that the earth's heat acts in the same manner as the fire below an aeolipile and causes vapors to rise, dilate, and extend as they set in motion winds (Fournier 1643, p. 696). Although not a Cartesian, Athanasius Kircher also explained the cause of wind as the rarefaction of air and water vapor, which he believed was the same principle the aeolipile applies in making artificial winds (Kircher 1680, pp. 172–73).

Yet, others were hesitant to make broad conclusions and modified Descartes' interpretation of the aeolipile, doubting whether the aeolipile corresponded closely to the phenomena. For example, the Dutch polymath Isaac Vossius likened the aeolipile's action to the cause of rapid whirlwinds that blow on shores or in the middle of the ocean, but he took it to be unsuitable for a "universal demonstration" of the cause of wind (Vossius 1663, p. 95).

The Englishman Ralph Bohun, in *A Discourse Concerning the Origine and Properties of Wind*, adapted the aeolipile to new theories of the air put forth by Robert Boyle. He believed that one cause, but not the only, of some winds, namely those in the tropics and in the sea, is "the resolution," or release, of the earth's and seas' "superficiall parts" caused by "celestial warmth" so that "Humid bodys are soon agitated, and volatilis'd" (Bohun 1671, p. 23). Bohun maintained that this action is similar to what happens in "that Vulgar, but very considerable Experiment, of the *Aeolipile*" that allows us "without difficulty [to] conceive, the most forcible emotions of *Wind* to be generated from the Rarefaction of water" (Bohun 1671, pp. 23–4). For him, the example of the device helps us to "conceive," or form an image in the mind. He wrote that "the Sagacity of Art do's so clearly interpret to us the operation of Nature" (Bohun 1671, p. 24). Considering this artifice allows that "we may Imagine the *Atmosphere* to be a soo [sic] Immense *Aeolipile,* continually dilating the Vapors" (Bohun, 1671, p. 25). Accordingly, for Bohun, the analogy differs from Descartes'. Instead of the mountains and clouds holding in air, the copper vessel replicates the entire sphere of air that surrounds the earth.

Bohun's understanding of the atmosphere as holding in vapors depended on the conviction that air has weight. In this light, Bohun relied on Boyle's conclusions about the nature of air. In doing so, Bohun provided a further modification to Descartes' theory. He noted that Boyle had "dilated" air through heat so that it occupied "13000 times the former extent"—Mersenne had only been able to increase it by 100 times (Bohun 1671, p. 15). Boyle's estimation, much greater than Descartes' proportion of two or three to one for the dilation or rarefaction of air through heat, meant that the rarefaction of air by the sun's heat, without water vapor, is "at least sufficient to create very impetuous Winds" (Bohun 1671, p. 15). For Bohun, therefore, the aeolipile need not contain water. This leads to two other causes of winds: the first echoes Bacon, namely the "Superoneration of the Atmosphere," when there are too many "particles of matter" crowded together; the second is any alteration in the "*Aequilibrium* of the *Atmosphere*" by which inequalities in the density of the air and vapors create wind (Bohun 1671, pp. 16–17).

Curiously, Mersenne and Boyle employed aeolipiles, although not as a model for winds. Both used aeolipiles in their attempts to weigh the air, weighing the device before and after its air had been expelled by extreme heating (Mersenne 1644, 1:140–44; Boyle [1660] 1999, 1:259). Boyle held that the causes of winds were various (Boyle [1665] 1999, 4:396). While rejecting the Cartesians' belief that all winds are generated in a manner similar to the aeolipile, nevertheless he noted the usefulness of the device for recreating atmospheric haloes, for experiments involving the condensation and rarefaction of air, and for a proof that the Aristotelian tenfold proportion of the expansion of water into air is wildly inaccurate (Boyle 2000, 13:302–3).

5. Conclusion

The aeolipile's appeal stemmed from its capacity to provide the imagination with an example of the power of heat to create strong lateral wind-like currents. Even if its image initially came from architectural treatises and spread through books on machines and mathematics, authors of these treatises and commentators on Vitruvius, steeped in humanist interpretations of antiquity, explained the device's workings in a similar manner to university professors. For example, Caus' description of the aeolipile's ability to replicate wind depended on his understanding of the cyclical transformation of water into air as it moves from the earth's surface to the middle region of the sky (Caus 1615, 2v).

The value of the aeolipile as model and tool for visualization increased during the seventeenth century because other experiments made it seem more likely that the rarefaction of water vapor and air could be the cause of wind. While Froidmont doubted the power of rarefaction, Mersenne's and Boyle's experiments that showed the degree to which heat caused air and water vapor to expand made it easier to accept the aeolipile as analogous to at least some natural winds. Edmond Halley estimated, in a rough calculation based on experimental trials conducted in London, that 5280 tons of vapor arise daily from the Mediterranean Sea, ensuring greater acceptance that the air's weight acting as the atmosphere can compress the air below (Halley 1686, p. 368). Vossius, Bohun, and Boyle disagreed with Descartes' reading of the aeolipile because they believed the types and causes of winds were more diverse than Descartes admitted. Natural histories of winds, such as Acosta's, Bacon's, and Boyle's, suggested that the aeolipile could not account for the anemological variety that travelers had experienced.

The aeolipile as meteorological model was remarkably long lived and diffuse. Into the first decades of the eighteenth century, English diarists referred to them in their weather journals (Golinski 2001, pp. 159, 163). Its long life as model stems in part from its flexibility. Vitruvius, Della Porta, Descartes, and Bohun had different understandings of the cause of winds and of the nature of air and vapors, adapting their interpretation of the action of this device to their own theories.

References

Acosta, José de. [1590] 1890. *Historia natural y moral de las indias*. Seville: Juan de Leon.

Albertus Magnus. 2003. *Meteora*. Edited by Paul Hossfeld. Vol. 6, bk. 1, of *Opera Omnia*. Münster: Aschendorf.

Bacon, Francis. 2007. *The Instauratio magna: Part III: Historia naturalis et experimentalis*. Edited by Graham Rees. Vol. 12 of *The Oxford Francis Bacon*. Oxford: Oxford University Press.

Barbaro, Daniele. 1567. *I dieci libri dell'architettura di M. Vitruvio tradotti et commentati*. Venice.

Benedetti, Giovanni Battista. 1585. *Diversarum speculationum mathematicarum, & physicarum liber.* Torino.

Berryman, Sylvia. 2009. *The Mechanical Hypothesis in Ancient Greek Natural Philosophy.* Cambridge: Cambridge University Press.

Beverwyck, Jan van. 1644. *Epistolicae quaestiones*. Rotterdam.

Boas, Marie. 1949. "Hero's Pneumatica: A Study of its Transmission and Influence." *Isis* 40: 38–48.

Bodin, Jean. [1596] 1597. *Universae naturae theatrum*. Frankfurt a.M.

Bohun, Ralph. 1671. *A Discourse Concerning the Origine and Properties of Wind*. Oxford.

Borrelli, Arianna. 2008. "The Weatherglass and its Observers in the Early Seventeenth Century." Pp. 67–125 in *Philosophies of Technology: Francis Bacon and His Contemporaries*. Edited by Claus Zittel, et al. Leiden: Brill.

Boyle, Robert. 1999–2000. *The Works*. Edited by Michael Hunter and Edward B. Davis. London: Pickering & Chatto.

Cabeo, Niccolò. 1646. *Commentaria in quatuor libros meteorologicorum Aristotelis*. Rome.

Cardano, Girolamo. [1557] 1663a. *De rerum varietate*. Vol. 3.1 of *Opera omnia*. Edited by Charles Spon. Lyon.

Cardano, Girolamo. [1570] 1663b. *In librum Hippocratis aere, aquis, et locis, commentarii*. Vol. 8.1 of *Opera omnia*. Edited by Charles Spon. Lyon.

Caus, Salomon de. 1615. *Les raisons des forces mouvantes*. Frankfurt a.M.

Cellauro, Louis. 2004. "Daniele Barbaro and Vitruvius: The Architectural Theory of a Renaissance Humanist and Patron." *Papers of the British School at Rome* 72: 293–329.

Cesariano, Cesare. 1521. *De architectura libri dece commentari*. Como.

Ciapponi, Lucia A. 1976. "Vitruvius." Pp. 399–409 in vol. 3 of *Catalogus translationum et commentariorum*. Edited by F. Edward Cranz. Washington, D.C.: Catholic University of America Press.

Colie, Rosalie L. 1955. "Cornelis Drebbel and Salomon de Caus: Two Jacobean Models for Salomon's House." *Huntington Library Quarterly* 18: 245–60.

Collegium Conimbricense. [1592] 1631. *In meteorologicos Aristotelis*. Cologne.

Della Porta, Giovan Battista. [1617] 2000. *De transmutationibus aeris*. Edited by Alfonso Paolella. Naples: Edizioni Scientifiche Italiane.

Descartes, René. 1637. *Discours de la méthode. Plus la dioptrique, les météores et la géométrie*. Leiden.

Descartes, René. 1982–91. *Oeuvres*. Edited by Charles Adam and Paul Tannery. 11 vols. Paris: Vrin.

Du Hamel, Jean Baptiste. 1660. *De meteoris et fossilibus*. Paris.

Ercker, Lazarus. [1574] 1629. *Beschreibung allerfürnemisten mineralischen Ertz unnd Bergwercks arten*. Frankfurt.

Falloppio, Gabriele. 1569. *De medicatis aquis atque fossilibus*. Venice.

Filarete. 1972. *Trattato di architettura*. Edited by Anna Maria Finoli and Liliana Grassi. 2 vols. Milan: Il Polifilo.

Fournier, Georges. 1643. *Hydrographie contenant la theorie et la practique de toutes les parties de la navigation*. Paris.

Froidmont, Libert. [1627] 1656. *Meteorologicorum libri sex*. London.

Gaetano of Thiene. 1476. *Commentarius in libros Meteorologicorum*. Venice.

Golinski, Jan. 2001. "'Exquisite Atmography:' Theories of the World and Experiences of the Weather in a Diary of 1703." *British Journal for the History of Science* 34: 149–171.

Halley, Edmond. 1686. "An Estimate of the Quantity of Vapour Raised out of the Sea by the Warmth of the Sun." *Philosophical Transactions of the Royal Society* 16: 366–370.

Heeffer, Albrecht. 2013. "Identifying Adequate Models in Physico-Mathematics: Descartes' Analysis of the Rainbow." Pp. 431–448 in *Model-Based Reasoning in Science and Technology: Theoretical and Cognitive Issues*. Edited by Lorenzo Magnani, et al. Berlin: Springer.

Hero of Alexandria. 1575. *Spiritalium liber*. Trans. Federico Commandino. Urbino.

Hildburgh, W. L. 1951. "Aeolipiles as Fire-blowers." *Archaeologia, or, Miscellaneous Tracts Relating to Antiquity* 94: 27–55.

Keller, Vera. 2010. "Drebbel's Living Instruments, Hartmann's Microcosm, and Libavius's Thelesmos: Epistemic Machines Before Descartes." *History of Science* 48: 39–74.

Kircher, Athanasius. 1680. *Physiologia kircheriana experimentalis*. Amsterdam.

Krinsky, Carol Hersell. 1967. "Seventy-eight Vitruvius Manuscripts." *Journal of the Warburg and Courtauld Institutes* 30: 36–70.

Laird, Walter Roy. 2008. "Nature, Mechanics, and Voluntary Motion in Giuseppe Moletti's Lectures on the *Mechanical Problems*." Pp. 173–183 in *Mechanics and Natural Philosophy before the Scientific Revolution*. Edited by Walter Roy Laird and Sophie Roux. Dordrecht: Springer.

Leurechon, Jean. [1624] 1627. *Récréation mathématicque*. Paris.

Leurechon, Jean. [1624] 1680. *Récréations mathématicques*. Lyon.

MacGregor, Arthur. 2007. "Jack of Hilton and the History of the Hearth-Blower." *The Antiquaries Journal* 87: 281–294.

Manning, Gideon. 2012. "Analogy and Falsification in Descartes' Physics." *Studies in History and Philosophy of Science* 43: 402–411.

Manning, Gideon. 2013. "Descartes' Healthy Machines and the Human Exception." Pp. 237–262 in *The Mechanization of Natural Philosophy*. Edited by Sophie Roux and Daniel Garber. Dordrecht: Springer.

Martin, Craig. 2011. *Renaissance Meteorology: Pomponazzi to Descartes*. Baltimore: Johns Hopkins University Press.

Mastri, Bartolomeo and Bonaventura Belluti. 1640. *Disputationes in libros de celo et metheoris*. Venice.

Mersenne, Marin. 1644. *Cogitata Physico Mathematica*. Paris.

Mitrovic, Branko. 1998. "Paduan Aristotelianism and Daniele Barbaro's Commentary on Vitruvius' De Architectura." *Sixteenth Century Journal* 29: 667–688.

Nifo, Agostino. [1523] 1560. *In libros meteorologicorum*. Venice.

Paré, Ambroise. 1633. *Les oeuvres*. Lyon.

Payne, Alina A. 1999. *The Architectural Treatise in the Italian Renaissance: Architectural Invention, Ornament, and Literary Culture*. Cambridge: Cambridge University Press.

Philandrier, Guillaume. 1552. *De architectura libri decem annotationes castigationes*. Lyon.

Piccolomini, Francesco. 1597. *Librorum ad scientiam de natura attinentium pars quarta*. Frankfurt a.M.

Pomponazzi, Pietro. 1563. *Dubitationes in quartum meteorologicorum librum*. Venice.

Rabelais, François. 1991. *Complete Works*. Trans. Donald M. Frame. Berkeley: University of California Press.

Rohault, Jacques. 1671. *Traité de physique*. Paris.

Rowland, Ingrid D. 1998. "Vitruvius in Print and in Vernacular Translation: Fra Giocondo, Bramante, Raphael and Cesare Cesariano." Pp. 105–121 in *Paper Palaces: The Rise of the Renaissance Architectural Treatise*. Edited by Vaughan Hart and Peter Hick. New Haven: Yale University Press.

Sennert, Daniel. 1618. *Epitome naturalis scientiae*. Wittenberg.

Vilain, Christiane. 2008. "Circular and Rectilinear Motion in the *Mechanica* and in the 16th Century." Pp. 149–173 in *Mechanics and Natural Philosophy before the Scientific Revolution*. Edited by Walter Roy Laird and Sophie Roux. Dordrecht: Springer.

Vimercati, Francesco. [1556] 1565. *In quatuor libros Aristotelis meteorologicorum*. Venice.

Vitruvius. 1547. *Architecture ou Art de bien bastir*. Translated by Jean Martin. Paris.

Vossius, Isaac. 1663. *De motu marium et ventorum*. The Hague.

Warren, Jeremy. 2004. "Sir Han Sloane as Collector of Small Sculpture." *Apollo* 159, 503: 31–38.

Wilkins, John. 1648. *Mathematical Magick*. London.

Zittel, Claus. 2008. "Descartes as Bricoleur." Pp. 337–372 in *Philosophies of Technology: Francis Bacon and His Contemporaries*. Edited by Claus Zittel, et al. Leiden: Brill.

Zittel, Claus. 2009. *Theatrum Philosophicum: Descartes und die Rolle ästhetischer Formen in der Wissenschaft*. Berlin: Academie Verlag.