

Modern Meteorology

Garry Toth

1 Introduction¹

The science of meteorology* is based on the laws of physics and, as with all the physical sciences, atmospheric phenomena are studied through the framework of the scientific method*.² Knowledge thus gained is the basis of understanding how the atmosphere works, which in turn is the basis for forecasting its future states. Ancient natural philosophers who pondered the atmosphere had neither observing instruments nor the framework of the scientific method. They had to operate with the limited tools available to them.

The observational roots of modern meteorology can be traced back to the 1600s, with the beginnings of the development of instruments such as thermometers, barometers, and anemometers.³ During subsequent centuries, a wide variety of weather observations fed into an evolving theory of the physics of the atmosphere. With the development of aviation and the two World Wars, the science of meteorology made great leaps forward, and that progress accelerated with the advent of the Space Age and the Computer Era. It can be said that the science of meteorology exploded in the latter half of the twentieth century.

Meteorology can be divided into two broad components, summarized in Mark Twain's famous aphorism "Climate* is what we expect, and weather* is what we get". Weather is what is happening right now in the atmosphere, while climate is the weather averaged over a suitably long period of time (30 years of observations is one standard). There are natural causes of climate change, but recent experience also points to a changing climate due to anthropogenic global warming caused by fossil fuel burning. A changing climate is also related to complex changes in the weather (more variability and more extremes, for example).⁴

1 All references to web pages were verified to work as of October 2024.

2 <https://www.merriam-webster.com/dictionary/scientific%20method>.

3 See the chapter by R. Vermij in this volume.

4 On this point, see also the section below titled "What About Anthropogenic Climate Change?"

Academic meteorologists are concerned with the theory of the atmosphere: its physics, its structures and increasingly its chemistry. They use imposing datasets (such as those from satellites) that are now an integral part of the science of meteorology and developing supercomputer techniques to ingest this data to analyze the current state of the atmosphere and forecast its likely future states. An operational meteorologist* uses the tools and techniques developed by others to issue weather forecasts. A climatologist considers all questions related to the climate, including climate change and infrastructure projects that depend on climatological data. For example, airports are not constructed in coastal areas that are foggy for 200 days out of every year. As the climate changes, it has been found that existing infrastructure, built under the standards imposed by the former climate, often cannot stand up to the changed climate.

Meteorologists generally work “behind the scenes”, usually as part of national meteorological services, which provide the necessary infrastructure: research, training, computer hardware and software, development of forecast techniques and formats and standards, and the communications systems necessary to handle large volumes of data from around the world and transmit meteorological information to users. One often sees weather presenters on TV or hears them on the radio. They are generally broadcasters with some meteorological training rather than professional meteorologists. There are exceptions, though. Some TV stations in the United States have their own meteorologists, who present the weather, and there exist private companies whose meteorologists appear on their cable TV weather channels (e.g. The Weather Network).

Why are weather forecasts important? The most general answer is that the information they contain is used to help protect lives and property and contribute to the economy of the nation. Key sectors, such as aviation, the marine community, and the public, depend on forecasts, as do various special interests. In his *Theogony*, Hesiod referred to the winds and their potential mortal danger for mariners:

From Typhoeus comes the strength of moist-blowing winds—apart from Notus and Boreas and clear Zephyrus, for these are from the gods by descent, a great boon for mortals. But the other breezes blow at random upon the sea: falling upon the murky sea, a great woe for mortals, they rage with an evil blast; they blow now one way, now another, and scatter the boats, and destroy the sailors; and there is no safeguard against this evil for men who encounter them upon the sea.

In the modern context, part of the remedy for the “evil” of major marine storms* at sea lies in the availability of accurate and timely weather forecasts, which can, for example, help mariners to avoid them. Such storms evolve at sea as mid-latitude low-pressure areas*, or as low-latitude tropical cyclones*, but can also hit land, and weather forecasts in advance of their life- and property-threatening winds and rain and flooding provide time for the necessary preparations. In the same way, advance warning of major winter storms minimizes the hazards that they present. There is also a wartime role for operational meteorologists—perhaps the best-known example is the forecasts issued in the days leading up to the D-Day invasion of 1944.

Operational meteorologists believe in the concept of “public service”. Their role melds “science” and “service”, as encapsulated in the motto “Service Through Science”, which the author encountered in the Canadian weather service. No operational meteorologist would claim that forecasts are always correct, but a significant portion of them *are* correct (and therefore useful). Moreover, they are slowly but surely becoming more accurate, even as the forecasting demands change, with increasing emphasis on details over smaller areas and shorter periods of time.

In her paper, Anne-Sophie Meyer (Chapter 14) includes the story of how Caesar hired the mariner Amyclas to take him across the sea. Amyclas was hesitant because he foresaw the arrival of a major marine storm, however, Caesar would have none of it and insisted on making the journey. Sure enough, the storm did arrive and their boat was thrown back to shore. Caesar just shrugged his error off with his usual divine arrogance, but for Amyclas the storm was a natural phenomenon that could be correctly predicted, an attitude that fits perfectly with the idea of “Service Through Science”. Caesar, on the other hand, didn’t care a whit about his poor prediction and its possible consequences. Amyclas would fit right in as a modern operational meteorologist. Caesar would not.

In the following sections, the word “meteorology” will refer to any of the components of the science described above. As required, more specific words (such as “weather” or “climate” or “operational meteorology” or “weather forecasting”) will be used.

2 Can Astronomy Be Related to Meteorology?

There exist correlations between astronomy and meteorology, but correlation does not imply causation. For example, the appearance of certain stars in a certain pattern occurs around a given date each year at a given point on Earth.

That location also has its own climate for that date. The two (astronomy and climate) are correlated, but there is no causal relationship in either direction. The ancient natural philosophers, however, did sometimes relate astronomy and meteorology through such correlations. Aristotle wrote that astronomy and meteorology are different branches of natural science while Epicurus felt that they are part of the same branch. In this sense, the modern meteorologist is Aristotelian rather than Epicurean.⁵ Some examples in which astronomy can be related (at least indirectly) to meteorology in the modern context are presented in the remainder of this section.

The tides are an astronomical phenomenon, a consequence of the relative positions of Earth, Sun and Moon. Weather forecasts issued for coastal areas must account for them. The highest tides by themselves may cause some coastal flooding in low-lying areas. High tides in conjunction with a storm surge^{*6} will enhance coastal flooding. In this regard, forecasters make use of tide tables, which integrate all the astronomical effects into numbers that are easily referenced.

Atmospheric “seeing”^{*7} refers to the degradation of the images of astronomical objects seen through ground-based optics, due primarily to atmospheric turbulence. It combines elements of astronomy and meteorology. It is not a traditional meteorological variable, but NWP (Numerical Weather Prediction)^{*}⁸ models can be used to forecast it. Amateur astronomers use the forecasts of seeing, along with the usual forecasts of clouds and other variables, to plan their observing activities. Professional astronomers have their own specialized techniques to minimize the effects of seeing, using adaptive optics.⁹

Space dust or small rocks striking Earth’s atmosphere are also an astronomical phenomenon. They burn up in the atmosphere and are known as meteors or shooting stars. Some create a brief flash of light; most remain invisible to the naked eye. They are more frequent than one might realize. A Norwegian research project¹⁰ has used radio waves to detect the atmospheric trails they

5 For more on Aristotle versus Epicurus in the modern meteorological context, see the section below titled “Is Meteorology Deterministic or Probabilistic?”

6 “A rise and onshore surge of seawater as the result primarily of the winds of a storm, and secondarily of the surface pressure drop near the storm center”: see https://glossary.ametsoc.org/wiki/Storm_surge.

7 <https://www.britannica.com/science/seeing>.

8 https://glossary.ametsoc.org/wiki/Numerical_forecasting.

9 <https://planetfacts.org/adaptive-optics/>.

10 https://partner.sciencenorway.no/forskningno-norway-ntnu/studying-shooting-stars-to-improve-weather-foreca_sting/1409144.

leave at around 100 km, and thus to deduce winds and temperatures at that level.

Large space rocks can also hit Earth, though rarely. The Chixulub asteroid, some 10–15 km in diameter, struck what is now the Yucatan Peninsula around 65 million years ago.¹¹ This event is of interest to climatologists because it is hypothesized to have changed Earth's climate by throwing vast quantities of matter into the atmosphere, which blocked so much sunlight that the climate cooled and photosynthesis was reduced to the point where much animal life, including most dinosaurs, became extinct.¹²

The advance and retreat of the Ice Age glaciers is an example of a natural climate change*. In the 1920s and 1930s, the Serbian engineer and mathematician Milutin Milanković* (1879–1958) developed mathematical relationships between long-term cycles in Earth's climate and changes in three of its orbital parameters: eccentricity, axial tilt (obliquity) and precession.¹³ They exhibit cycles of change over tens or hundreds of thousands of years. Milanković shows how those astronomical cycles can interact so that at some times there is more sunlight striking Earth and at others there is less. When there is less, snow and ice accumulate and glaciers advance, forming an Ice Age. When there is more, there is warming and the ice retreats.

3 What Causes the Wind*?

The wind is a key atmospheric variable in both modern and ancient meteorology. It is defined, most generally, as the three-dimensional motion of the air, which means that it has both horizontal and vertical components. People who think of the wind are invariably thinking of the horizontal wind (unless they are meteorologists!). The vertical wind is usually much smaller than the horizontal wind, so that in what follows only the horizontal wind is considered.

It is now known that the physical causes of the wind run the gamut from large spatial scales* (1000+ km) to intermediate scales (often referred to as the mesoscale*¹⁴) to very small scales (1 km, or even 1 m or 1 cm). Their temporal

11 Another possible factor in the extinction is the possible extensive volcanic activity at the time in what is now central India. See <https://www.nhm.ac.uk/discover/how-an-asteroid-caused-extinction-of-dinosaurs.html>.

12 <https://www.nhm.ac.uk/discover/how-an-asteroid-caused-extinction-of-dinosaurs.html>.

13 <https://climate.nasa.gov/news/2948/milankovitch-orbital-cycles-and-their-role-in-earths-climate/>.

14 <https://glossary.ametsoc.org/wiki/Mesoscale>.

scales* also vary (from days down to seconds). Smaller spatial and temporal scales generally go together, as do larger spatial and temporal scales.¹⁵

In the simplest possible terms, wind occurs when air is pushed from higher pressures to lower pressures (due to what is called the pressure gradient force*¹⁶). The movement is not direct, however, because Earth is a rotating reference frame*. Newton's laws of motion*, which serve as the basis for the equations governing the motion of the atmosphere, must be modified to include the effects of that rotation. Because of it, any moving object is subjected to a small fictitious force known as the Coriolis force*,¹⁷ which acts to deflect its motion sideways. The deflection is to the right in the northern hemisphere, so that the wind ends up being parallel to the isobars, with lower pressure to the left (this is known as Buys Ballot's law¹⁸). The opposite is true in the southern hemisphere. This balance between the pressure gradient force and the Coriolis force is known as the geostrophic wind* balance.¹⁹ It is the simplest possible estimate of the wind. It shows that the wind flow must be cyclonic²⁰ (in a counterclockwise sense in the northern hemisphere and opposite in the southern hemisphere) around a low-pressure area. However, there are many other physical factors that influence wind speed and direction. The winds that result from those factors are called ageostrophic winds*.²¹ Here are some factors related to the ageostrophic wind (situations in which the wind is *not* geostrophic):

1. Isobaric curvature (e.g. winds in hurricanes and tornadoes)
2. Friction at the surface (e.g. the wind observed in an open flat field (low friction) is very different from that observed in an adjacent forest (high friction))
3. Rapid deepening of a low-pressure system ("pulls" the wind toward it—known as the isallobaric wind²²)
4. Winds associated with warm and cold fronts*
5. Winds generated by thunderstorms (can be cold and gusty, in advance of the thunderstorm)
6. Land and sea breezes* (also referred to in the next section)
7. Katabatic winds*²³ (and other downslope winds*)

15 <https://i.pinimg.com/originals/62/64/39/62643937581494ecee211130ea5f0154.png>.

16 https://glossary.ametsoc.org/wiki/Pressure_force.

17 <https://sciencedemonstrations.fas.harvard.edu/presentations/coriolis-force>.

18 <https://www.britannica.com/science/Buys-Ballots-Law>.

19 https://glossary.ametsoc.org/wiki/Geostrophic_wind.

20 https://glossary.ametsoc.org/wiki/Cyclonic_circulation.

21 https://glossary.ametsoc.org/wiki/Ageostrophic_wind.

22 https://glossary.ametsoc.org/wiki/Isallobaric_wind.

23 https://glossary.ametsoc.org/wiki/Katabatic_wind.

8. Other terrain/ mountain effects (e.g. wind channeling in valleys and blocking by barriers and rushing around the solid edges of barriers)
9. Barrier and corner flow effects due to man-made structures
10. The solar day/ night cycle (the diurnal cycle, also referred to in the next section).

The wind is the sum of the effects of all the causal factors, both geostrophic and ageostrophic. As they change in time, so too does the wind. Some are more important than others, depending on the changing meteorological situation, the geographic circumstances of the measurement site and the time of day. Using the limited information that was available to them, the ancient natural philosophers discussed the wind as best they could, without the benefit of a full understanding of all the physical mechanisms involved.

4 Diurnal^{*24} Changes in the Wind Due to Solar Effects

Darcy Krasne (Chapter 15) refers to this topic. The Sun can influence the wind, but there are all kinds of details to consider. For example, over land, in a cloud-free area such as a dry high-pressure area*, the Sun heats the land during the day, producing rising convective currents²⁵ (due to the effects of buoyancy*), which through vertical mixing^{*26} have the effect of transferring upper-level momentum^{*27} downward to near the ground. In this situation, the wind speed increases after the Sun rises. The reverse occurs at night, after the Sun sets. The effect will be lessened under cloudy skies. The story is different if we are speaking of a coastal area. In that case, the sea breeze is set up after the Sun rises (heated air over the land rises, which induces a wind from sea to land). At night, after the Sun sets, the land breeze takes over (cooled air over the land sinks, inducing a wind from land to sea). In the coastal case the main effect of the Sun from day to night and back again is to change the direction of the wind. The speed may or may not change much.

From these examples, we see that the Sun can cause a change in wind between night and day. However, its influence will often not be the primary one, since the contributions to the wind of various other physical factors, as outlined in the previous section, can overwhelm the solar effects.

24 <https://glossary.ametsoc.org/wiki/Diurnal>.

25 <https://glossary.ametsoc.org/wiki/Convection>.

26 <https://www.britannica.com/science/vertical-mixing>.

27 https://glossary.ametsoc.org/wiki/Momentum_flux.

5 Clear Sunsets Versus Cloudy (“Disturbed”) Sunsets: Signs of Fine Versus Stormy Weather?

This is one of several weather signs referred to by Robert Mayhew (Chapter 7). A clear sunset means that the Sun is visible to the west, which in turn can mean the arrival of high pressure and fine weather, while a cloudy sunset, with the Sun hidden behind clouds to the west, can presage the arrival of even more clouds, and perhaps a storm.

Another more well-known version of this sign is the proverb “Red sky at morning, sailors take warning; red sky at night, sailors’ delight”, which can be traced back to Matthew 16:3 in the New Testament:

And in the morning, It will be foul weather to day: for the sky is red and lowering (King James Version); or

Red sky in the morning, cloudy and storming. (International Standard Version)

Does this weather sign hold true? Often yes, in the mid-latitudes, where the prevailing wind* patterns move systems approximately from west to east, with an average speed and size that are implicit in the rule. If the clouds are red in the morning (bases illuminated by the rising Sun) then the clouds may be thickening from the west (“lowering” in the KJV text), and bad weather may follow. If they are red in the evening (corresponding to Mayhew’s “clear sunset”), then the Sun is illuminating them from the west, which means that the overcast skies have passed to the east, so that good weather from the west should follow. However, there are cases in which this sign is incorrect. For example, it does not work if the weather system is unusually fast or slow; or if it is unusually large or small; or if it is not moving in the usual roughly west to east direction of the prevailing wind (it may come from the north, the east, or the south); or if the remnants of other clouds (often convective clouds*) are persistent enough to still cover the sky at sunset.

6 Does Lightning* Cause Strong Winds?

In Aristophanes’ *Clouds* (423 BCE), Strepsiades asks what the thunderbolt is, and Socrates replies:

When a dry wind rises skyward and gets locked up in these Clouds, it blows them up from within like a bladder, and then by natural compulsion

it bursts them and is borne out in a whoosh by dint of compression, burning itself up with the friction and velocity.

404–407, trans. HENDERSON 1998

Socrates' explanation about the formation of lightning implies the formation of a strong wind. In the *De Signis*, traditionally attributed to Theophrastus,²⁸ the author writes:

In summer from whatever quarter lightning and thunder come, there will be violent winds: if the flashes are brilliant and startling, the wind will come sooner and be more violent; if they are of gentler character and come at longer intervals, the wind will get up gradually. In winter and autumn however the reverse happens, for the lightning causes the wind to cease: and, the more violent the lightning and thunder are, the more will the wind be reduced.

32, trans. HORT 1916

For the summer, the author associates strong winds with lightning, but this conclusion is misleading. Lightning²⁹ is an atmospheric electric effect associated with cumulonimbus clouds* (the clouds that produce thunderstorms). Thunder*³⁰ is caused by lightning. Thunderstorms and cumulonimbus clouds are most frequent in the summer when solar heating of the ground unleashes the atmospheric convective instability*³¹ that allows them to grow vertically in the right meteorological environment of an unstable atmosphere* (as opposed to a stable atmosphere*). There are both updrafts* (cloud-scale currents of rising air) and downdrafts* (cloud-scale currents of descending air) in a cumulonimbus cloud. The downdraft from a cumulonimbus (with or without lightning) may be intense enough to penetrate down to the surface and so cause moderate or strong winds there (an ageostrophic wind, referred to in a previous section). Who has not felt the cool and gusty wind that can rise suddenly just ahead of a summertime thunderstorm? To a lesser extent, the effect can be felt in the presence of weaker convective clouds that have no associated lightning. The wind effect is enhanced if several cumulonimbus clouds are organized in

28 See the chapter by Mayhew in this volume.

29 <https://glossary.ametsoc.org/wiki/Lightning>.

30 <https://glossary.ametsoc.org/wiki/Thunder>.

31 https://glossary.ametsoc.org/wiki/Convective_instability.

some way that strengthens them as a group (e.g. together along a cold front or in a mesoscale convective complex [MCC*]³²).

In such summertime cases, strong wind at the surface is caused by the cumulonimbus clouds rather than by the lightning. Many such clouds do include lightning, which is perhaps their most striking (no pun intended!) feature. That may be why some ancient natural philosophers saw a cause-and-effect relationship between lightning and strong winds rather than between convective clouds and strong winds.

In winter, the situation is different. Cumulonimbus clouds with lightning can occur but are not usually initiated by solar heating. They are instead induced by other atmospheric mechanisms (known generally as dynamic effects*³³). The atmosphere near the ground in winter is stable and so downdrafts from convective clouds have a hard time breaking through to the surface. In the winter case, therefore, the author of the *De Signis* had the right idea (in that the wind effect is smaller in winter than in summer), but his statement that the more intense the lightning and thunder the more the winds cease is misleading, since a winter cumulonimbus cloud with intense lightning and thunder may behave like a summer system.

7 The Auroras*³⁴

Are the auroras a meteorological phenomenon? They occur in the upper atmosphere and are meteorological in that sense but also depend critically on what is happening in near-Earth space. They must also therefore be considered to fall within the burgeoning science of space weather.³⁵

The auroras are an astounding celestial spectacle. The Barnum and Baily Circus was called *The Greatest Show on Earth*³⁶ and that grandiose expression has been modified by some to apply to the auroras: *The Greatest Light Show on Earth* (e.g. by the Swedish Tourist Bureau³⁷). In the northern hemisphere they are called the aurora borealis or the northern lights. They are often seen in the high latitudes (around 60° N or farther north) but can encroach, rarely, into the middle latitudes (Athens is at 38° N).

32 https://glossary.ametsoc.org/wiki/Mesoscale_convective_complex.

33 <https://www.sciencedirect.com/topics/earth-and-planetary-sciences/dynamic-meteorology>.

34 <https://www.weather.gov/fsd/aurora>.

35 <https://www.spaceweather.gov/>.

36 <https://barnum-museum.org/the-greatest-show-on-earth/>.

37 <https://visitsweden.com/the-northern-lights/>.

The ancient peoples of the polar latitudes often saw the auroras. Those of the middle latitudes saw them much less often but nevertheless knew that something strange and beautiful could take place in the sky. The earliest known possible reference to the auroras dates from 2600 BCE in China: “Fu-Pao, the mother of the Yellow Empire Shuan-Yuan, saw strong lightning moving around the star Su, which belongs to the constellation of Bei-Dou, and the light illuminated the whole area.”³⁸ The term “lightning” in this context is one often used in the classical Chinese descriptions of the northern lights; “Bei-Dou” is the Big Dipper. A late Babylonian astronomical text from a clay tablet includes one of the earliest accounts of the auroras that can be dated with confidence. During the thirty-seventh year of the reign of Nubuchadnezzar II (568/ 567 BCE), official astronomers described an unusual red glow that flared up in the west during the night. The exact date can be worked out: the night of 12–13 March, 567 BCE.³⁹

Many references to the auroras in the ancient Western world have been documented by Richard Stothers in his *Ancient Aurorae*.⁴⁰ One of them is in Aristotle’s famous work *Meteorologica*:

Sometimes on a fine night we see a variety of appearances that form in the sky: ‘chasms’ for instance and ‘trenches’ and blood-red colours. These too have the same cause. For we have seen that the upper air condenses into an inflammable condition and that the combustion sometimes takes on the appearance of a burning flame, sometimes that of moving torches and stars. So it is not surprising that this same air when condensing should assume a variety of colours.

I.5.342a34–b5, trans. WEBSTER in BARNES 1984

Mankind would continue to be fascinated with the shimmering, mysterious and elusive auroras. Sometimes they would be tinged with pink, reminiscent of the dawn, and in 1619 Galileo Galilei described them as *questa boreale aurora* (“this northern dawn”) after *Aurora*, the Roman Goddess of the Dawn. That was the first known use of the word “aurora” in this regard.⁴¹

38 <http://www.unmuseum.org/7wonders/northernlights.htm>.

39 Stephenson, Willis, and Hallinan (2004).

40 Stothers (1979).

41 *Discorso sulle comete fatto da lui nell'Accademia fiorentina nel suo medesimo consolato*, page 39, line 25, https://www.loc.gov/resource/gdcwdl.wdl_04185/?sp=56&st=image&r=-1.172,0.267,3.344,1.45,0.

The term *aurora borealis* that is common today was introduced in 1621 by the French philosopher and astronomer Pierre Gassendi.⁴² Later scientists began to suspect that the auroras must be related somehow to Earth's magnetic field. In 1790, the English scientist Henry Cavendish made enough auroral observations that he was able to calculate by triangulation that their height was between 100 and 130 km.⁴³ Today it is known that their base is at around 100 km and their tops are often in the range of 200–300 km. This places the auroras in the atmospheric layer known as the thermosphere*.⁴⁴

Auroral research has grown by leaps and bounds with the advent of the Space Era. Earth has a well-defined magnetosphere*,⁴⁵ a kind of protective magnetic sheath, in which the motion of charged particles is controlled by that magnetic field. The Sun emits a constant stream of charged particles known as the solar wind*,⁴⁶ which was discovered by the American interplanetary satellite Mariner-2⁴⁷ in 1962. Sometimes solar storms explode with titanic energy, sending into space massive amounts of solar wind particles and/or electromagnetic radiation and/or parts of the Sun's magnetic field. Those features can, under the right circumstances, interact with Earth's magnetosphere in a complicated electrical and magnetic dance, with the result that some of the solar wind particles are accelerated and directed toward Earth's polar regions where they crash into upper atmospheric molecules, releasing energy, which is visible as the auroras. Oxygen gives off green and red light. Nitrogen glows blue and purple.

8 Atmospheric Rotation in Ancient and Modern Meteorology

The ancient texts tell us that the monster *Typhon* could generate a *typhon* (a rotational storm; in modern terms a tornado or a waterspout) or a *prester*—a fiery (interpreted as including lightning) *typhon*.⁴⁸ The modern word “typhoon” (a hurricane in the western Pacific) may have a different etymology.⁴⁹

42 <https://pwg.gsfc.nasa.gov/Education/whaur1.html>.

43 <https://auroratracks.com/how-and-when-does-northern-lights-happen/>.

44 <https://scied.ucar.edu/learning-zone/atmosphere/thermosphere>.

45 https://www.nasa.gov/mission_pages/sunearth/multimedia/magnetosphere.html.

46 <https://www.swpc.noaa.gov/phenomena/solar-wind>.

47 <https://www.jpl.nasa.gov/missions/mariner-2>.

48 Another possible meaning of *prester* as a pyroclastic flow is ignored here but is presented below in the section titled “Is Vulcanism Related to Meteorology?”

49 <https://www.etymonline.com/word/typhoon>.

These days, meteorologists know that tornadoes and tornadic waterspouts are intense rotating storms, often with lightning. Rotational motion of the atmosphere is a fundamental variable in meteorology. Interestingly, the Latin word *vertex*, meaning rotation, has been carried through to the modern English word *vortex*, meaning a (usually large) atmospheric cyclonic circulation*. The word *vortex** is commonly used in this sense in meteorology. Of even greater interest is the modern English word *vorticity**,⁵⁰ apparently from the same root. It is a fundamental meteorological variable, which defines the atmospheric rotation at any point. Operational meteorologists work with displays of vorticity (along with those of many other meteorological variables) every day. In the old days (through the 1970s), the displays were on paper charts. These days, of course, everything is on a computer screen.

9 Is Volcanism Related to Meteorology?

There is no evidence that changes in atmospheric variables, such as temperature and pressure, can cause volcanic eruptions. However, in the other direction, eruptions do have effects on weather and climate. The ash from major eruptions can block solar radiation and so cause atmospheric cooling, at least locally, with possible negative effects on agriculture, and therefore on people, as discussed by Andrew Hill (Chapter 10). In the modern context, major volcanic eruptions have been measured to slow down or even reverse, temporarily, the rise in global temperatures due to anthropogenic warming. The most recent example is the eruption of the Mt. Pinatubo volcano on 15 June 1991. It was the second-largest eruption of the twentieth century and pumped large amounts of sunlight-absorbing aerosols*⁵¹ into the stratosphere*, which caused a measured decrease in average global temperature of around 0.6°C ⁵² over the 15 months following the eruption.⁵³ Observing the effects of volcanic eruptions (and of the El Niño-Southern Oscillation, or ENSO*⁵⁴) provides climatologists with clues about the mechanisms of global warming and cooling.

Volcanic eruptions also have a weather effect that forecasters must not ignore. Volcanic ash in the atmosphere is a significant hazard for aircraft. After

50 <https://glossary.ametsoc.org/wiki/Vorticity>.

51 <https://glossary.ametsoc.org/wiki/Aerosol>.

52 <https://earthobservatory.nasa.gov/images/1510/global-effects-of-mount-pinatubo>.

53 This ignores the effects of the 1991–1992 El Niño event, a complicating factor since it had its own global temperature effects—researchers had to separate the effects of the two to better understand each one.

54 <https://www.weather.gov/mhx/ensowhat>.

some major eruptions, in the 1980s an international program under the World Meteorological Organization developed tools and techniques and an international infrastructure to allow operational meteorologists to issue volcanic ash forecasts.⁵⁵ The goal is to keep aircraft out of harm's way.

A devastating element of some volcanic eruptions is the pyroclastic flow, a fast-moving and turbulent current of tephra (hot gas and volcanic material) that races down the slopes of some erupting volcanoes. It is not a meteorological phenomenon because its source is volcanic rather than atmospheric. It is a burning apocalyptic wind from hell that can have surreal local effects. A pyroclastic flow from the Mt. Vesuvius eruption in 79 CE killed the inhabitants of Pompeii.⁵⁶ In May 1902, the pyroclastic flow from the eruption of Mt. Pelée in Martinique raced down its slopes and engulfed the town of St. Pierre, incinerating the vast majority of the 30,000 people who were there.⁵⁷ Ancient natural philosophers were aware of this phenomenon.⁵⁸ It has been proposed that the Greek term for a pyroclastic flow could have been *presteres*, since mythological stories refer to Hephaestus' forge among the seamounts off Sicily and say that it emitted "smoky *presteres*".⁵⁹

10 Mountains: the Ancient Versus the Modern Meteorological Context

J. J. Hall (Chapter 12) points out that, based ultimately on mythological conceptions about the home of the Gods, such as in the description of Mt. Olympus in the *Odyssey*, it was a widely held Greek belief that there is no wind above the highest mountains. Through observations, the science of meteorology has established that the wind usually increases with height and that mountain peaks, and the area above them, can be very windy indeed. The ancient natural philosophers had no such measurements, but they could perhaps have used some indirect observations such as the spindrift blowing off high mountain peaks to deduce that it must be windy up there. Better yet, they could have found a mountain to scale so they could hike to the top to see what the wind

55 <https://community.wmo.int/en/activity-areas/aviation/hazards/volcanic-ash>.

56 <https://www.theguardian.com/world/2021/mar/22/vesuvius-wiped-out-all-life-pompeii-15-minutes-study-pyroclastic-flow-cloud-gases-ash>.

57 <https://volcanofoundation.org/mount-pelee-martinique/>.

58 See chapter by Le Blay in this volume.

59 On this point, see the chapter by Krasne in this volume. A more common translation of the word *prester* is found in the section above titled "Atmospheric Rotation in Ancient and Modern Meteorology".

was like. No anemometer would have been necessary; a subjective “feeling” of the wind would have sufficed.

There is also the question of the formation of mountains. While not directly meteorological, it is of fundamental scientific interest. Colin Murtha (Chapter 19) outlines the mountain-building theories of the *Brethren of Purity* and of Avicenna. These days it is accepted that the process is geological and is explained by the science of plate tectonics*.

In meteorology, mountains are significant because they have a major effect on weather and climate. For example, a mountain range has on average increased precipitation and cloud on its windward side and decreased amounts to its lee. There are temperature effects as well, such as the warm chinook winds to the east of mountain ranges due to the descent of air down their lee side. Mountains also have significant effects on the winds (some of which were mentioned above in the section titled “What Causes the Wind?”). Air flowing through a valley or other constriction is compressed, which increases the wind speed. Air flowing around barriers (such as boulders, cliffs, ridges, spines, peaks, and so on) interacts in complex ways with those barriers, changing both the wind speed and direction in sometimes unexpected fashion. Katabatic winds can howl as they flow down mountain slopes. Mountain airflow can be related to significant updrafts or downdrafts, and all the preceding effects can result in moderate or severe turbulence. In such cases aircraft must steer well clear of the mountains. Worse yet, mountain effects can extend well above the mountaintops themselves. In some circumstances,⁶⁰ mountain wave clouds^{*61} can be created above the mountains. If there is enough humidity, they form the lenticular-shaped clouds known as ACSL (altocumulus standing lenticularis*).⁶² The clouds are beautiful but potentially deadly. Aviators beware when such clouds are observed!

11 Ancient Versus Modern Ideas on the Vertical Structure of the Atmosphere

Extensive observations from within the atmosphere (e.g. from weather balloons, instrumented aircraft and rockets) and from above (e.g. from remote-sensing satellites) have established the average vertical structure of the

60 <https://skybrary.aero/articles/mountain-waves>.

61 <https://www.weather.gov/mrx/mountainwaves>.

62 https://www.weather.gov/abq/features_acsl.

atmosphere. Most weather (such as clouds, winds and hydrometeors^{*63}) occurs in the troposphere*, the lowest layer (roughly, up to 10 km), in which the temperature usually decreases with height. Above that is the stratosphere (roughly, 10–50 km), mostly cold and very dry but warming in its upper levels. Above that lie other layers. A meteorologist is particularly interested in deviations from the average in the structure of the troposphere because they often are related to significant weather. The stratosphere can also experience major changes, the most common of which are known as sudden stratospheric warmings* (ssws).⁶⁴ ssws may have significant effects on tropospheric weather, but the linkages between the two layers are not well understood. Higher levels⁶⁵ (mesosphere*,⁶⁶ thermosphere, exosphere*⁶⁷) are of little importance in operational meteorology. However, certain exotic clouds (noctilucent clouds*⁶⁸ and polar mesospheric clouds*⁶⁹) do occur in the mesosphere and the auroras are found at even higher levels in the thermosphere.

In his paper, Colin Murtha (Chapter 19) discusses Avicenna’s Model of the Sublunary Strata. This model can be compared to the known structure of Earth and the atmosphere, as follows:

Avicenna	Modern View of the structure of Earth & its atmosphere
Nearly pure Earth	Core
Mud	Mantle
Land and sea	Earth’s surface (land, vegetation, liquid water and ice)
Warm air	Lower troposphere (the warmer part, contains clouds)
Cold Air	Upper troposphere (the cooler part, also contains clouds)
Nearly pure air	Stratosphere (dry [the sense of ‘pure’?], cold, few clouds)
Smoke	Unclear (a boundary between the stratosphere and space?)
Fire	Space, dominated by the “fire” of solar radiation

These relationships bring forth the grains of truth in Avicenna’s model.

63 <https://glossary.ametsoc.org/wiki/Hydrometeor>.
 64 https://www.weather.gov/bis/sudden_stratospheric_warming_events.
 65 https://www.nasa.gov/mission_pages/sunearth/science/atmosphere-layers2.html.
 66 <https://scied.ucar.edu/learning-zone/atmosphere/mesosphere>.
 67 <https://scied.ucar.edu/learning-zone/atmosphere/exosphere>.
 68 https://glossary.ametsoc.org/wiki/Noctilucent_clouds.
 69 https://glossary.ametsoc.org/wiki/Polar_mesospheric_clouds.

Another way to look at this question could be through the traditional elementary theory of Fire, Air, Earth and Water, a theory immensely popular among natural philosophers dealing with meteorological issues in Antiquity and the Middle Ages. A modern meteorologist might relate the four elements to the structure of the Earth and the atmosphere as follows:

Earth	The solid parts of Earth's surface (land, ice, vegetation)
Water	The liquid parts of Earth's surface
Air	The atmosphere (in any of its layers)
Fire	Space, dominated by the "fire" of solar radiation

12 Is Meteorology Deterministic or Probabilistic*?

Determinism in meteorology means that values of meteorological elements are forecast with no allowance for uncertainty. However, meteorologists know that the details of the initial state* of the atmosphere, termed the "analysis" (such as patterns of wind, pressure, temperature, humidity and clouds) are not cast in stone. That uncertainty must therefore spill over in some way into the forecasts, which can include a probabilistic element (e.g. "70% chance of showers"). Techniques have been developed (such as the ensemble*—a set of forecasts made by slightly different models but all valid at the same forecast time(s)⁷⁰) that can provide information about the meteorological uncertainty.

Did the ancient natural philosophers have anything to say about this? J. J. Hall (Chapter 12) asks rhetorically if Posidonius might have acknowledged the uncertainty of his meteorological theories. In reply to that question, he points out that although there is no direct evidence, the answer is, quite possibly, "Yes". A comparison of the meteorological approaches of Aristotle and Epicurus can shed some light on this question. Aristotle provides rather confident explanations ("deterministic forecasts*" in the modern context) for what could be termed "regular" meteorological phenomena (interpreted in the modern context as events that don't deviate much from the climatology) and ignores what might be termed "deviant" phenomena (uncommon events—those falling far from the usual climatological norms). Epicurus, on the other hand, considers weather "appearances" (any weather phenomena,

⁷⁰ https://glossary.ametsoc.org/wiki/Ensemble_forecast.

common or not), whose explanations, according to Diogenes of Oinoanda, can be more or less probable. Modern meteorology is closer to the probabilistic forecast of Epicurus than the determinism of Aristotle.

13 What About Anthropogenic Climate Change*?

These days, this subject is an elephant in every meteorologist's room. Malcolm Wilson's title *Meteorology as a Prefiguration of Life in Aristotle* (Chapter 6) suggests a climate change-related analogy: *Climate Change as a Prefiguration of Life in the 21st Century*. Wilson relates Aristotle's views in the *De Caelo* and the *De Generatione et Corruptione* with those found in the biological corpus via Aristotle's *Meteorologica*, which he considers as a sort of link, or boundary, between the two. In an analogous manner, in the modern context one can link life at the surface with the changes induced in the atmosphere by anthropogenic global warming through the boundary connecting the two, which is known as the atmospheric boundary layer* (ABL) or planetary boundary layer* (PBL).⁷¹ The analogy can be used to present some examples of how living things at Earth's surface are being affected by global warming and climate change. Operational meteorologists didn't usually deal with such biological considerations in the past, but these days they can be explicit or implicit in some forecasts. For example, in a frigid winter cold snap with high wind chill*,⁷² the risk of frozen exposed skin can be emphasized directly in the forecast. In the opposite case of a heat wave, specialists can use forecasts of temperature and humidity to plan for cooling shelters so that excess deaths can be minimized.

The changing climate is changing the weather, which is becoming more variable. Extremes are becoming more frequent. This means that operational meteorologists are forecasting extremes and records (in temperatures or in precipitation amounts, for example) more frequently than ever before. Not only must the events themselves be forecast but more and more their impacts must be as well. In this regard, academic meteorologists try to figure out how the changing climate is changing the weather, and what impacts those changes will bring. Weather forecasters can at times integrate some of that information into their forecasts.

71 <https://www.britannica.com/science/planetary-boundary-layer>.

72 https://glossary.ametsoc.org/wiki/Wind_chill.

14 The Aesthetics of Meteorology

Some meteorological phenomena have astounding beauty: a lightning storm, a rainbow, hoar frost or fresh snow on tree branches, red clouds at sunset or sunrise, a snowflake, a drop of dew. The spatial scales run the gamut from the macroscopic to the microscopic. These days, the meteorologist has the advantage of being able to see weather systems from above as well. Meteorological structures observed from the vantage point of satellites can look elegant to the eyes of a meteorologist—there's a sublime organization within the apparent chaos. That perspective from space, of weather systems such as low-pressure areas and their clouds, or fronts*, or lines of thunderstorms, or hurricanes, is a symbol of the meteorology of the late twentieth and early twenty-first centuries.

The ancient natural philosophers must have appreciated meteorological beauty, and the myriad forms and types of clouds might have been one source of their weather reveries. It took two millennia, though, before the Englishman Luke Howard finally produced a systematic cloud classification*, which he published in 1803.⁷³ His work, in modified form, remains in effect to this day,⁷⁴ while the clouds in all their shapes and sizes remain as fascinating and elusive as ever. Some artists of Howard's time are known for their depictions of clouds and storms ("cloudscapes" and "stormscapes"), such as the Englishmen J. M. W. Turner (1775–1851) and John Constable (1776–1837), and the Russian Ivan Aivazovsky (1817–1900). Their artistic style could even be considered an artistic current, worth pursuing in its own right! These days, some artists have turned to cloud photography or to the photomicrography (photography using a microscope) of ice crystals and snowflakes.⁷⁵ Meteorological beauty is all around us.

The author is a native of southeastern Alberta, Canada. On a fine day, the Rocky Mountains are visible, far to the west. The sky is so big that it is like looking out to infinity—a humbling vastness. The American state of Montana, just across the border, is popularly referred to as "Big Sky Country". That's exactly how I felt about the majestic forever sky over southern Alberta. Within that sky, meteorological phenomena can be grandiose, while an individual meteorologist, miniscule, still belongs in some way to the sweep of sky and cloud

73 A systematic cloud classification is one in which observed properties of clouds are used to develop a relatively small set of categories, by which other observers can identify them.

74 <https://cloudatlas.wmo.int/en/home.html>.

75 The American Kenneth Libbrecht has built a website that celebrates the art and science of snowflakes. It is found at <http://snowcrystals.com>.

and wind and rain (and even snow!). Perhaps the ancient natural philosophers were attracted to the science of meteorology by similar thoughts.

Bibliography

- Barnes, J. *The Complete Works of Aristotle. The Revised Oxford Translation.* 2 vols. Princeton, N.J., 1984.
- Galilei, G. *Discorso sulle comete fatto da lui nell'Accademia fiorentina nel suo medesimo consolato.* In *Opere di Galileo Galilei, Parte 3, Tomu 12: Astronomia.* <https://www.loc.gov/item/2021666741>.
- Henderson, J. ed. and trans. *Aristophanes.* Clouds. Wasps. Peace. Cambridge, MA, 1998.
- Hort, A. F. *Theophrastus.* Enquiry into Plants, *Volume 11: Books 6–9.* On Odours. Weather Signs. Cambridge, MA, 1916.
- Most, G. M. ed. and trans. *Hesiod.* Theogony. Works and Days. *Testimonia.* Cambridge, MA, 2018.
- Stephenson, F. R., D. M. Willis, and T. J. Hallinan. "The earliest datable observation of the aurora borealis." *Astronomy & Geophysics* 45, no. 6 (2004): 15–17.
- Stothers, R. "Ancient Aurorae." *Isis* 70, no. 1 (1979): 85–95.