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978-1-108-47154-1 — Exploring Planetary Climate
Ralph D. Lorenz
Excerpt
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The Age of Wonder: Learning the Earth, Oceans and Sky

440 BC to ~1760

440 BC – Herodotus considers Nile flood lagging seasons, notes sea-shells on hills and salty soil indicating Egypt was once underwater, recognizing terrestrial conditions vary with time

350 BC – Aristotle writes *Meteorology*, a work that discusses a range of phenomena in the sky, including meteors as well as weather and climate

c. AD 80 – Chinese philosopher Wang Chong states that rain is evaporated from water on the earth into the air and forms clouds and rain

1021 – Alhazen investigates refraction of light and twilight, and deduces an effective height of the Earth's atmosphere as about 20 miles

1450 – Leone Battista Alberti develops a swinging-plate gauge, considered the first anemometer

1543 – Nicolaus Copernicus proposes a heliocentric architecture of the solar system

1604 – Cornelis Drebbel writes a *Treatise on the Elements*, noting the tremendous expansion of water into vapor. Drebbel goes on to invent a submarine, and a self-regulating oven with a thermostat

1607 – Galileo Galilei constructs a thermoscope, and defines heat as a distinct property of matter, rather than as one of the classical four elements (Fire, Water, Air and Earth). Observes mountains on the Moon, phases of Venus

1643 – Evangelista Torricelli invents the mercury barometer

1648 – Blaise Pascal rediscovers that atmospheric pressure decreases with height, and deduces that there is a vacuum above the atmosphere

1650–1690s – Christiaan Huygens discovers Titan, contemplates conditions on other worlds, recognizes atmosphere and fluid may be made of different substances, different densities etc. Calculates how long a bullet would take to reach the planets

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1660s – Cassini observes polar caps on Mars
1686 – Edmond Halley makes a systematic study of the trade winds and monsoons and identifies solar heating as the cause of atmospheric motions. Defines the relationship between barometric pressure and height above sea level
1724 – Gabriel Fahrenheit creates reliable scale for measuring temperature with a mercury-type thermometer
1729 – Pierre Bouger pioneers light measurement, and develops the law of attenuation of light by atmospheric absorption (later called the Beer–Lambert law)
1735 – The first idealized explanation of global circulation is the study of the trade winds by George Hadley
1742 – Anders Celsius, a Swedish astronomer, proposes the centigrade temperature scale, which led to the current Celsius scale
1743 – Benjamin Franklin is prevented from seeing a lunar eclipse by a hurricane, he decides that cyclones move in a contrary manner to the winds at their periphery
1755 – Tobias Mayer calculates dependence of temperatures on latitude and altitude
1761 – Joseph Black discovers that ice absorbs heat without changing its temperature when melting

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Climate is a subject that concerns everyone, and considerations of climate problems enter some of the first intellectual records in existence. For example, Herodotus' *Histories*, written (or at least told) around the 440s BC, document aspects of geography as well as history. In particular, Herodotus notes the non-intuitive behavior of the Nile river, that its level begins to rise around the summer solstice and does so for a hundred days, then the level falls throughout winter. Herodotus considers whether winds could be a factor (the Nile's usefulness as a transport artery arises from the generally northerly winds, allowing boats to sail south upriver, they could then furl their sails and float back down). In fact summer snowmelt is responsible for the changing flow but Herodotus (incorrectly) dismisses snow, since it was known that the further south one got, the hotter and drier it was, so how could there be snow near the torrid equator?

Interestingly, Herodotus also ventures some speculations on the origins and past of Egypt, noting that the soil is dark, as one might expect alluvial (water-delivered) deposits to be, in contrast to the windblown sands to the west in Libya. Furthermore, he notes that shells characteristic of aquatic animals are found on hilltops and that there is salt in the soil, and ventures that much of Egypt was once underwater. Herodotus recognized (Bishop Ussher not yet having set an age of the Earth of only four millenia before his time!) that these changes may have taken tens of thousands of years.

A more focussed work, and generally acknowledged as the first serious work on the topic (~350 BC), is the *Meteorologia* compiled by Aristotle. This treatise covers a wide range of geophysical and astronomical topics, such as the saltiness of the sea and the nature of comets as well as the causes of wind and rain (the separation of the study of meteors and meteorites into disciplines distinct from "meteorology" came later, as science became more specialized). Naturally, since the concepts of heat and energy were unknown, and the description of matter was limited to four elements (Earth, Air, Fire and Water),[1] Aristotle's explanations are flawed, but he does a fair job of laying out some interesting problems (for example, why should hailstones, made of ice and obviously associated with cold, be more common during summer than winter?). He captures the essence of the hydrological cycle as follows:

> *Now the Sun, moving as it does, sets up processes of change and becoming and decay, and by its agency the finest and sweetest water is every day carried up and is dissolved into vapor and rises to the upper region, where it is condensed again by the cold and so returns to the earth.*

[1] Four or five elements feature in much ancient thought. The "classical" four were originally proposed by Empedocles, and Aristotle popularized them, adding a fifth, "aether", for the uncorruptible heavens.

Other Greek philosphers of the time contemplated that there might be many worlds: Metrodorus (a disciple of Epicurus) suggested in the fourth century BC, "*To consider the Earth as the only populated world in infinite space is as absurd as to assert that in an entire field of millet, only one grain will grow*."

After Aristotle's compilation, there was little substantial progress in meteorology in the Western world. Yet, as in other fields, many Muslim philosophers and scientists made steps towards understanding the natural world, notably from the tenth through fifteenth centuries. The scholar Ibn al-Haytham ("Alhazen"), in what is now Iraq, used geometric arguments to deduce the thickness of the sensible atmosphere.[2] Knowing the diameter of the Earth, and the fact that twilight began or ended with the Sun 19 degrees below the horizon, he deduced that the effective scattering height of the atmosphere could be no more than 52,000 paces. Indeed, at such heights – not physically reached for almost another thousand years – the air density is only a fraction of one percent of what it is at the ground.

Similarly, in China, some relevant ideas were emerging. In 1074, Shen Kuo[3] reasoned – like Herodotus – that a belt of bivalve fossil shells in mountains inland implied that the terrain there must have once been a seashore, and that mountains must be eroded and sometimes uplifted (in the West, as we see later in this chapter, James Hutton, seven centuries later, reached similar conclusions and took them further). He also recognized that petrified bamboo, revealed by a landslide in a place where bamboo does not grow today, implied that the climate had been different in the past.

The pivotal role of the Sun in controlling climate was obvious even to the ancients, but systematic consideration of the climate of Earth and of other worlds relied on correctly laying out the architecture of the solar system. While some Greek scientists got this right, it was not until the Copernican revolution beginning in 1543 that progress could really be made. An additional early challenge to understanding climate and weather is that diurnal changes of wind are in near synchrony with tidal changes in the sea, and thus the role of the Moon in influencing winds was initially thought to be significant.

With the Copernican layout of the universe established with the Sun at the center, backed by Kepler's laws, it became possible in the 1600s to consider the other planets in their proper place (e.g. Figure 1.1). English astronomer Thomas Digges realized that the stars may stretch into infinite space,[4] and the scholar Giordano Bruno even

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[2] For a modern version of this measurement, see M. Beech [1].

[3] I'd never learned of Shen Kuo until I started writing this book. Making discoveries is one of the main joys of writing.

[4] Digges attempted to measure the parallax of Tycho Brahe's supernova, but could only establish a lower limit, determining that the star had to be beyond the Moon. Digges is a relatively poorly-known astronomer and mathematician, typically overshadowed by Giordano Bruno whom he may have influenced in England in the 1580s; see Ref. [2].

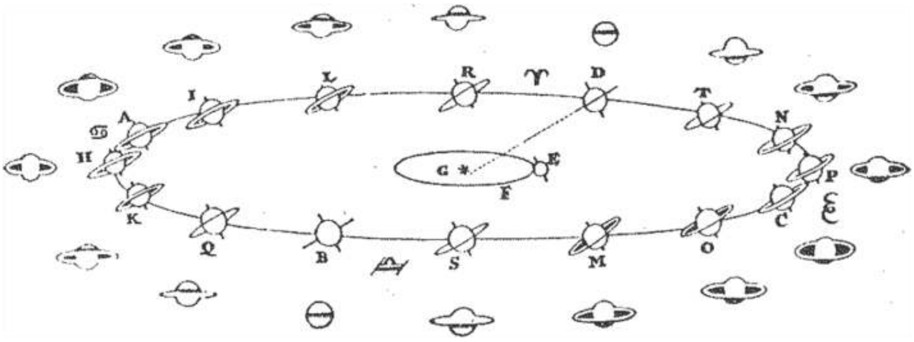

Figure 1.1 Seasons on another planet. This admirable graphic from Huygens' 1659 book *Systema Saturnium* shows not only Saturn's relationship to the Sun and Earth, but also how Saturn's appearance from Earth changes due to the fixed orientation of Saturn's ring and pole with respect to space.

speculated that stars were other suns with their own planets, and that such planets might be inhabited. The invention of the telescope and Galileo's observation of crescent phases of Venus made it clear that Venus was closer to the Sun than is Earth.[5] On the other hand, Mars, Jupiter and Saturn (e.g. Figure 1.1) always appeared almost completely round, implying they were further away.

The development of instruments not only augmented astronomers' vision, but also enabled the quantitative measurement of the world. Instruments to first visualize, and later measure, temperature were also first developed around this time. Galileo developed a thermoscope (only with the addition of a numerical scale does it become a thermometer), while an ingenious Dutchman working in England in the early 1600s, Cornelis Drebbel, devised an oven with a mercury tube that not only displayed a measure of heat, but regulated the air flow into it – a primitive thermostat and perhaps the first example of a feedback control system. Drebbel also ground lenses for optical instruments, showing some to his visiting countryman, the diplomat Constantyn Huygens. Remarkably, Drebbel is also reported to have invented a submarine, and conveyed King James I under the surface of the River Thames in it: the depth of the submersible was indicated with a tube of mercury, in effect a barometer [3].

Evangelista Torricelli in Tuscany, confronting the problem that suction pumps could only lift water 10 meters or so, showed in 1643 that a column of mercury in a tube closed at one end was limited to only 76 cm long – the same weight

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[5] Although Galileo is sometimes credited with the invention of the telescope, it was likely invented in the Netherlands in 1608, but quickly spread. Thomas Harriot in England observed the sky with it in 1609. Galileo was an early and enthusiastic adopter of the new invention, and quickly built his own and improved the design, and, importantly, wrote down his findings.

per unit area as 10 meters of water – and thus that this had to be the same as the weight per area, or pressure, of the atmosphere. Thus began the systematic, and eventually quantitative, understanding of the physics of atmospheres: he famously remarked, "*We live submerged at the bottom of an ocean of air*."

Galileo's use of the telescope in 1610, revealing that Jupiter had moons, and that our own Moon is a world with mountains and craters, stimulated thinking about planets as places, and thus about their conditions. The Polish astronomer Hevelius documented the topography of the Moon in detail in 1647. This widening perspective was perhaps most enthusiastically embraced by the Dutch astronomer Christiaan Huygens (Constantyn's son). Huygens ground his own lenses, and was the first to measure the rotation rate of the planet Mars, finding that the length of its day was rather similar to our own, and in 1655 he discovered Titan. He correctly imagined how seasons and shadow would work on other worlds (Figure 1.2). In the mid-1660s, Jean-Dominique Cassini in Paris, observed polar caps on Mars, and Huygens made the first sketch of them in 1672.

Huygens considered that other worlds might have seas composed of fluids with properties different from water [4]: "*Every Planet therefore must have its Waters of such a temper, as to be proportioned to its Heat: Jupiter's and Saturn's must be of such a Nature as not to be liable to Frost…*", a remark that rather nicely anticipates methane rain on Titan. He even speculates that there is a lot of room in between

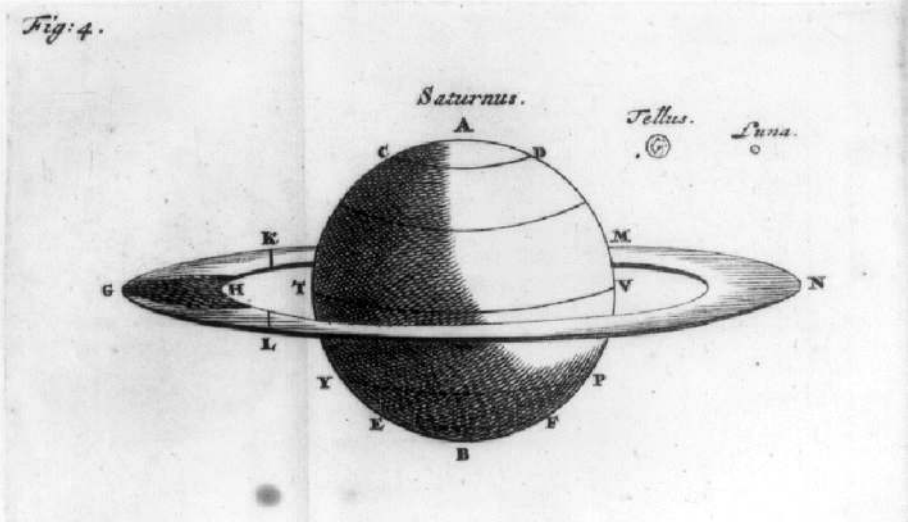

Figure 1.2 A billion-mile leap of the imagination. Not only does Huygens discover Titan and ascertain correctly the architecture of the rings, he expresses his knowledge in a picture, showing a view that cannot be obtained from Earth. He mentally transports himself out to Saturn, to visualize how in summer Saturn would cast a shadow on its rings, but that shadow is generally hidden from our view.

the densities of air and water on Earth for fluids on other planets: "*The Sea perhaps may have such a fluid lying on it, which tho' ten times lighter than Water, may be a hundred Times heavier than Air*", and notes that on worlds with denser atmospheres it would be easier for birds to fly. Indeed, this is not too far off what Titan is like today: Titan's air is four times denser than ours, and its seas about half as dense. So Titan's seas are indeed about 100 times denser than its air, rather than the ~800 times for Earth. If birds – or even people – could breathe and not freeze, they would find that Titan's low gravity makes it a very easy place in which to fly.

Huygens closes his book with breathless happiness:

> *What a wonderful and amazing Scheme have we here of the magnificent Vastness of the Universe! So many Suns, so many Earths, and every one of them stock'd with so many Herbs, Trees and Animals, and adorn'd with so many Seas and Mountains! And how must our Wonder and Admiration be increased when we consider the prodigious Distance and Multitude of the Stars?*

Huygens notes, in an appealingly self-consistent if slightly optimistic argument, that the astronomers on hot Mercury, so close to the Sun, would think that the Earth would be inhospitably cold. And yet here we are; and therefore it follows that, while we might think Jupiter or Saturn too cold to support life, it might nonetheless be present, albeit in somewhat adapted form. Huygens draws on the fact that plants and animals had been found in another new world – America – that were quite different from those known in Europe, and wonders if the differences between lifeforms on different planets might actually be less than the differences between those from widely separated parts of the Earth.

Huygens outlook, one we might call an extreme NeoCopernican, was not limited to astrobiologists on other worlds, but also sailors who probably used similar sails and anchors, pullies and rudders on other seas.[6] He even expresses some jealousy of "*the great Advantages Jupiter and Saturn have for Sailing, in having so many Moons to direct their Course, by whose Guidance they may attain easily to the Knowledge that we are not Masters of, of the Longitude of Places*" (the problem of determining longitude at sea was not to be practically solved for another several decades[7]). Yet, while his imagination ranged across the solar system, Huygens

[6] A French author of the time, Bernard de Fontenelle, lauded planetology and astrobiology, writing, "What can more concern us, than to know how this world which we inhabit, is made; and whether there be any other worlds like it, which are also inhabited as this is?" (1688 translation of *La Pluralite des Mondes*).

[7] Galileo had suggested the arrangement of the Jovian moons could be used as a sort of universal clock (for terrestrial, rather than Jovian, sailors to calculate longitude) but this relied on telescopic observations from a heaving ship, which had severe challenges. Halley confronted the problem in various ways, considering occultations of stars by the Moon, or

was well-grounded enough to recognize the practical challenges of traveling to other worlds. He noted that a bullet (the fastest object with which he was familiar – which traversed a hundred fathoms in a heartbeat) would take 250 years to reach Saturn.

Huygens was not alone in his age – an English clergyman and co-founder of the Royal Society, John Wilkins [5], imagined the Moon might be inhabited, and while recognizing that the upper air was cold and thin and that there would be no inns en route to offer victuals and shelter,[8] affirmed "*it possible to make a Flying Chariot, in which a Man may sit, and give such a Motion unto it, as shall convey him through the Air. And this perhaps might be made large enough to carry diverse Men at the same time …*". He went on to make the remarkable prediction "*Supposing a Man could fly, or by any other means, raise himself twenty miles upwards, or thereabouts, it were possible for him to come unto the Moon*" – three centuries later these two landmarks in aviation were in fact met only thirteen years apart.[9]

Daniel Defoe briefly considered the climate on the Moon in his 1705 *The Consolidator*,[10] where "*the Elasticity of the air is quite different, and where the pressure*

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the use of the dip of the Earth's magnetic field. Ultimately it was the development in 1761 of the marine chronometer, a clock that maintained sufficiently accurate time despite temperature changes and the ship's motion, that allowed practical navigation.

[8] Indeed, this logistical aspect of spaceflight was also pointed out by the *Spokesman-Review* newspaper in 1920, on the publication of Robert Goddard's proposals for rocket-powered spaceflight "THAT FLIGHT TO PLANET MARS – Would take a year and the traveler would be hungry". See Ref. [6].

[9] No human reached 20 miles (105,600 ft or 32 km) upward until the 1950s (38.5 km in the Bell X-2 rocket plane in 1956, 13 years before Apollo 11). Although ballooning began long before heavier-than-air aviation, the 20-mile threshold was only breached (113,740 ft) in the StratoLab High V balloon in 1961, shortly after Kittinger's famous parachute jump (102,800 ft, 31 km) from the Excelsior III balloon in August 1960. See Table 10.1 in [7]. The StratoLab V flight of over 9 hours gave its two aeronauts the honour of being the highest-flying Americans for exactly one day, that title passing to Alan Shepard on a suborbital flight on a Mercury rocket (though of course Yuri Gagarin had flown in orbit a month before).

[10] The work, *The Consolidator; or, Memoirs of Sundry Transactions from the World in the Moon* (London, 1705), is actually a satirical commentary, using the device of people on the Moon viewing the Earth from afar to show the absurdity of aspects of human society. The "Consolidator" is the name of the feathered machine ("Engine"), which has wings about 50 yards in breadth, and cavities "*filled with an Ambient Flame … order'd as to move about such springs and wheels as kept the Wings in a most exact and regular Motion*". This seems somewhat inspired by Wilkins' idea, and indeed the book mentions him. Upon attaining a height where "*gravity having passed a certain line*" (Newton's *Principia* was published only 7 years before), the wings became more applied to controlling the engine's descent down to the Moon than to raising it, a scenario that nicely anticipates Jules Verne's *From the Earth to the Moon*. Defoe was of course most famous for his *Robinson Crusoe*, written in 1722. The literary device of extraterrestrial visitors commenting on Western culture was

of the Atmosphere has for want of Vapor no Force" (in spite of which the narrator is able to travel to the Moon in a feathered machine!). The Moon has "*very seldom any clouds at all, and consequently no extraordinary storms*". The previous year Defoe had written *The Storm*, an early journalistic work compiling personal accounts of the Great Storm of 1703, a cyclone that felled millions of trees and killed thousands.

The New World too was reported to be meteorologically challenging – even just the title of one account, by James MacSparran, says it all: "*America Dissected, Being a full and true account of the American Colonies, shewing the intemperance of the climates, excessive heat and cold, and sudden violent changes of weather, terrible and mischievous thunder and lightning, bad and unwholesome air, destructive to human bodies, etc.*" That said, these were exciting times – as Robert Hooke noted, "*new Lands, new Seas are daily found out, and fresh descriptions of unknown Countreys still from both brought in; so that we are forced to alter our maps, and make anew the Geography of both again.*"

An understanding of the Earth's climate at the planetary scale first requires a realization that the Earth is round. While this was of course understood by many prior to the age of exploration, the quantitative implications in terms of the amount of sunlight deposited at different latitudes requires trigonometry, and the amount was first calculated by astronomer Edmond Halley [8]. In a paper published in 1693 he showed by geometric arguments[11] how the combination of the declination of the Sun and the varying length of day can conspire to deliver more sunlight (averaged over a 24-hour period) to the pole at midsummer than to the equator (Figure 1.3). However, the nature of heat was not yet fully understood, and so the exact implications for temperature had to wait another century or two.

Halley may also have been the first to quantitatively consider the hydrological cycle. More particularly, he adopted the thoroughly modern approach of obtaining experimental data, and applying it to a global-scale model [9]. Specifically, he warmed an eight-inch pan of water on a set of scales to the temperature of a hot summer day, regulating the temperature by holding coals nearby, and observed that in the course of two hours the pan lost half a Troy ounce of liquid. This value of 1/10 of an inch per day is rather close to the terrestrial average flux of evaporation and precipitation, of about one meter per year. That said,

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also employed by Voltaire in *Micromegas*, where a 37-km tall visitor from a planet around Sirius enounters a 1.8-km tall member of the Academy of Saturn with whom he travels to Earth, and is astonished to find that the tiny beings on that planet are actually intelligent. The notion of a planet around Sirius appears to have raised no more eyebrows than the rest of the book.

[11] The result is expressed in rather arcane terms: "*to give the proportional degree of Heat or the sum of all the Sines of the Sun's Altitude while he is above the Horizon in any oblique sphere, by reducing it to the finding of the Curve surface of a cylindrick Hoof, or of a given part thereof.*"

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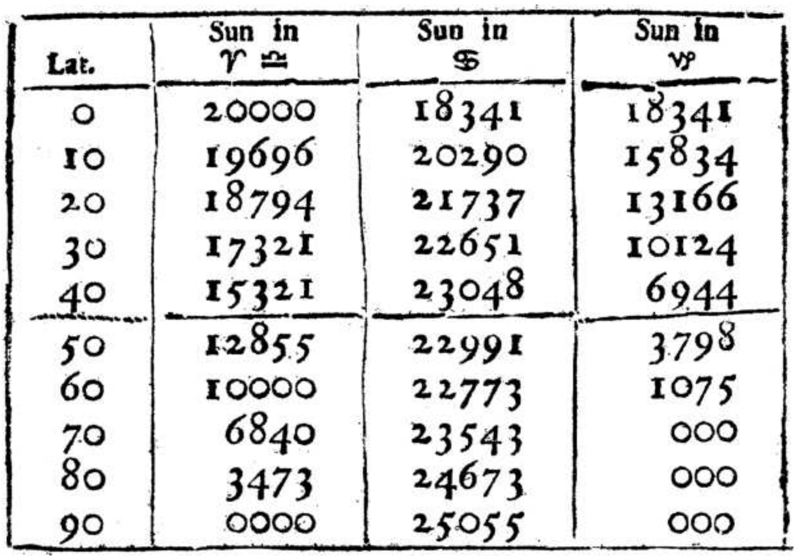

Lat.	Sun in ♈ ♎	Sun in ♋	Sun in ♑
0	20000	18341	18341
10	19696	20290	15834
20	18794	21737	13166
30	17321	22651	10124
40	15321	23048	6944
50	12855	22991	3798
60	10000	22773	1075
70	6840	23543	000
80	3473	24673	000
90	0000	25055	000

Figure 1.3 Halley's calculation of the relative amounts of sunshine over 24 hours as a function of latitude and season. The rows are latitude, and the columns refer to spring equinox, summer solstice and winter solstice, respectively. Note the surprising result that there is more sunshine in total in polar summer (25,055 units) than at the equator; Halley is essentially using integer arithmetic, hence the numbers are expressed relative to the equator at equinox (20,000).

the agreement is perhaps fortuitous – although Halley notes that he made the water salty like the sea, he does not record the weather conditions such as wind or humidity, which we now know would substantially affect such an experiment.

Halley then bravely upscales this measurement to the Mediterranean Sea, which he briskly approximates as a 4 × 40 degree box (one degree being 69 English miles) to determine that the Mediterranean should lose 5280 million tons of water per day.[12] He estimates the water influx via large rivers (scaling from the Thames, whose depth and flowspeed were known to him by personal experience, having experimented with diving bells for salvage) and concludes that the Mediterranean must experience a deficit of water, restored by inflow from the Atlantic through the Straits of Gibraltar. This is probably the earliest example of a mass balance calculation.

Halley also considers the salt cycle on the Earth. Anticipating the nineteenth-century geology view that "the present is the key to the past", he notes that the

[12] I made similar sweeping approximations myself in performing essentially the same calculation for methane evaporation from Titan's seas [10]. I think Halley would approve.