Prime Meridian

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The imminent death of planet Earth?

The Venus Syndrome

In an interview for the BBC on July 2, 2017, the world famous physicist and cosmologist Prof Stephen Hawking stated:

"We are close to the tipping point where global warming becomes irreversible. Trump's action could push the Earth over the brink, to become like Venus, with a temperature of two hundred and fifty degrees, and raining sulphuric acid"

Runaway greenhouse or runaway rhetoric?

The surface of Venus imagined in a drawing by J. Whatmore. ESA.

Prof. Hawking dropped his dramatic statement during an interview with the BBC and it was seized upon by the newspapers. Coming from such a respected figure, it had a world-wide impact at a time when concerns are running high about global warming due to human release of greenhouse gases.

For that reason alone, this claim must be examined closely and objectively before environmentalists take up this rhetoric. Could the Earth be driven by careless human activity into a Venusian condition? If so, how close are we to doing so?

A warning in the dawn sky?

The planet Venus is presently a morning star. It rises in the dark hours and it remains gleaming defiantly against the dawn twilight, a pearly point of light that refuses to be overwhelmed until shortly before sunrise.

When Venus is seen as an evening star, its gleam emerges powerfully as the sky darkens, but, orbiting closer to our star, it can never stray into the midnight skies and its glow is lost through layers of air and cloud as it follows the Sun below the horizon.

Looking sunwards from our Earth, a world of deep oceans swirled with white clouds, of forest and savannah and croplands; a world where unimaginable numbers of micro-organisms teem in the merest drop of water and somehow survive in its most inhospitable wastes, we see a sister world of lethal extremes. Venus has nearly 82% the mass of the Earth and 0.95 its diameter, but it is a very different kind of place.

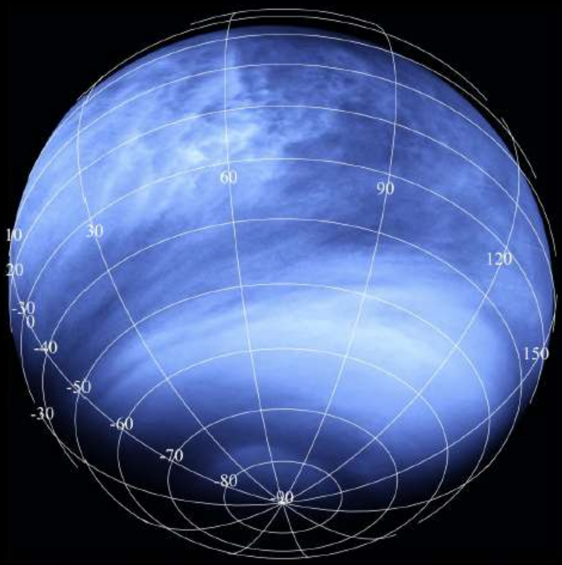
The beautiful star that is Venus owes its brilliance to a planet-smothering haze of sulphuric acid droplets that ride tens of kilometres high in a massive atmosphere that is mostly carbon dioxide. Beneath that shroud lies an environment that predictably elicits cliches about a hellish inferno from astronomy writers. The atmosphere bears down on its waterless landscapes with a pressure 93 times greater than that of our air and the surface temperature is 467°C day and night. Space probes have sent back desolate panoramas of layered bedrock and loose slabs extending to lifeless horizons.

Venus may be showing us our own future. Our Sun is growing steadily brighter over time. This is a consequence of the nuclear fusion reactions in our star's core that produce its energy. Hydrogen is fused to helium and, in the process, over 4 million tonnes of matter are annihilated directly into energy every second. The accumulation of helium "ash" in the core causes physical adjustments in the Sun. The Sun formed out of a cloud of gas and dust around 4.6 thousand million years ago and settled down as a star with just 72% of its present luminosity. Venus, just 72% our distance from the Sun, has always received around twice the energy falling on Earth. Could it be that Venus once offered a clement climate for life, but was overcome as the blaze of solar energy intensified remorselessly?

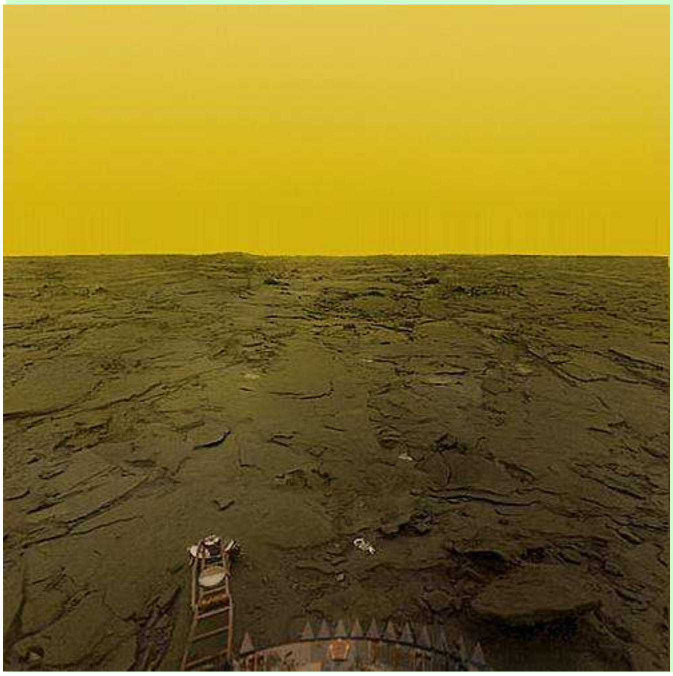
Venus still haunting the dawn sky while clouds and the trails from high flying planes catch the gleam of the Sun.

August 25, 2017.

05:30 BST = 04:30 GMT



Above: Venus in natural colour. Mariner 10. 1962. NASA.NASA. Image processing by R. Nunes. Left: An ultraviolet view of Venus from the Venus Express mission. Credit: ESA/MPS/DLR/IDA. Below left: The view seen in 1982 by the Soviet probes Venera 13 (upper) and Venera 14 (lower) in vicinity of Phoebe Regio.



Hawkins' warning that we can bring on the Venus Syndrome echoes that issued eight years ago by James E. Hansen, climate scientist and environmental activist.

A former head of the NASA Goddard Institute for Space Studies, he now leads the Program on Climate Science, Awareness and Solutions at Columbia University. His passion about the climate threat runs deep and he has been prepared to be arrested at demonstrations. He has been dubbed the Father of Climate Change Awareness.

In his 2009 book *Storms of My Grandchildren*, Hansen argued that if we continue to pump CO_2 into the atmosphere ice sheets would melt on a timescale of centuries. Sea level would rise by about 75 m.

The fate of methane hydrates in a warming world must also be factored in. These are clathrates, or molecules whose cage-like lattice can trap other molecules. In this case, water ice traps methane molecules. There are believed to be huge deposits of methane clathrates the Arctic permafrost and on the ocean floor. Global warming, which has been fastest in the Arctic, threatens to de-stabilise these deposits and to release the greenhouse gas methane (which would eventually be oxidised to another greenhouse gas: CO_2).

Ultimately, he argued: *“After the ice is gone, would Earth proceed to the Venus syndrome, a runaway greenhouse effect that would destroy all life on the planet, perhaps permanently? While that is difficult to say based on present information, I’ve come to conclude that if we burn all reserves of oil, gas, and coal, there is a substantial chance we will initiate the runaway greenhouse. If we also burn the tar sands and tar shale, I believe the Venus syndrome is a dead certainty.”*

Climate scientists predict that the road from the habitable Earth to the Venus Syndrome lies through two potential climate catastrophes, the moist greenhouse and the runaway greenhouse. These may have already happened on innumerable life-bearing planets in our Galaxy, leaving them devoid of life. As stars grow in brightness, the inner margin of the Habitable Zone will creep inexorably outwards, leaving dead worlds behind.

The term "*runaway greenhouse*" has been used to mean different things by different sections of the scientific community. It was coined by Andrew P. Ingersoll (1968;1969) in papers exploring the possible history of water on the planet Venus and has a precise meaning, however, for scientists investigating the Habitable ("*Goldilocks*") Zone around the Sun and other stars. The HZ is defined as the zone within which a suitable planet could retain liquid water (necessary for life-as-we-know-it) on its surface. Astrobiologists occasionally look at the possibility of life that uses other solvents, but all the organisms presently known to science require water. If a planet is too close in, its water will be lost to space. If it is too far out, it will freeze.

Water vapour is an effective greenhouse gas. It allows through short-wave radiation from the Sun. Part of this is reflected back into space from the ground, but part of it is absorbed and warms the ground. The ground, having been heated, emits long-wave radiation to space. This is mostly in the infra-red part of the spectrum and a substantial amount is absorbed by greenhouse gases and re-radiated back to the ground, raising the temperature of the Earth's surface. The warmer conditions become at the surface, the more easily will water vapour be evaporated and the more water vapour that enters the atmosphere, the more intense the greenhouse effect will become. This was understood by The potential of water vapour to intensify warming caused by other greenhouse gases and was understood in late 19th C and early 20th C by Svante August Arrhenius *(*1859-1927) and Thomas Chrowder Chamberlain (1843-1928) (Chamberlain, 1899, Flemming, 1998; Held & Soden, 2000).

There is a potential here for a fatal feedback, which might, under the right conditions, continue until the Earth's surface becomes so hot that the entire ocean (which has a mass of 1.4×10^{24} g) has evaporated into the atmosphere. This would raise the surface pressure by about 270 bars (one bar is a good approximation for one Earth atmosphere pressure). The temperature could then soar to over 1600ºC. For comparison, basaltic (typical of the ocean floor) becomes runny lava at 1000-1250ºC and rhyolite (more closely allied with the silica-rich rocks of the continental crust) becomes sticky lava at 700 to 900ºC. Our planet would be smothered by molten rock. The surface environment of the Earth as we know it would have ceased to exist. UV from the Sun would break up water molecules in the upper atmosphere and hydrogen would leak away rapidly into space. This hellish regime would only last for a few tens of millions of years, but it would leave behind a waterless and lifeless world with little indication of the lush biosphere that had once flourished here. Have we already set the ball rolling on this process?

Note, by the way, that although the ferocious temperature of Venus is sometimes described as a runaway greenhouse, this is not strictly correct according to the definition above. The runaway would have been a short-lived phase, while Venus lost all but traces of its water. If this has actually happened on Venus, what we are seeing today is the desolate aftermath.

Less dramatic would be the moist greenhouse. Rising surface temperatures would change the structure of the atmosphere enabling it to become wet at high altitudes. The water mixing ratio need be only 0.1%, but that is still two orders of magnitude higher than the amount of water in the stratosphere today, and water would be lost to space over hundreds of millions of years - not leaving enough for a runaway greenhouse to take place. Could this be the way that most planets are destined to evolve into lifeless deserts.

7.5 thousand million years from now (depending on astrophysicists' models), the nuclear reactions that produce the Sun's energy will have filled our star's core with helium. Nuclear burning of hydrogen will begin in a shell around the core and the Sun's outer atmosphere will expand – turning the Sun into a red giant that will loom vast in Earth's skies, even if it eventually fails (it could be touch-and-go) to actually swallow the Earth. However, the Sun's luminosity has been rising by about 1% every 110 million years. In the natural order of things, the Earth will be overtaken and sterilised by a climate catastrophe of some sort long before the Sun becomes a red giant.

What do climate models tell us about the conditions needed for the moist greenhouse and runaway greenhouse to set in? There is no simple, definitive and unequivocal answer. Researchers have come up with different results.

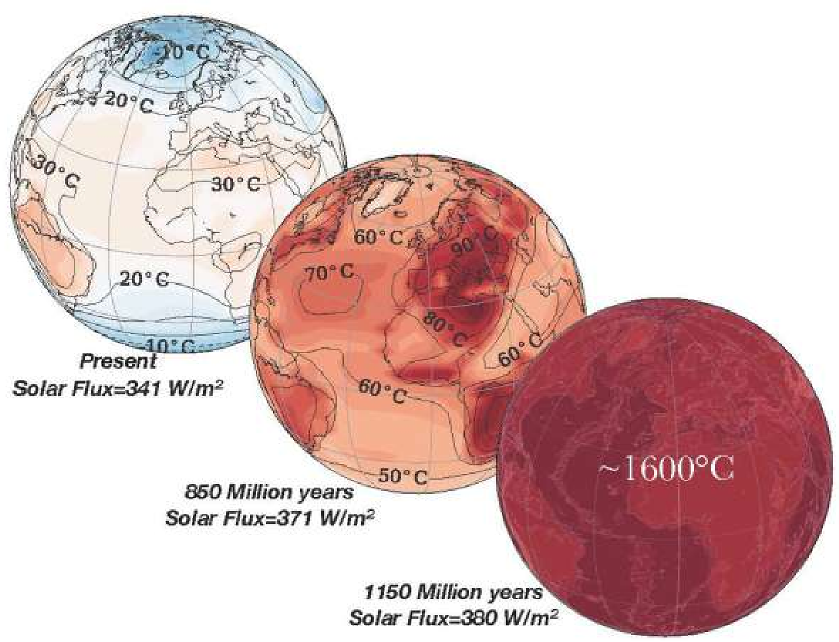
Back in 1986, James F. Kasting and Thomas P. Ackerman of the NASA Ames Research Center, California looked at what would happen if a Venusian-like100 bars of CO_2 were added to the atmosphere of the present day Earth. They found that the surface temperature would rise to 233ºC. Under these conditions, around 29 bars of water vapour would also end up in the atmosphere – but the ocean would still be about 100ºC below the temperature for it to boil under a total atmospheric pressure approaching 130 bars. However, if the CO_2 pressure was a mere 0.2 bar, then the there would be peak concentration of water vapour in the stratosphere, from where it could be lost to space. Kasting and Ackerman estimated that the oceans could be lost in about 9 billion years (about twice the present age of the Solar System) - so this would not be a fast process. With a 10% increase in the brightness of the Sun, however, surface temperatures could rise by around 30ºC. The oceans could then be lost in a few hundred million years.

In a classic 1993 paper about the HZ, James F. Kasting, now at the Pennslyvania State University and co-workers (1993) estimated that a runaway greenhouse would occur at 1.4 times and a moist greenhouse regime would occur with 1.1 times the amount of energy received by the Earth from the Sun. These levels of solar energy would be received at 0.84 AU and 0.95 AU from the present day Sun (one Astronomical Unit is the mean Earth-Sun distance of 149.6 million km).

A follow-up paper two decades later, with Ravi Kumar Kopparapu of Penn State as first author and Kasting as one of the co-authors (Kopparapu *et al.*, 2013), revised these figures downwards. Runaway greenhouse conditions would occur at 1.06 and moist greenhouse conditions at 1.02 for the amount of energy falling on earth at the present day. These amounts of energy would correspond to planets in orbit at 0.97 and 0.99 AU. This is getting close to home! The last figure gives us just 1% leeway between us and disaster, and the authors suggested that these estimates might not be taken too literally. For one thing, these climate models don't take into account the effects of clouds. Clouds can be highly reflective, but can also act to trap heat.

Another recent study (Leconte *et al.*, 2013b) indicated that the Earth need not enter the moist greenhouse state at all, but that it could switch directly to a runaway greenhouse state when the Sun rises to 1.10 its present luminosity. The graphic below illustrates the escalating temperature of the future Earth with time.

Graphic credit: J. Leconte. From physics.org.



Another recent study, this time from E. T. Wolf & O. B. Toon of the University of Colorado (Wolf & Toon, 2015), changed the goalposts yet again. They concluded that at only 1.19% the solar energy falling on our planet today, the Earth could lose its water in 3.5 thousand million years (0.92 AU today), but at 1.21% (0.91 AU), water loss through the moist greenhouse would speed up - the oceans could be gone in 130 million years. This, then, would be the inner edge of the HZ. Earth would die through a moist greenhouse, not a runaway.

When water has gone, then CO_2 emitted from volcanic activity will no longer being removed through weathering with rocks and it will build up in the atmosphere, producing something like the CO_2-rich atmosphere that we see on Venus. This is all academic as far as *Homo sapiens* is concerned. We cannot survive sustained temperatures above 310 K (37ºC), which would be reached in this model, when the Sun rises to 112.5% its present brightness (or if we had an Earth just 0.94 AU from the Sun) the global temperature over land would be 323.4 K (50ºC) and by that point, lethal temperatures should be expected everywhere on Earth. Wolf *et al.* (2017) adopted 355 K (82ºC) as the warmest habitable planet, at which point water could be lost from the Earth over the course of a thousand million years.

Much of this work, the reader will have noted, is mostly of concern to those of us who are interested in the width of the Sun's Habitable Zone and the implications for the kind of life that might thrive into the Earth's future or on worlds far distant from the Solar System. It does not immediately resonate with the fears of environmentalists about the damage that we undoubtedly doing to our home world here and now.

How close are we to pushing ourselves over the brink through our emissions of greenhouse gases?

In 2012, Colin Goldblatt and Andrew J. Watson of the School of Earth and Ocean Sciences, University of Victoria, British Columbia, published a study responding to James Hansen's concerns about the Earth being driven by us towards the Venus Syndrome.

They asked (Goldblatt & Watson, 2012):

". . . could we bring on such a catastrophe prematurely, by our current climate altering activities? . . . The good news is that almost all lines of evidence lead us to believe that is unlikely to be possible, even in principle, to trigger full a runaway greenhouse by addition of non-condensible greenhouse gases such as carbon dioxide to the atmosphere."

They warned, however that, "*our understanding of the dynamics, thermodynamics, radiative transfer and cloud physics of hot and steamy atmospheres is weak. We cannot therefore completely rule out the possibility that human actions might cause a transition, if not to full runaway, then at least to a much warmer climate state than the present one.*"

Goldblatt and three co-workers returned to the topic and revised their ideas in 2013. It was going to be easier to kick off the runaway greenhouse than they had suggested in their 2012 paper. They concluded (p. 666): "*Revisiting the classic planetary sciences problem of the runaway greenhouse with modern modelling tools, we have shown that the thermal radiation limit is lower and that more solar radiation is absorbed. The runaway greenhouse may be much easier to initiate than previously thought. A renewed modelling effort is needed, addressing both Earth and planetary science applications.*"

Scientific American (July 31, 2013) ran an article by space and physics editor Lee Billings, discussing this and asking whether the possibility of human activity causing a runaway greenhouse was fact or fiction. Goldblatt was quoted: "*We've estimated how much carbon dioxide would be required to get this steamy atmosphere, and the answer is about 30,000 ppm of atmospheric carbon dioxide, which is actually good news in terms of anthropogenic climate change*".

That last figure was 75 times more than the amount of CO_2 presently in the atmosphere and over 100 times greater than the pre-industrial level of 280 ppm. Billings noted that: "*Thirty thousand ppm is about 10 times more carbon dioxide than most experts estimate could be released from burning all available fossil fuels, he notes, although such high values could in theory be reached by releasing large amounts of carbon dioxide from the Earth's vast deposits of limestone and other carbonate rocks.*"

Ramses M. Ramirez (a research associate and founding member of the Carl Sagan Institute: Pale Blue Dot and Beyond, Cornell University) and various co-workers, including Kasting (Ramirez *et al*., 2014) responded to this sceptically.

They explained in their abstract: "*Recent one-dimensional (globally averaged) climate model calculations by Goldblatt et al. (2013) suggest that increased atmospheric CO_2 could conceivably trigger a runaway greenhouse on present Earth if CO_2 concentrations were approximately 100 times higher than they are today. The new prediction runs contrary to previous calculations by Kasting and Ackerman (1986), which indicated that CO_2 increases could not trigger a runaway, even at Venus-like CO_2 concentrations. . . . the older result is probably still valid, although our model nearly runs away at ~ 12 preindustrial atmospheric levels of CO_2 when we use the most alarmist assumptions possible.*"

They continued: "*However, we argue that Earth's real climate is probably stable given more realistic assumptions . . . Potential CO_2 increases from fossil fuel burning are somewhat smaller than this, 10-fold or less*"

Image credit: Terry Virts aboard the ISS.

What these climate models are showing us is how the Earth really could evolve into a planet similar to Venus. However, the timescales for key events are tens, hundreds, or even thousands of millions of years and the amounts of carbon dioxide that would have to be put into the atmosphere are very much greater than the scale of our emissions.

Last year, a paper by Max Popp of the Max Planck Institute for Meteorology, Hamburg, Germany and collaborators took a rather different look at the problem. They asked how increasing the amount of the greenhouse gas CO_2 in the atmosphere compared with increasing the amount of energy received from the Sun as a means of pushing our planet towards the moist greenhouse. Rising CO_2 concentrations, no less than our Sun's long-term rise, could change the global circulation of the atmosphere and so, the effect of clouds on climate.

The Earth's climate, however, would not head straight for a runaway greenhouse, but enter a new steady state favouring moist greenhouse conditions, where the surface temperature was around 60ºC. They found that with just 1520 ppm of CO_2 in our atmosphere (less than four times the present level) the Earth could transition into this warm moist greenhouse state within mere decades.

On the face of it, this figure is disturbing. Fortunately, things may not be quite as bad as this, because the model assumed a planet that was completely ocean covered and it was warmer than the real Earth to start with.

The Venus Syndrome is a red herring. What climate models do tell us is that we are in danger of endangering ourselves and many other species, by rising temperatures. This would happen long before the Earth could reach the necessary surface temperatures for the moist or runaway greenhouse.

James Hansen himself, the harbinger of the Venus Syndrome, modified his own stance half a decade ago. In a piece he wrote in 2013, he summed up the situation succinctly: "*If Earth's lower atmosphere did warm enough to accelerate escape of hydrogen it would still take at least hundreds of millions of years for the ocean to be lost to space. Additional time would be needed for massive amounts of CO_2 to accumulate in the atmosphere from volcanoes associated with plate tectonics and convection in Earth's mantle. So Venus-like conditions in the sense of 90 bar surface pressure and surface temperature of several hundred degrees are only plausible on billion-year time scales.*"

Goldblatt and Watson (2012) were unequivocal: "*we emphasize that nothing in this study should detract from the fact that anthropogenic greenhouse gas emissions are a major threat to global society and ecology. While we make the technical point that these emissions are unlikely to cause a 'runaway greenhouse', very severe and dangerous climate change is a real possibility. Abrupt change to a hot 'moist greenhouse' state, which though not technically a 'runaway' would nonetheless be dire, is not excluded. The imperative to cut greenhouse gas emissions remains.*"

Ramirez *et al*. (2013) cautioned about potentially realistic carbon emissions "*such increases could still cause sufficient warming to make much of the planet uninhabitable by humans.*"

Describing a paper on which he was first author (Hansen *et al*., 2013) Hansen (2013) insisted: "*climate sensitivity is in the upper half of the range that has usually been estimated. Furthermore, slow feedbacks, such as change of ice sheet size and methane emissions, make the sensitivity still higher.*" He said: "*if we should "succeed" in digging up and burning all fossil fuels, some parts of the planet would become literally uninhabitable, with some time in the year having wet bulb temperature exceeding 35°C. At such temperatures, for reasons of physiology and physics, humans cannot survive . . . Temperatures even several degrees below this extreme limit would be sufficient to make a region practically uninhabitable for living and working.*"

Climate scientists have winced at Hawking's Venus Syndrome rhetoric. Zeke Hausfather of U.C. Berkeley/Berkeley Earth) tweeted in response: "*A good example that even brilliant scientists sometimes say silly things when it's outside their field of expertise.*"

Stephen Hawking is a deeply-respected and much-loved figure on the UK science scene. He has spoken out controversially on many issues. These include the dangers of naïve contact with alien civilisations, the home-grown threat from artificial intelligence and, more prosaically, the UK's National Health Service. In every case, he has done so with a transparent and applaudable motive of concern for humanity. He is correct to warn of the dangers of human-made global warming, even if the apocalyptic vision of the planet Venus is too picturesque.

Climate scientists, environmentalists and governments committed to the Paris Climate Agreement are deeply concerned by President Trump's decision to remove the USA from the process, and about the potential consequences of unabated global warming.

Hawking could count on widespread support when he declared: "*Climate change is one of the great dangers we face, and it's one we can prevent if we act now. By denying the evidence for climate change, and pulling out of the Paris Climate Agreement, Donald Trump will cause avoidable environmental damage to our beautiful planet, endangering the natural world, for us and our children.*"

Papers published in recent weeks have highlighted the dangers of mass mortality through heat waves accompanying climbing global temperatures. The Venus Syndrome may not be an urgent concern, but the danger of creating what James Hansen has called a "*mini-runaway*" remains.

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Much interest has been focussing on relatively short-lived warm spells in Earth history known as "*hyperthermals*," which will be the subject of a meeting at the Royal Society later this month.

The announcement of the meeting explained: "*Earth's history is peppered with rapid and extreme global warming events collectively known as hyperthermals. Although none were as rapid as human-induced climate change, most are associated with major extinction events and were invariably caused by the injection of huge volumes of carbon into the ancient atmosphere.*"

We shall return to the question of deadly heat waves and hyperthermals in future issues of Prime Meridian.

Meanwhile, here's a challenging thought for anyone who happens to be watching Venus in the morning sky. A climate simulation for Venus published last year (Way *et al.*, 2016) indicated that the planet could have been habitable until 715 million years ago, when the Sun's output was around 94% that of the present day and the amount of solar energy falling on Venus was about 180% that which the Earth receives today. Planetary rotation, amount of water and distribution of land were key issue. How much do we really know about the past history of our nearest planetary neighbour?

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Prime Meridian

This newsletter is published by the Ecospheres Project, a trans-Atlantic research and media collaboration. Prime Meridian follows global environmental issues alongside the cycle of the seasons in South East England. It steps back to look at the Earth in its astronomical context and it pursues the search for other habitable worlds.

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