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Key Points:
- Earth remains habitable with at minimum 15.5% increase in the solar constant
- Subsaturation, clouds, and dynamics responsible for extending habitability
- Clouds may dissipate in hot climates due to large saturation vapor pressures

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Delayed onset of runaway and moist greenhouse climates for Earth

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Abstract As the Sun slowly grows brighter over its main sequence lifetime, habitability on Earth's surface will eventually become threatened probably leading to moist and then runaway greenhouse climates. One-dimensional climate models predict that a catastrophic thermal runaway will be triggered by a 6% increase in the solar constant above its present level. However, here simulations using a three-dimensional climate model with fixed carbon dioxide and methane indicate that surface habitability may be maintained at significantly larger solar constants. A 15.5% increase in the solar constant yields global mean surface temperatures of 312.9 K, well short of moist and runaway greenhouse states. Numerical limitations prevent simulation of climates much warmer than this. Nonetheless, our results imply that Earth's climate may remain safe against both water loss and thermal runaway limits for at least another 1.5 billion years and probably for much longer.

Life has proven to be remarkably resilient, surviving and recolonizing the Earth after snowball glaciations [*Pierrehumbert et al.*, 2011], abrupt warming episodes [*McInerney and Wing*, 2011], and catastrophic meteor impacts [*Toon et al.*, 1997]. However, in the distant future a Venusian climate, which life may not survive, probably awaits our home planet. At present the Sun is increasing in brightness by 1% every ~110 million years [*Gough*, 1981]. Increased solar radiation should at some point trigger moist and then runaway greenhouse climates, ending any hope for continued surface habitability. Surface habitability of a planet is traditionally defined as the ability to support liquid water.

The limits of Earth (and Earth-like exoplanet) habitability have been estimated using one-dimensional (1-D) radiative convective climate models [*Kasting*, 1988; *Kasting et al.*, 1993; *Selsis et al.*, 2007; *Kopparapu et al.*, 2013]. However 1-D models remain fundamentally deficient when it comes to probing the hot limit of planetary habitability. Three-dimensional dynamical calculations are critical for determining the distribution of water vapor and clouds in the atmosphere. Both clouds and the relative saturation of the atmosphere play important roles in determining the strength of the water vapor greenhouse feedback and thus the onset of a thermal runaway [*Pierrehumbert*, 1995; *Rennó*, 1997; *Selsis et al.*, 2007; *Goldblatt et al.*, 2013].

A classical runaway greenhouse is characterized by a positive feedback loop where rising surface temperatures accelerate evaporation, causing water vapor to become the dominant constituent in the atmosphere. Strong absorption by water vapor causes the atmosphere to become opaque to outgoing thermal radiation and thus surface temperatures rocket upward as the planet is unable to sufficiently shed energy to space. A stable climate may not be reached until surface temperatures reach 1600 K with the entirety of Earth's oceans turning to vapor in the process [*Goldblatt et al.*, 2013]. Recent calculations using cloud-free 1-D models with fully saturated atmospheres (100% relative humidity) predict that Earth will enter a catastrophic thermal runaway when the solar constant becomes 6% brighter than the present day [*Kopparapu et al.*, 2013]. This limit will occur in ~650 million years [*Gough*, 1981].

While a catastrophic runaway greenhouse would unquestionably sterilize the planet, habitability may become threatened before this ultimate tipping point is reached. A more stringent estimate for the hot limit to planetary habitability is based on the so-called moist greenhouse climate. A moist greenhouse is a stable climate state where hot temperatures throughout the atmosphere reduce the effectiveness of the tropical cold trap, allowing the stratosphere to become moist. If the stratosphere becomes sufficiently wet, the rate of hydrogen lost to space becomes large owing to water vapor photolysis. *Kasting et al.* [1993] estimate from 1-D models that if the Earth's mean surface temperature were to reach 340 K, the water vapor mixing ratio in the stratosphere would grow to $\sim 3 \times 10^{-3}$, increasing the photolysis rate sufficiently as to allow Earth's oceans to effectively evaporate away to space in less than the age of the Earth. The moist greenhouse limit is typically taken as the inner edge of planetary habitability in the context of exoplanet studies [*Kasting et al.*, 1993; *Selsis et al.*, 2007; *Kopparapu et al.*, 2013].

Cloud-free 1-D models with saturated atmospheres predict that Earth will reach moist greenhouse conditions ($T_s = 340$ K) when the solar constant increases by only 1.5% above its present level [*Kopparapu et al.*, 2013]. Thus, our home planet may be subject to a moist greenhouse climate in a mere ~170 million years [*Gough*, 1981]. When considering Earth's future, the moist greenhouse limit becomes of primary importance only if the water loss timescale becomes shorter than the timescale for the Sun's luminosity to trigger a runaway greenhouse. With $T_s = 340$ K, water loss rates are likely too slow to be of primary concern [*Kopparapu et al.*, 2013]. However, water loss rates are proportional to the water vapor concentration in the stratosphere. Since the saturation vapor pressure increases exponentially with temperature, water loss rates would increase rapidly as surface temperatures push past 340 K, hastening the loss of Earth's oceans as the solar constant inches higher.

Here we reexamine Earth's fate under the brightening Sun using a 3-D climate model. We use the Community Atmosphere Model version 3 provided by the National Center for Atmospheric Research [*Collins et al.*, 2004, 2006]. Simulations are configured with thermodynamic ocean and sea ice models. We assume the modern land configuration; however, we remove semipermanent glacial features from Antarctica, Greenland, and in high mountain regions. We have updated the native radiative transfer scheme to a correlated-*k* model that treats CO_2, H_2O, and CH_4 [*Wolf and Toon*, 2013]. Correlated-*k* distributions for line absorption are derived from the HITRAN (High-Transmission) 2008 spectroscopic database [*Rothman et al.*, 2009] accessed via LBLRTM (Line-By-Line Radiative Transfer Model) [*Mlawer et al.*, 1997]. The HITEMP (High-Temperature) spectroscopic database is not used here since the added spectral line density for water vapor is needed only if temperatures rise above 350 K [*Kopparapu et al.*, 2013]. Continuum absorption for H_2O, CO_2, and N_2 are derived from the MT_CKD (Mlawer, Tobin, Clough, Kneizys, Davies) continuum model [*Clough et al.*, 2005]. Clouds are treated using bulk microphysical parameterizations for condensation, precipitation, and evaporation that control atmospheric water vapor, ice cloud condensate, and liquid cloud condensate fields [*Rasch and Kristjánnson*, 1998]. For simplicity we have omitted O_2 and O_3 from the model. While varying ultraviolet fluxes have a significant effect on ozone heating and stratospheric chemistry, ozone feedback on surface temperatures are minimal [*Segura et al.*, 2003]. However, the amount of stratospheric water vapor could be sensitive to the presence of O_3. For example, the current Earth has much higher stratospheric temperatures and water vapor compared with simulations shown here under the present day solar constant. All simulations assume 500 ppm of CO_2 and 10 ppm of CH_4 with a mean sea level pressure of 1.013 bar. N_2 is the broadening gas.

Our baseline simulation has a solar constant of 1367.0 W m^{-2}, yielding a global mean surface temperature of 289.5 K. We then incrementally increase the solar constant. The global mean solar forcing can be approximated as $\Delta S(1 - A)/4$, where ΔS is the change in the solar constant and A is the top-of-atmosphere albedo from our baseline simulation (0.354). A 1% increase in the solar constant then equals a radiative forcing of +2.22 W m^{-2}. Thus, a 2% increase in the solar constant is approximately equivalent to doubling CO_2 [*Hansen et al.*, 2005].

With a 15.5% increase in the solar constant (+34.2 W m^{-2} solar forcing), we find that the global mean surface temperature stabilizes at 312.9 K. Annual mean tropical surface temperatures (23°S $< \varphi <$ 23°N) reach 318.5 K while annual mean polar surface temperatures ($\varphi \geq$ 66°) reach 296.5 K (Figure 1a). Our results predict that stratospheric water vapor mixing ratios will remain near 10^{-6}, 3 orders of magnitude below that needed to initiate significant water loss to space (Figure 2b). While such a hot climate would undoubtedly provide great challenges for humanity, Earth will remain safe from both water loss and thermal runaway limits to habitability even for a 15.5% increase in solar constant.

Numerical instabilities emerge in the convection and vertical diffusion schemes when the solar constant is increased by 16%, limiting the range of our study; however, this is not indicative of a tipping point to a thermal runaway. While the climate sensitivity (the change in mean surface temperature per unit forcing) begins to steepen for increases to the solar constant beyond 10% (Figure 1b), further increases to the solar constant appear possible without endangering the habitability of Earth. The relatively steep upturn in climate sensitivity found beyond a 14% increase in solar constant is concurrent both with rapid increases to the water vapor column and also with an inflection in the cloud water column (Figures 3a and 3c). At the inflection, the water vapor greenhouse continues to increase in strength while cloud forcings weaken (less negative) allowing even more sunlight to reach the surface (Figures 3b and 3d). There is a competition between water in the vapor and condensate phases. As climate warms, the saturation vapor pressure increases exponentially. If temperatures

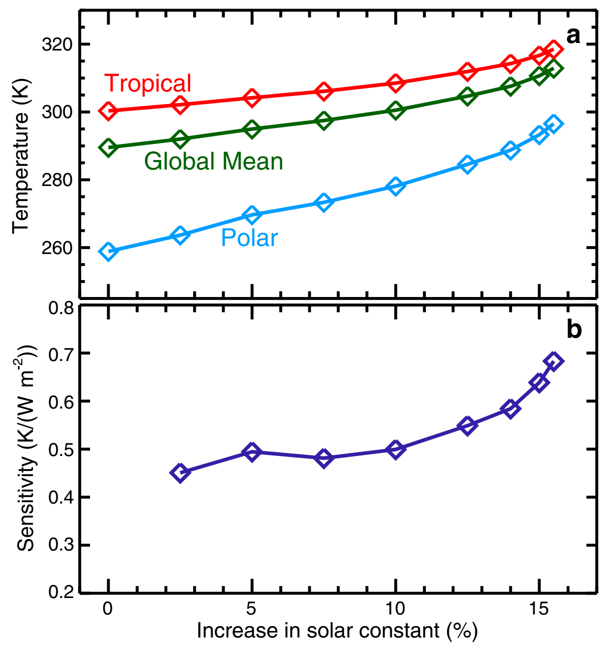

Figure 1. (a) Annual mean surface temperatures versus increase in solar constant above the present value. The tropical mean surface temperatures are averaged between 23° north and south latitude. The polar mean surface temperatures are averaged for latitudes greater than 66°. (b) Climate sensitivity versus increase in solar constant. Diamonds indicate results from simulations.

get too warm, water vapor may not readily condense to form clouds, thus favoring a steam atmosphere over a cloudy atmosphere. Results here imply that for hot climates, there may be a state transition where upon clouds begin to dissipate. A similar feature has recently been proposed to explain enhanced climate sensitivities for hot paleoclimates [*Caballero and Huber*, 2013]. Clouds remain a considerable uncertainty in modern climate models and more work is needed to determine how clouds may behave in hot climates.

Our results contrast with estimates from recent 1-D modeling studies [*Kopparapu et al*., 2013]. It will take ~1.5 billion years before the solar constant increases by 15.5%. Thus, at an absolute minimum, our results indicate an increase in the lifetime of Earth against a thermal runaway by a factor of 3 and an increase in the lifetime against moist greenhouse conditions by a factor of 10 compared with recently published 1-D results.

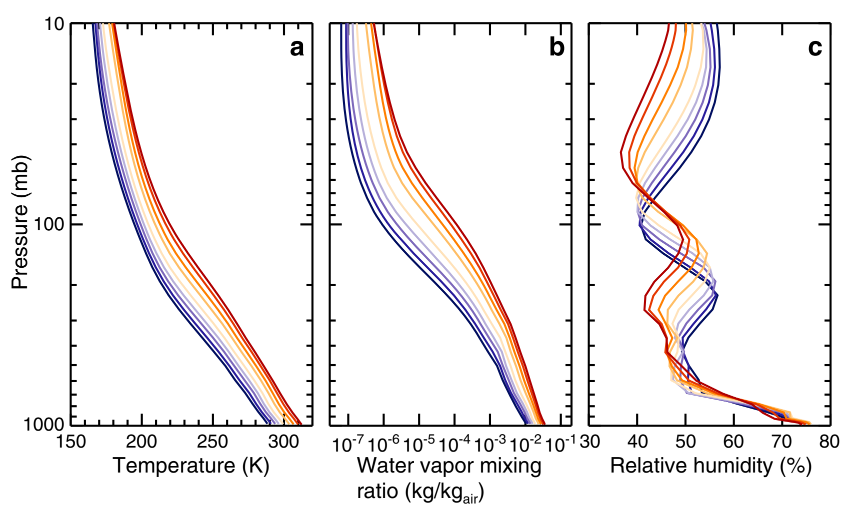

Figure 2. (a–c) The dark blue line is from our baseline simulation, the coolest simulation ($T_s = 289.5$ K) with the solar constant equal to present day. The dark orange line is from our hottest simulation ($T_s = 312.9$ K) found with a 15.5% increase in the solar constant. Global and annual mean temperature profiles for all simulations (Figure 2a). Global and annual mean water vapor mixing ratio profiles (Figure 2b). Global and annual mean relative humidity profiles (Figure 2c).

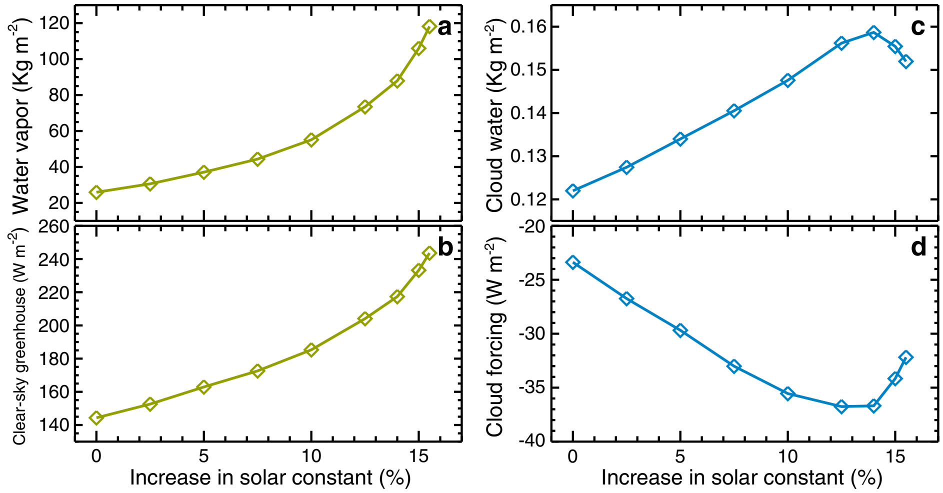

Figure 3. (a) Global and annual mean water vapor column, (b) clear-sky greenhouse forcing, (c) cloud water column, and (d) cloud radiative forcing versus increase in solar constant.

The 3-D representation of atmospheric dynamics and their effect on the hydrologic cycle is chiefly responsible for extending the habitability of Earth compared with 1-D models. Large-scale dynamics yield subsiding air over the subtropics, creating dry (subsaturated) columns that efficiently radiate surface energy to space compared with moist equatorial regions [*Pierrehumbert*, 1995]. This excess energy radiation to space is evident in the zonal mean outgoing longwave fluxes which peak near 30° latitude while being lower over the equator (Figure 4d). Heat is ultimately transported from the equator to cold polar regions, homogenizing zonal mean temperatures and corresponding outgoing longwave fluxes (Figures 4a and 4d). While the tropics may remain in a state of local runaway, a planet-wide runaway cannot be reached until global mean values reach the radiation limit [*Pierrehumbert*, 1995; *Ishiwatari et al*., 2002; *Goldblatt et al*., 2013]. There is an inherent limit to how much radiation can be emitted from a hot, moist (saturated) atmosphere (282 W m^{-2} for a pure water vapor atmosphere) [*Goldblatt et al*., 2013]. If the absorbed solar energy is above this limit, a thermal runaway should occur (Figure 4c). However, in a subsaturated atmosphere absorbed solar and outgoing longwave radiation can exceed this limit locally, without triggering a runaway. Here the

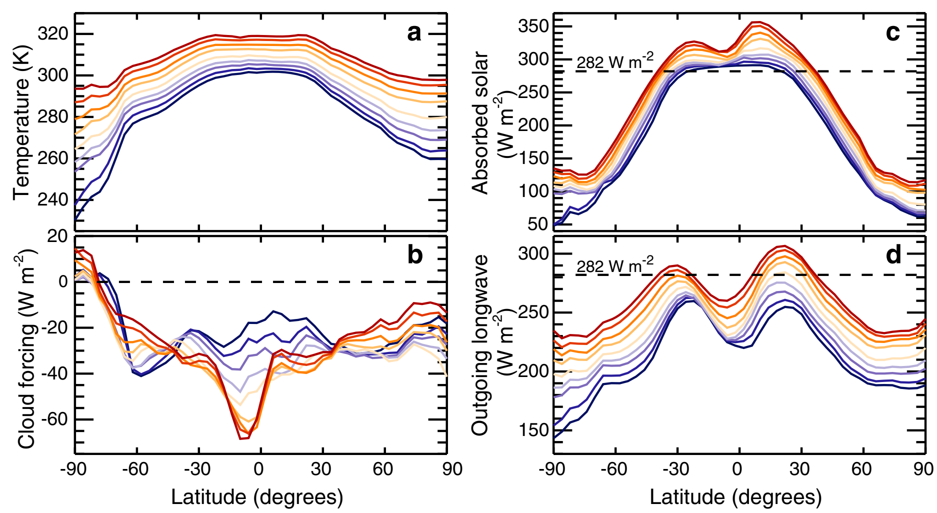

Figure 4. Annual and zonal mean (a) surface temperature, (b) cloud net radiative forcing, (c) net absorbed solar flux, and (d) outgoing longwave flux. Two hundred eighty two Watts per square meter is the theoretical emitted-radiation limit deduced by *Goldblatt et al*. [2013] for pure water vapor atmospheres. In Figures 4a–4d, the dark blue line is from our baseline simulation (T_s = 289.5 K) with the solar constant equal to present day while the dark orange line is from our hottest simulation (T_s = 312.9 K) with a 15.5% increase in the solar constant.

atmosphere remains subsaturated in all simulations (Figure 2c). Global mean relative humidities are near 75% at the surface and 50% above 700 mb. One-dimensional studies typically assume fully saturated atmospheres and thus they artificially amplify the strength of the water vapor greenhouse [*Kasting*, 1988; *Kasting et al*., 1993; *Goldblatt et al*., 2013; *Kopparapu et al*., 2013].

Clouds also provide a cooling influence on climate, a feature lacking from many 1-D studies. For our baseline simulation, the contribution of clouds to the planetary albedo is 0.179. Up to the inflection near a 14% increase in solar constant, global mean cloud forcings become stronger (more negative) (Figure 3d). Cloud forcings preferentially increase in magnitude (more negative) over the equator and thus clouds may provide an effective mechanism for regulating tropical temperatures as climate warms [*Ramanathan and Collins*, 1991, Figure 4b]. However, if clouds were artificially removed from our baseline simulation, the planet would gain a net global mean radiative forcing of +23.4 W m^{-2}. If the planet were forced to artificially maintain a saturated atmosphere everywhere (without changing the cloud structure), our baseline simulation would increase its global mean greenhouse effect by +17.6 W m^{-2}, owing to a ~33% increase in the global mean water column. While such test cases are physically unrealistic, they demonstrate that both the presence of clouds and subsaturated columns impart a sizable cooling influence on the Earth. These effects are driven by dynamics, thus 3-D simulations are needed to capture these effects. One-dimensional studies of hot climates err in that they are approximating the planet as a single column, thus artificially eliminating natural dynamical processes that slow global mean warming.

Our results pose no contradiction for Venus having achieved a runaway state long ago. Venus orbits at a distance of 0.723 AU, and thus today it receives 2615.1 W m^{-2}, a ~91% increase compared to Earth's present insolation. Neglecting any orbital migrations, even in its earliest history (circa 3.8 Ga) when the Sun was only 75% as bright as today, Venus would have received 1961.3 W m^{-2} of solar radiation. This is equivalent to a ~43% increase in the present day solar energy received by Earth. While stable climates are found here with a 15.5% increase in the solar constant, the steepening of the climate sensitivity curve (Figure 1b) leaves little hope that habitability could be maintained with a 43% increase in the solar constant. Any habitable period on Venus was probably tantalizingly brief.

Our results also have implications for the study of exoplanet habitability. For an Earth-like exoplanet, having an atmosphere in constant contact with oceans, our results indicate that the inner edge of the habitable zone can be moved closer in toward the parent star compared with results from 1-D cloud-free models. A similar result is also found from 3-D climate models of exoplanets in spin-orbital resonance with M dwarf stars [*Yang et al*., 2013]. The results of *Kopparapu et al*. [2013] place the present day Earth precariously close to the inner edge of habitability. They suggest with the present solar luminosity, if Earth were placed at an orbit of 0.97 AU, a complete thermal runaway would occur while with an orbit at 0.99 AU, a moist greenhouse climate would occur. In this study, if the Earth-Sun distance decreased to 0.93 AU, the mean surface temperature would still be 27 K below that of a moist greenhouse climate and 60 K below the boiling point of water.

Ideally, one would like to simulate a true thermal runaway with a 3-D climate model. However, at present off-the-shelf general circulation models are not up to the task. Cloud physics, convection, and vertical diffusion (and likely other parameterizations) will need careful examination and modification to increase their robustness and appropriateness for hot climates. However, even in a limited study such as this, some important concepts come to light. Clouds, subsaturation, and equator to pole heat transport all help delay the onset of moist and runaway greenhouse climates. Three-dimensional dynamical modeling is critical for determining realistic cloud, water vapor, and energy distributions, all of which may strongly modulate hot climates. Our preliminary 3-D results imply that Earth may remain habitable for far longer than is indicated from 1-D simulations.

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