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Har yaushe Duniya za ta iya ci gaba da zama kore? Climate model ya ba da kewayo, ba ranar ƙarshen duniya ba

Three-dimensional climate simulations 29 sun sanya limits daban-daban ga photosynthetic biosphere na Duniya tsakanin kusan biliyan 1.35 da 1.87 daga yanzu. K'imomin suna dogara da paths da aka saukaka da gangan na rock weathering, zafi da mafi karancin carbon dioxide da plants za su iya amfani da shi. Ba forecast ba ne na lokacin da duk plants, duk life, civilization ko Duniya za su ƙare.

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Har yaushe Duniya za ta iya ci gaba da zama kore? Climate model yana ba da kewayo, ba ranar ƙarshe ba

Ganye yana rayuwa ne a cikin wani ƙuntataccen daidaito. Yana buƙatar haske, ruwa, carbon dioxide da zafin da tsarin sinadaransa zai iya jurewa. A tsawon rayuwar mutum, Rana tana kama da abin da ba ya sauyawa a wannan daidaito. Amma idan aka kalli shekaru biliyan, ba haka ba ne.

Yayin da Rana ke tsufa a babban sequence, tana ƙara haske a hankali. Ƙarin hasken Rana yana dumama Duniya, amma duniya tana da wata dogon lokaci response: reactions tsakanin ruwan sama, carbon dioxide da silicate rocks za su iya cire carbon dioxide daga atmosphere. Hakan yana raunana greenhouse effect kuma yana rage wani ɓangare na warming. Amma wannan tsarin da ke sanyaya duniya zai iya daga ƙarshe rage carbon dioxide har photosynthetic organisms su rasa isasshen carbon da suke amfani da shi wajen gina living tissue.

Wata sabuwar takarda a Journal of Geophysical Research: Atmospheres ta tambayi wane limit ne zai iya zuwa da farko: zafi mai yawa, ko carbon dioxide mai ƙaranci. Amsarta ba ranar da Duniya za ta mutu ba ce. A cikin future paths biyu da aka saukaka da gangan, limits da aka ɗauka ga photosynthetic life suna tsakanin kusan **biliyan 1.35 da 1.87 daga yanzu**.

Wannan kewayon yana magana ne game da **vegetative biosphere**: ɓangaren living system na Duniya da photosynthetic organisms suke riƙewa, musamman plants da sauran rayuwa da ke juya haske da carbon dioxide zuwa biological material. Ba forecast ba ne ga kowane microbe. Ba lifetime na human civilization ba ne. Kuma ba lifetime na planet ba ne.

Planetary thermostat yana da settings biyu da ba a san ƙarfinsu sosai ba

Babban rashin tabbas shi ne **silicate weathering**. Carbon dioxide yana narkewa a cikin ruwan sama, yana reacting da silicate rocks, sannan daga ƙarshe ana ɗaukar sinadaran zuwa oceans da sediments. Volcanoes suna mayar da carbon dioxide cikin atmosphere a geologic timescales. Tare, waɗannan processes wani ɓangare ne na carbonate-silicate cycle, wanda sau da yawa ake kwatanta da thermostat na duniya.

A duniya mai zafi da ruwa, weathering na iya sauri kuma ya cire carbon dioxide da sauri. Amma masana ba su san yadda wannan response zai sarrafa Duniya ƙarƙashin Rana mai ƙara haske a nan gaba ba. Saboda haka Jacob Haqq-Misra da Eric Wolf ba su zaɓi hanya guda da suka ce ita ce "daidai" ba. Sun model **end members** biyu: deliberately extreme cases da ake amfani da su wajen sanya iyakar rashin tabbas.

- A **weak-weathering end member**, atmospheric carbon dioxide yana tsaya a 400 parts per million yayin da Rana mai ƙara haske ke ɗaga temperature.
- A **strong-weathering end member**, global mean surface temperature yana tsaya a 288 kelvin, kusan 15 degrees Celsius, yayin da carbon dioxide ke raguwa yayin da sunlight ke ƙaruwa.

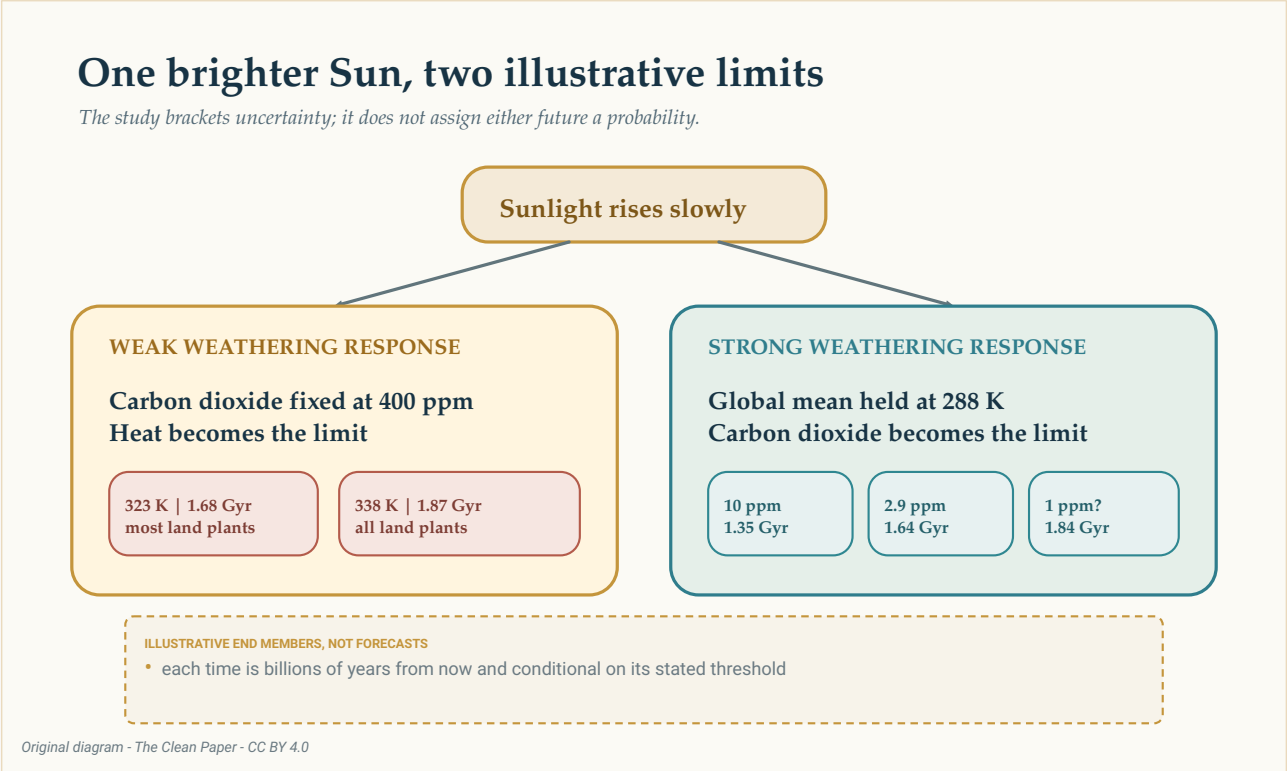
Ba a gabatar da kowanne branch a matsayin ainihin makomar Duniya ba. Na farko yana tambayar abin da heat zai yi idan carbon dioxide ya ci gaba da kasancewa mai yawa. Na biyu yana tambayar abin da carbon starvation zai

yi idan weathering ya riƙe global temperature kusa da mean na yau.

Ta yaya weathering zai iya yin aiki kamar thermostat?

Analogy ɗin yana magana ne game da feedback, ba literal control knob ba. Idan warmer climate ya sa chemical weathering ya ƙaru, ƙarin atmospheric carbon dioxide zai iya ƙarewa a dissolved material, minerals da sediments. Cire wannan greenhouse gas yana rage wani ɓangare na warming na farko. A very long timescales, volcanic outgassing yana mayar da carbon dioxide.

Ƙarfin kowane link ya dogara da rainfall, exposed rock, erosion, biology, tectonics da ocean chemistry. Wannan ne ya sa takardar ta gwada limiting responses maimakon ta ɗauki thermostat ɗin a matsayin machine da muka riga muka san yadda yake aiki.



Takardar ta sanya uncertain future tsakanin illustrative end members biyu. Idan weathering ya amsa da rauni, rising heat zai kai adopted land-plant thresholds. Idan ya amsa da ƙarfi, falling carbon dioxide zai kai adopted photosynthesis thresholds. Waɗannan conditional model branches ne, ba probabilities ko countdown dates ba.

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Model worlds 29 da suka settle, ba movie guda na shekaru biliyan biyu ba

Masu binciken sun yi amfani da ExoCAM, three-dimensional global climate model, don lissafa **steady-state climates 29** a combinations na ƙarin sunlight da ƙarancin carbon dioxide. Kowane case an gudanar da shi na model years 70. A nan model year guda annual cycle guda ne da aka simulate ƙarƙashin fixed conditions: runtime ne da ake amfani da shi don barin artificial climate ya settle, ba mataki guda a year-by-year forecast na makomar Duniya ba. Bayan climate ɗin ya sami lokacin settle, an ɗauki matsakaici na final 20 years.

Waɗannan cases 29 separate model worlds ne. Kowane run point guda ne a grid, yana amsa tambayar "wane settled climate ne ya dace da wannan chosen pair na sunlight da carbon dioxide?" Computer ɗin bai fara da Duniya ta yau sannan ya continuously evolve atmosphere, rocks, oceans da living things na shekaru biliyan biyu masu zuwa ba. Maimakon haka, marubutan sun bi schematic weathering paths biyu ta cikin precomputed points ɗin; path tsakanin points ba a simulate shi da kansa ba.

Teburin nan yana sake nuna combinations na sunlight da carbon dioxide daga official model-bayanai archive. Case IDs kayan taimakon karatu ne da aka ƙara a nan bisa archive order. **S/S0** shi ne relative solar constant: incoming solar energy da aka yi amfani da ita a model divided by present-day ƙima, S0. Saboda haka ƙima na 1.2 yana nufin 20 percent ƙarin incoming solar energy fiye da yau. **CO2 (ppm)** shi ne atmospheric carbon-dioxide mixing ratio a molecules per million atmospheric molecules.

Case ID	S/S0	CO2 (ppm)
1	1.0	400
2	1.0	180
3	1.0	11.25
4	1.0	1.40625
5	1.044	400
6	1.044	180
7	1.044	135
8	1.044	11.25
9	1.044	1.40625
10	1.081	400
11	1.081	180
12	1.081	11.25
13	1.081	1.40625
14	1.091	400
15	1.091	180
16	1.091	34
17	1.091	11.25
18	1.091	1.40625
19	1.143	400
20	1.143	180
21	1.143	11.25
22	1.143	6
23	1.143	1.40625

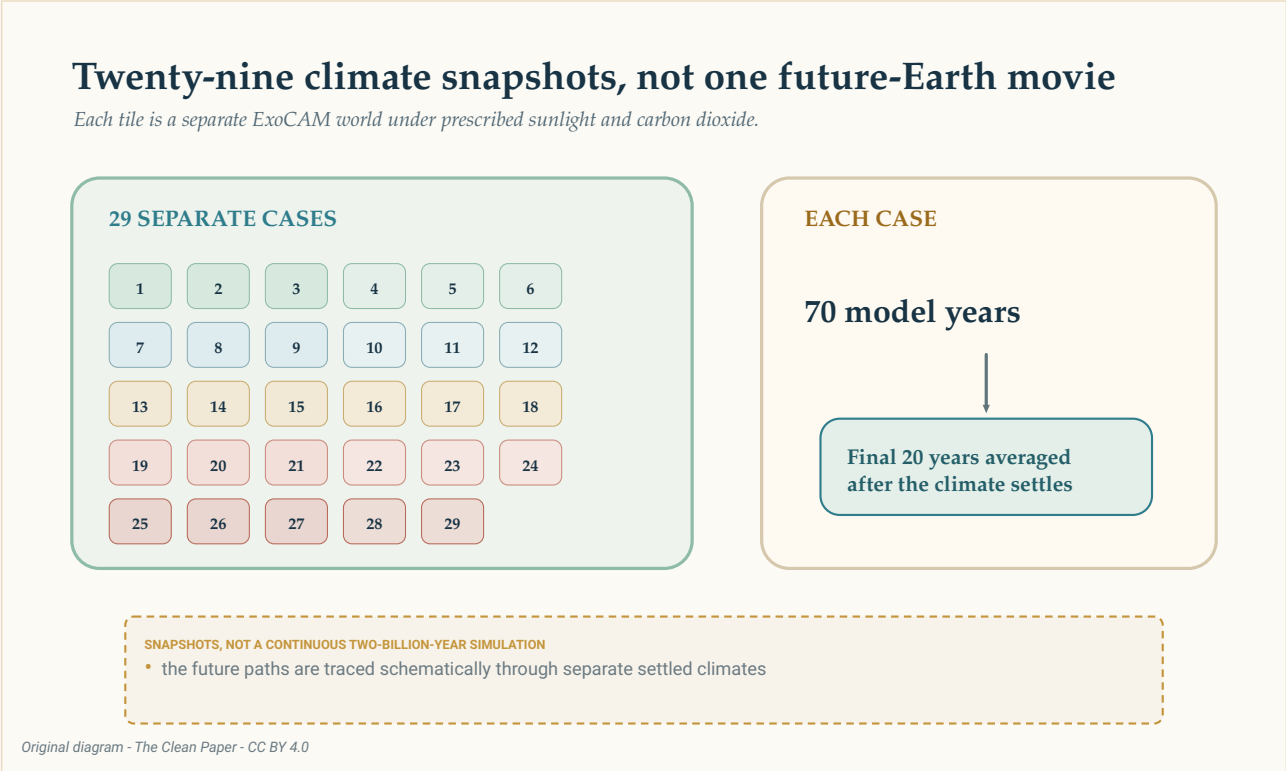
Case ID	S/S0	CO2 (ppm)
24	1.2	400
25	1.2	180
26	1.2	11.25
27	1.2	1.40625
28	1.2	0.45
29	1.2	0

Model Earth ɗin ana iya gane ta, amma an taƙaita ta da gangan. Girman ta kamar Duniya ne kuma tana amfani da geography na yau. Tana da simplified slab ocean maimakon fully circulating ocean, atmospheric pressure kusan na Duniya ta yau (bar ɗaya), da fixed methane. Orbit ɗinta perfectly circular ne (zero eccentricity), kuma rotation axis ba shi da tilt (zero obliquity). Ba ta ƙunshi explicit soils, vegetation ko feedback daga changing biosphere ba. Abu mafi muhimmanci shi ne climate samfurin ba dynamically coupled yake da rock-weathering model ba. Wato ExoCAM ba ya lissafa weathering, ya yi amfani da shi ya update carbon dioxide, sannan ya gudanar da climate na gaba a feedback loop. Maimakon haka, masu binciken sun prescribed limiting paths biyu sannan suka bi su ta cikin 29-case climate grid.

Menene “steady state” a climate model?

Steady-state case climate ne da aka ba shi lokaci ya settle ƙarƙashin chosen Sun da atmosphere guda. Weather har yanzu yana sauyawa daga rana zuwa rana da shekara zuwa shekara a cikin simulation, amma long-term averages ba sa ci gaba da drifting sosai.

Wannan yana da amfani wajen tambayar “wane climate ne ya dace da waɗannan conditions?” Amma ya bambanta da yin hasashe na exact route da real Earth za ta bi daga conditions guda zuwa na gaba.



Kowane tile separate ExoCAM climate run ne na model years 70, tare da matsakaici na final 20 years. Binciken ya sample settled climates 29 a prescribed sunlight da carbon-dioxide conditions; bai simulate Duniya guda tana continuously evolve tsawon biliyan biyu ba.

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End member na farko: carbon dioxide ya isa, amma zafi ya yi yawa

A weak-weathering branch, carbon dioxide yana fixed a 400 parts per million. Yayin da solar input ke ƙaruwa, zafi yana zama limiting factor.

Takardar ta yi amfani da global mean temperature thresholds guda biyu daga previous work:

- A **323 kelvin**, kusan **50 degrees Celsius** a matsayin global annual mean, ana ɗaukar duniya ta yi zafi sosai ga yawancin land plants. samfurin ya kai wannan threshold a kusan **biliyan 1.68 daga yanzu**.
- A **338 kelvin**, kusan **65 degrees Celsius** a matsayin global annual mean, ana ɗaukar duniya ta yi zafi sosai ga duk land plants. samfurin ya kai wannan threshold a kusan **biliyan 1.87 daga yanzu**.

Waɗannan adopted biological limits ne, ba universal temperatures da kowane photosynthetic organism dole ya kasa a kansu ba. Global mean kuma yana ɓoye manyan regional differences. Binciken ya kuma duba inda combinations na temperature da water za su iya ci gaba da dacewa, amma label a climate map ba zai iya lissafa kowane future refuge ko adaptation ba.

End member na biyu: zafi mai jurewa, amma carbon dioxide ya yi ƙasa sosai

A strong-weathering branch, global mean temperature an riƙe shi a 288 kelvin, kusan 15 degrees Celsius, yayin da atmospheric carbon dioxide ke raguwa. A nan amsar ta dogara da yadda carbon kaɗan photosynthetic pathways daban-daban za su iya amfani da shi.

- A traditional **10 parts per million** threshold - molecules 10 na carbon dioxide ga kowane million atmospheric molecules - limit ga C4 photosynthesis ya zo a kusan **biliyan 1.35 daga yanzu**. C4 photosynthesis na amfani da plants ciki har da maize da sugar cane kuma yana tattara carbon dioxide kusa da enzyme da ke fix carbon.
- Amfani da alternative **2.9 parts per million** C4 threshold da previous work ya tattauna yana matsar da limit ɗin zuwa kusan **biliyan 1.64**.
- Tentative **1 part per million** threshold, da ake danganta shi da yiwuwar wasu CAM plants - plants masu amfani da crassulacean acid metabolism, wanda ke ware carbon-dioxide uptake da dare daga use ɗinsa da rana - ko aquatic plants da za su iya amfani da dissolved bicarbonate, yana matsar da limit ɗin zuwa kusan **biliyan 1.84**.

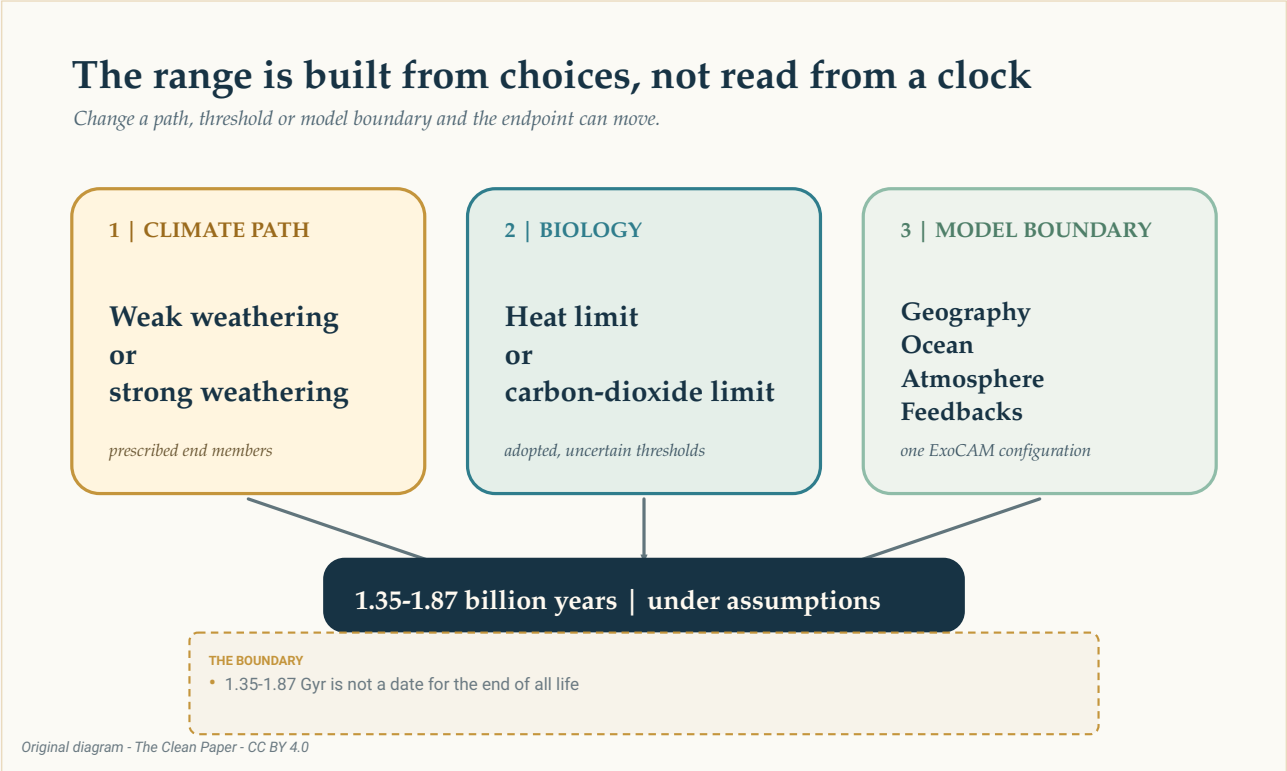
Lambar ƙarshe tana da biological caveat mafi girma. Marubutan sun kira one-part-per-million limit tentative kai tsaye. Ba experimentally established survival threshold ba ne ga duk CAM plants ko aquatic vegetation a future-Earth conditions.

> **C3, C4 da CAM strategies ne, ba matakan tsani ba**
>
> Plants suna amfani da biochemical routes daban-daban wajen kama carbon. **C3 photosynthesis** shi ne mafi yawan. **C4 photosynthesis**, wanda plants ciki har da maize da sugar cane ke amfani da shi, yana tattara carbon dioxide kusa da enzyme da ke fix carbon kuma zai iya aiki da kyau idan carbon dioxide ya yi ƙasa. **Crassulacean acid metabolism (CAM)** yana raba carbon uptake da use tsakanin dare da rana, yana taimaka wa plants da yawa su rage asarar ruwa.
> Waɗannan families na strategies ne da species-level differences da yawa, ba successive ranks na “better” plants ba. Very low carbon-dioxide thresholds na takardar assumptions ne don bincika mai yiwuwa limits, ba guarantees cewa future ecosystem zai evolve ya iya amfani da su ba.

Me ya sa biliyan 1.86 ba ranar ƙarewa ba ce

kanun labarai estimate na takardar na kusan **biliyan 1.86** matsakaici ne na optimistic upper endpoints biyu: biliyan 1.84 a carbon-dioxide-limited branch da biliyan 1.87 a heat-limited branch. Taƙaitaccen bayani ne na scenarios biyu daban. Ba na uku model sakamako da greater precision ba ne, kuma ba best-estimate date ba ne.

Ko broader span na biliyan 1.35 zuwa 1.87 ba ya ɗauke da probability guda. Lower da upper ƙimomi ɗinsa suna dogara da different weathering assumptions, different biological thresholds da climate-model configuration guda. Kewayon yana auna choices da aka yi a gwaji kusan daidai da yadda yake auna lokaci.



Kewayon biliyan 1.35 zuwa 1.87 yana fitowa ne kawai bayan zabar weathering path, biological threshold da model boundary. Taswirar assumptions ce, ba agogon da zai ƙare da extinction na duk life ba.

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Wasu limits na iya zuwa da farko

Longest vegetative-biosphere estimates suna kusantar wani boundary dabam mai rashin tabbas: moist ko runaway greenhouse da zai iya haifar da major ocean loss. Climate models suna da babban disagreement kan lokacin da waɗannan states za su fara a ƙarƙashin ƙarin sunlight, musamman nesa da present conditions. Wasu estimates suna sa su kafin most optimistic photosynthesis limit.

Wannan yana nufin upper branch ba za a karanta shi a matsayin alkawarin cewa Duniya za ta ci gaba da samun oceans, familiar continents ko habitable surface conditions har zuwa biliyan 1.87 daga yanzu ba. Haka kuma model bai haɗa future plate tectonics, changes in land area, evolving ecosystems ko fully dynamic ocean ba. Calculations ɗinsa na yadda atmosphere ke absorb da emit energy ma ana tura su zuwa regimes na intense sunlight da extremely low carbon dioxide inda different models ke rabuwa.

Evolutionary adaptation da technological intervention sun bayyana a discussion na takardar a matsayin possibilities. Ba outputs na climate simulations 29 ba ne. Model ba ya nuna future organisms suna evolve one-part-per-million photosynthetic pathway, kuma ba ya nuna civilization tana manage atmosphere tsawon biliyan shekara.

Wannan ba sakamako ne game da climate crisis na yau ba

Solar brightening yana aiki tsawon hundreds of millions zuwa billions of years. Modern human-driven warming yana fitowa daga rapidly increasing greenhouse gases tsawon decades da centuries. Forcings ne daban, a timescales da suka bambanta ƙwarai, kuma suna amsa tambayoyi daban.

Babu wani abu a wannan bincike da ke rage hujjar present climate change ko ya ba da dalilin jinkirta action. Biosphere da zai iya riƙe wani photosynthetic life a distant model scenario ɗaya ba daidai yake da climate da societies da ecosystems na yau za su kasance lafiya a cikinsa ba.

Takardar tana da amfani domin tana sa tambaya mai nisa ta zama more disciplined. Tana nuna cewa earlier, simpler models na iya yin warming da yawa idan sunlight ya ƙaru yayin da carbon dioxide ya tsaya fixed, kuma photosynthetic life na iya samun hanyoyin persistence fiye da canonical carbon threshold guda. Haka kuma tana nuna dalilin da ya sa kowane ƙarin fraction na biliyan shekara yake zuwa ne tare da jerin assumptions.

Ranar da ke ciyar da ganye tana canzawa a hankali. Ko Duniya za ta ci gaba da zama kore har wani biliyan 1.35, 1.87 ko wani adadi daban zai dogara da rocks, water, atmosphere da life suna amsawa tare. Sakamakon gaskiya ba date ba ne. Faɗaɗa fahimtar wannan daidaito ne.

Takaitaccen bayani

Wani three-dimensional climate bincike ya tambayi tsawon lokacin da vegetative - photosynthetic - biosphere na Duniya zai iya ci gaba yayin da Rana ke ƙara haske a hankali. Masu binciken sun lissafa separate steady-state climates 29 sannan suka bi illustrative end members guda biyu ta cikinsu. Da weak weathering da carbon dioxide fixed a 400 parts per million, adopted heat limits na land plants suna faruwa a kusan biliyan 1.68 da 1.87 daga yanzu. Da strong weathering da global mean temperature fixed a 288 kelvin, kusan 15 degrees Celsius, adopted carbon-dioxide limits na photosynthesis suna faruwa a kusan biliyan 1.35, 1.64 da, ta amfani da tentative threshold, 1.84. Lambar biliyan 1.86 da ake yawan ambata rounded matsakaici ce kawai na optimistic upper endpoints biyu. Waɗannan scenario-dependent model ranges ne, ba ranar da Duniya, humanity ko all life za su ƙare ba. Model yana amfani da prescribed paths, present geography, slab ocean da babu explicit soil-vegetation ko climate-weathering coupling, kuma longest estimates suna kusantar uncertain greenhouse da ocean-loss limits.

Binciken ba tare da ƙarin hayaniya ba

Abin da takardar ta nuna: A wannan ExoCAM configuration, three-dimensional climates gabaɗaya suna warming ƙasa ƙarƙashin increasing sunlight da fixed carbon dioxide fiye da simplified models da aka yi amfani da su wajen comparison. A cikin prescribed weathering end members biyu da adopted biological thresholds da dama, limits na vegetative biosphere suna tsakanin kusan biliyan 1.35 da 1.87 daga yanzu.

Abin da yake yiwuwa amma ba a tabbatar ba: Cewa wasu CAM plants ko aquatic plants da ke amfani da dissolved bicarbonate za su iya ci gaba da photosynthesis kusa da one part per million atmospheric carbon dioxide; cewa adaptation ko technology za su iya tsawaita photosynthetic life; da cewa real climate-weathering path zai

kasance tsakanin model end members biyu.

Abin da ba ya nuna: Fixed date ga ƙarshen all plants, all life, human civilization, oceans na Duniya ko planet; continuous simulation guda na next two billion years; ko wani dalili na rage muhimmancin present human-caused climate change.

Manyan iyakoki: Steady-state cases 29 daga climate-model family guda; prescribed maimakon dynamically coupled weathering paths; present-day geography; slab ocean; fixed methane; zero obliquity da eccentricity; babu explicit soils, vegetation ko biosphere feedback; uncertain heat da carbon-dioxide thresholds; da wide model disagreement kusa da moist da runaway greenhouse conditions.

Yaya yawan amincewar da mai karatu na gama-gari ya kamata ya yi? Babban amincewa cewa binciken ya faɗaɗa mai yiwuwa model range kuma ya gano assumptions da ke sarrafa shi. Matsakaicin amincewa a numerical span a matsayin useful bracket a cikin wannan model. Ƙaramin amincewa ga exact date, domin most distant endpoints suna dogara da deliberately extreme climate paths da uncertain biology.

Majiyoyi

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