The role of the Advisory Board is to advise the Board of County Commissioners and appropriate departments on environmental and science-related issues that affect Larimer County.

Environmental and Science Advisory Board.

MINUTES

Date: December 10th, 2024.

Time: 6:00 – 9:00 p.m.

Location: Rm 150 Carter Lake, 200 West Oak St., Fort Collins, Colorado and Virtual by Zoom.

Contact: Shelley Bayard de Volo, sbayard@larimer.org or 970.498.5738.

MEMBERS	-	STAFF	-	GUESTS
Rodger Ames – Chair	X	John Kefalas *	X	Tim Skolds
Tasha Carr	X	Shelley Bayard de Volo ¥	X	Jared McGlothlin
Anna Cloud	X	Heidi Pruess§	X	George Rinker
Jim Gerek	X	-		-
Leo Grassens	X	-		-
Matthew Haag	X	-		-
Michael Lee Jones	X			
Zachary Maffeo	X	-		-
Lark Murphy	-	-		-
Andrew Newman	-	-		-
Barry Noon	X	-		-
Nicole Poncelet-Johnson	-	-		-
Natalie Walsh	X	-		-
Chris Wood	-	-		-

X = present; * = Commissioner Liaison; ‡ = Engineering; ¥ = ESAB Liaison; § = Climate and Sustainability Program; α = Larimer County Health and Environment; £ = Community Infrastructure, Planning and Resources.

Call to Order: 6:00 p.m.

1. **Amendments or additions to the agenda** – None

2. **Introduction of members, staff and guests** – Guest speaker and former ESAB member, George Rinker, introduced himself. New ESAB applicants Tim Skolds and Jared McGlothlin introduced themselves

3. **Public Comment** – Shelley received a public comment via email. Tiffen Vaughn was not able to attend tonight's meeting and asked that her email be read into the record. Rodger read the email. One point made in the email was that Ms. Vaughn asked the ESAB to advise the BOCC to deny a permit development project. Rodger noted that the ESAB does not typically comment on development projects and Shelley supported that fact by noting that to do so would be outside the scope of the Board's defined role. The Commissioner noted that the project will come before the Planning Commission and the BOCC next year. If members were interested, they could comment as individuals at that meeting. For the record, the email comment provided by Ms. Vaughn is included in these minutes.

4. **Commissioner's Update** – The Planning Commission adopted the Larimer County Water Master Plan at their November meeting, after which the BOCC also approved the Plan. The Larimer County Extension Office engaged with agricultural producers in a survey, and the results are presented in a report available from their website. The County budget will be approved tomorrow at 2:30 during an open public meeting. The BOCC will also certify a number of mill levies.

   Discussion Items

   - Modelling Climate Change – George Rinker presented his research on the factors that drive climate change using a model he developed. He handed out hard copies of a report he put together that describes his model and the parameters, and the results from testing his model. He also presented slides and went through the figures that show changes over time. The report with slides is attached with these minutes.

   - ESAB Comments on the Larimer County Woody Biomass Strategy – Anna, Barry, Tasha and Leo presented their draft memo on the comments they compiled from the last meeting where Josh Roberts from Larimer County Office of Emergency Management presented their Woody Biomass Strategy. Anna provided a little background on the Strategy and then went over the six key areas where they provided comments. Leo motioned to accept the memo as drafted, understanding that Barry had a few minor edits to add some of his details as well as a few citations. Tasha seconded the motion, and all were in favor and the motion passed. The final memo will be included in the appendix with the ESAB 2024 Annual Report.

   - ESAB Draft 2024 Annual Report - Shelley presented the draft annual report explaining the sections of the report and asked for feedback. Members had a few suggestions for content to add. Shelley will revise the report and present it to the Board in January.

   - ESAB Officer Elections – Rodger indicated that he had talked with Anna Cloud about replacing him as the ESAB Chair for 2025. Anna presented why she wanted to serve as Chair and what she saw as her qualifications. Rodger then officially nominated Anna to serve as Chair and Barry seconded. He called for other nominations and there were none. All were in favor and Anna was successfully elected as ESAB Chair for 2025. Anna indicated that she had talked with Rodger about continuing as Vice Chair for 2025 and Rodger indicated that he was willing. Anna then formally nominated Rodger to serve as Vice Chair and Barry seconded. No other nominations were forthcoming. All were in favor and the motion passed, electing Rodger as ESAB Vice Chair for 2025.

5. **Approval of Minutes** – Shelley noted the edits that Jim provided prior to tonight's meeting. Jim motioned to approve the November minutes, as amended by Shelley, and Anna seconded. All were in favor and the November minutes were approved.
6. **Updates and Round Table**
    - No roundtable items for tonight's meeting
7. **Issue Index** – will be updated with tonight's discussion items.
2. **Agenda Topics for Future Meetings** –In January, Eric Tracy, Engineering, will present on Larimer on the Move – the Larimer County Transportation Plan. The Big Thompson Watershed Coalition will present their projects in February and the March agenda will include an update on air quality monitoring from CSU professors Jeffery Collett and Emily Fischer.
8. **Adjourn** – The meeting adjourned at 8:50 PM.

LARIMER COUNTY

Shelley Bayard de Volo <bayardsh@co.larimer.co.us>

public comment - submission for 12/10/24 ESAB board mtg

T V <tiffinv@gmail.com> Fri, Dec 6, 2024 at 1:22 PM
To: "sbayard@larimer.org" <sbayard@larimer.org>

Dear Shelley,

I will not be able to attend the meeting to public comment on 12/10/24, but please include my correspondence and information into the public record. (My comment is not a topic on the agenda.)

Below are just some examples why the Environmental & Science Advisory Board should advise the BOCC to **deny** the Aragon Holdings, Inc (Loveland Ready Mix, LLC) application to build and operate a concrete batch plant at 516 N Hwy 287, FC. **This concrete batch plant poses a safety risk to both people, protected wildlife, and a large water source (Terry Lake).**

1) The City of FC is in opposition against the concrete batch plant for numerous environmental reasons. (see attached memos)

2) This proposed area **already** scores 94 out of 100 on the Colorado Enviroscreen. (see attached fact sheet with sources cited.)

3) There are 5 mobile home parks all except for 1 that are within 1-1.5 mi. from Aragon Holdings location which would be exposed to additional air pollution if this concrete plant is approved. (The other 1 is 1.7 mi. and is one of the largest in FC, a 55+ yr. old community) A common way to cool these mobile homes is using swamp coolers that pull in air directly from outside. Several residents in the 55+ community also rely on oxygen tanks.

4) Aug. 2024, Director of LC Board of Health, Tom Gonzales informs us our area is already out of Federal compliance on air quality and ground ozone levels. Air quality film

5) From a wildlife standpoint, there are active Bald Eagle nest(s) and migratory birds both as we know are federally protected by the Bald & Golden Eagle Protection Act & Migratory Bird Treaty Act. (not to mention other wildlife) Bald Eagle buffer zones exist because "human activity may negatively impact Bald Eagles at breeding sites or winter roosts." Buehler 2020
Bald Eagle nest(s) exist within the 1/4 - 1/2 mile buffer zone from Aragon Holdings (I've included the CO Parks & Wildlife doc) CPW has identified this area as of "special concern."

Attached photos are taken by my neighbor. Bald Eagle perched with Aragon Holdings in background, and existing fugitive dust on windy day at Aragon Holdings, before a plant is even built.

*Please let me know you have received my email, and if you have any questions.

Thank you in advance for your support on this very important issue.

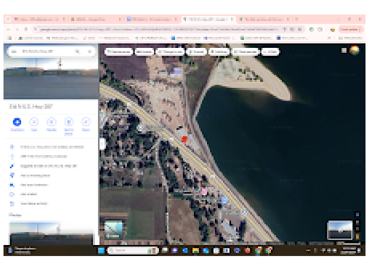
Sincerely,
Tiffin Vaughn
970-556-1570
FC resident - 80524

Literature Cited

Buehler, D.A. 2020. Bald Eagle (Haliaeetus leucocephalus), version 1.0 In Birds of the World (A.F. Poole and F.B. Gill, Editors). Cornell Lab of Ornithology, Ithaca, NY, USA. https://doi.org/10.2173/bow.baleag.01

Colorado Parks and Wildlife. 2020. Recommended buffer zones and seasonal restrictions for Colorado raptors. Colorado Division of Wildlife. https://cpw.state.co.us/Documents/WildlifeSpecies/LivingWithWildlife/Raptor-Buffer-Guidelines.pdf

7 attachments



Screenshot (43).png
1433K

DSCN3777 (2).JPG
4491K

DSCN3880 - Copy.JPG
4280K

DSCN3931.JPG
4619K

Memo - Read Before Packet - 07_02_2024 - Memorandum from Clay Frickey re Update on Aragon Holdings Batch Plant Development Proposal (3).pdf
3653K

STOP CONCRETE PLANT fact sheet July 2024.pdf
138K

raptor-buffer-guidelines-cpw-2020 (1).pdf
602K

Colorado EnviroScreen 2.0 Report

Colorado EnviroScreen overview

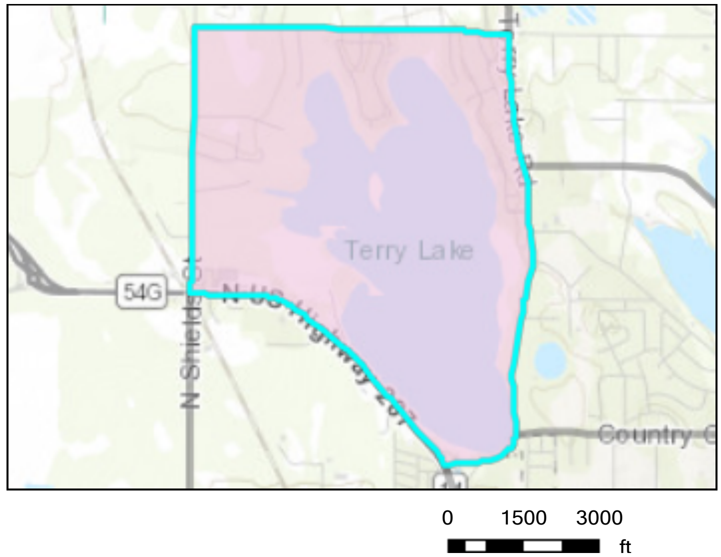
Larimer County

Census block group 080690013081

Colorado EnviroScreen percentile score

14.58

The EnviroScreen percentile score combines population characteristics and environmental burdens. The score ranges from zero to 100, with the higher scores representing the most significant burden.



Component scores

The component scores listed below make up the final Colorado EnviroScreen percentile score. Like the overall EnviroScreen score, component scores reflect relative rankings (percentiles).

Environmental exposures percentile score 33.73

The environmental exposure score represents a community's exposure to certain environmental risks relative to the rest of the state. The score ranges from zero to 100, with higher scores indicating higher burden. The environmental exposure score does not cover all pollutants; it is the average data on diesel particulate matter, traffic proximity, ozone, particulate matter 2.5, air toxics, other air pollutants, lead exposure risk, drinking water violations, and noise.

Environmental effects percentile score 58.18

The environmental effects score represents the number of hazardous or toxic sites in a community relative to the rest of the state. The score ranges from zero to 100, with a higher score indicating a higher burden. The score is the average of data on proximity to mining, oil and gas operations, impaired surface waters, wastewater discharge facilities, Superfund sites, facilities that use hazardous chemicals, and facilities that generate, treat, store, or dispose of hazardous wastes.

Climate vulnerability percentile score 14.32

The climate burden score represents a community's risk of drought, flood, extreme heat, and wildfire compared to the rest of the state. The score ranges from zero to 100, the higher the score, the higher the burden.

Sensitive populations percentile score 16.16

The sensitive populations score captures how at risk a community is to environmental exposures and climate impacts related to health. For example, air pollution has a stronger impact on older and younger people and people with chronic conditions such as asthma. The score ranges from zero to 100, with a higher score being higher vulnerability. We calculate the score using data on asthma hospitalization rate, cancer prevalence, diabetes prevalence, heart disease prevalence, life expectancy, low birth weight rate, mental health, population over 65, and population under five.

Demographics percentile score 11.35

The demographics score represents a community's social and economic vulnerabilities. The score ranges from zero to 100, with a higher number representing a higher vulnerability. We calculate it using data on people with disabilities, housing cost burden, educational attainment, limited English proficiency, income, and race and ethnicity.

The pollution and climate indicators section lists the selected census block group's environmental exposures, environmental effects, and climate vulnerability indicator percentile scores. See pages 25 to 31 of the Colorado EnviroScreen technical documentation for the pollution and climate indicator data sources and methodology. The indicator percentile ranking is highlighted in red if it is above the 80th percentile, indicating that the census block group and the selected location have a higher burden based on that indicator than other Colorado communities.

Pollution and climate indicators

Indicator	Value	Unit	Percentile
Air toxics emissions	0.04	distance weighted measure of estimated air toxics emissions	59.57
Diesel particulate matter	0.09	micrograms per cubic meter	27.53
Drinking water regulations	49.02	population weighted duration (in weeks) of resolved and unresolved health based violations from active community public water systems	67.79
Fine particle pollution (PM 2.5)	7.69	micrograms per cubic meter	42.61
Impaired streams and rivers	53.46	average impairment and assessment status of streams	46.79
Lead exposure risk	0.03	percentage of housing units built before 1960, as an indicator of potential exposure to lead	14.87
Noise	41.18	decibles A	25.75
Other air pollutants	0.01	distance weighted measure of estimated other air pollutant emissions	53.48
Ozone	47.36	parts per billion	37.8
Proximity to hazardous waste facilities	0.85	distance weighted count of hazardous waste facilities within 10 km	38.33
Proximity to mining locations	1.83	distance weighted measure of the total number of active coal, hard rock, and construction materials mining permits	88.45
Proximity to National Priorities List sites	0	distance weighted count of proposed or listed NPL sites within 10 km	0
Proximity to oil and gas sites	34.81	distance weighted measure of the total number of active oil and gas locations	62.47
Proximity to Risk Management Plan sites	0.51	distance weighted count of RMP facilities within 10 km	51.29
Traffic proximity and volume	418946.29	amount of vehicular traffic nearby, and distance from roads	27.05
Wastewater discharge indicator	183.54	toxic chemical concentrations in stream segments per km	16.55
Drought	30.27	sum of weekly total percent of an area experiencing a severe, extreme, or exceptional drought	43.62
Extreme heat days	24	average number of high heat days between May and September from 2019 to 2023	48.3
Floodplains	0.61	percentage of each geographic area where there is at least a one percent chance of flooding annually	23.71
Wildfire risk	140.86	mean wildfire hazard potential within each geographic area as determined by the US Forest Service, 2023	7.89

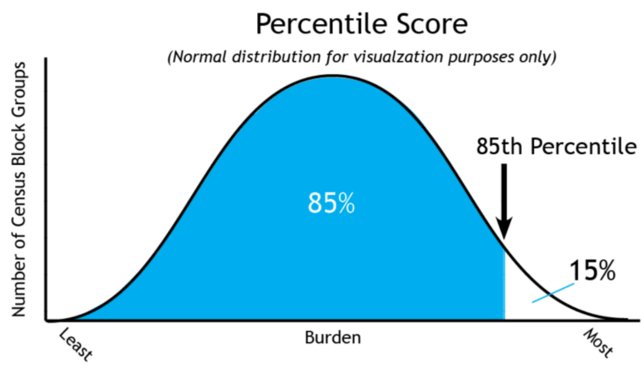
The health and social indicators section lists the selected census block group's sensitive populations and demographics percentile scores. See pages 36 to 52 of the Colorado EnviroScreen technical documentation for the health and social Indicators data sources and methodology. The indicator percentile ranking is highlighted in red if it is above the 80th percentile, indicating that the census block group and the selected location have a higher burden based on that indicator than other Colorado communities.

Health and Social Indicators

Indicator	Value	Unit	Percentile
Asthma hospitalization rate	15.59	rate of hospitalization per 100,000 people	19.03
Cancer index	91.23	percent of adults	97.7
Diabetes index	28.36	percent of adults	17.61
Heart Disease index	52.41	percent of adults	47.13
Life expectancy	84.2	years	7.26
Low birth weight	4.97	percent of singleton births	3.68
Mental health indicator	13.8	percent of adults	17.64
Population over 64 years of age	32.55	percent of total population	92.2
Population under five years of age	3.13	percent of total population	28
Disability	6.91	percent of total population	18.36
Housing cost burdened	18.73	percent of households	19.53
Less than High School education	3.75	percent of total population	35.76
Linguistic isolation	0	percent of total population	0
Low income	15.49	percent of total population	38.28
People of color	3.6	percent of total population	1.92

Understanding the Data

The values shown in the last column of the Pollution and Climate Indicator and Health and Social Indicator tables are percentiles. Percentiles are a way to see how one area compares to other areas in Colorado. Percentile values range from 0 - 100. A higher score indicates a higher burden. Specifically, the percentile tells you the percentage of places in Colorado that have a lower score than the selected location. For example, an area with an 85 percentile score for the noise indicator ranks in the top 15% of areas impacted by noise in Colorado. That means that 85% of the other census block groups in Colorado have a lower score for noise impacts.



The data in the report comes from Colorado EnviroScreen version 2.0. Developed in 2022 by CDPHE and Colorado State University, EnviroScreen maps the overlap of environmental exposures and effects, climate vulnerability, sensitive populations, and demographics to better understand environmental injustice and environmental health risks in Colorado. For more detailed information on the data sources used in Colorado EnviroScreen Version 2.0 see the

technical documentation.

Colorado EnviroScreen does:

-Show which areas in Colorado are more likely to have higher environmental health injustices.
-Identify areas in Colorado where government agencies can prioritize resources and work to reduce pollution and other sources of environmental injustice.
-Provide information to empower communities to advocate to improve public health and the environment.
-Identify areas that meet the updated definition of "Disproportionately Impacted Community" under House Bill 23-1233 adopted a definition that applies to all state agencies, including CDPHE.

Colorado EnviroScreen does not:

-Define a healthy or unhealthy environment.
-Establish causal associations between environmental risks and health.
-Define all areas that may be affected by environmental injustice or specific environmental risks.
-Provide information about an individual person's health status or environment.
-Take all environmental exposures into account.
-Tell us about smaller areas within a census block group that may be more vulnerable to environmental exposures than other areas.
-Provide information about non-human health or ecosystem risks.

Disproportionately impacted community definition criteria

Criteria	Yes/No	Value
Low-income population above 40%	No	15.49%
People of color population above 40%	No	3.6%
Linguistically isolated households above 20%	No	0%
Housing cost-burdened population above 50%	No	18.73%
Area under tribal jurisdiction	No	N/A
Colorado EnviroScreen percentile score	No	14.58
Within a Justice 40 census tract	No	N/A

The table above lists the disproportionately impacted community criteria outlined in Colorado Revised Statute 24-4-109. CDPHE released the most recent version of the disproportionately impacted community map in November 2024.

Demographic data are from the Census Bureau American Community Survey 2018-2022. Colorado EnviroScreen Percentile Score comes from Colorado EnviroScreen version 2.0, released November 2024. Areas identified as "within a Justice 40 Census Tract" are flagged as "Disadvantaged" by the Climate and Economic Justice Screening Tool released in November 2022, which aims to identify communities for the Justice40 Initiative.

For more information about the definition of Colorado EnviroScreen, visit https://cdphe.colorado.gov/ej/learn .

Additional Resources

CDPHE Office of Environmental Justice

Colorado EnviroScreen version 2.0 Reports, Guides, and Resources folder

Colorado EnviroScreen 2.0 Report

COLORADO Department of Public Health & Environment

Colorado EnviroScreen overview

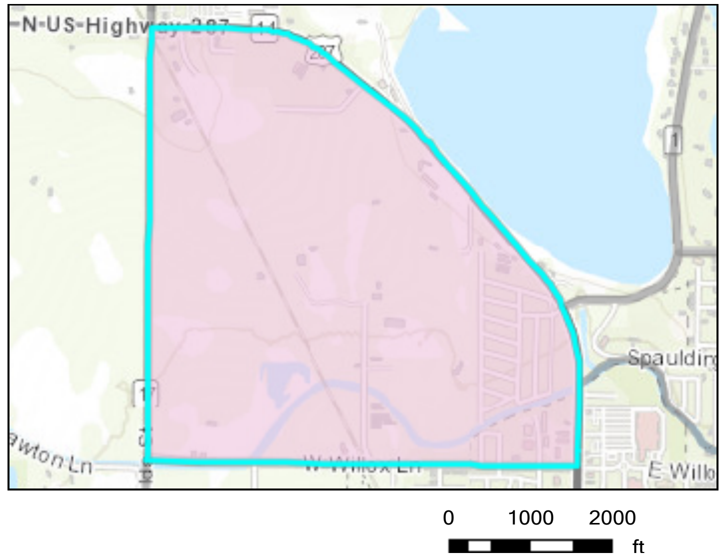
Larimer County

Census block group 080690013041

Colorado EnviroScreen percentile score

78.21

The EnviroScreen percentile score combines population characteristics and environmental burdens. The score ranges from zero to 100, with the higher scores representing the most significant burden.



Component scores

The component scores listed below make up the final Colorado EnviroScreen percentile score. Like the overall EnviroScreen score, component scores reflect relative rankings (percentiles).

Environmental exposures percentile score 54.94

The environmental exposure score represents a community's exposure to certain environmental risks relative to the rest of the state. The score ranges from zero to 100, with higher scores indicating higher burden. The environmental exposure score does not cover all pollutants; it is the average data on diesel particulate matter, traffic proximity, ozone, particulate matter 2.5, air toxics, other air pollutants, lead exposure risk, drinking water violations, and noise.

Environmental effects percentile score 63.26

The environmental effects score represents the number of hazardous or toxic sites in a community relative to the rest of the state. The score ranges from zero to 100, with a higher score indicating a higher burden. The score is the average of data on proximity to mining, oil and gas operations, impaired surface waters, wastewater discharge facilities, Superfund sites, facilities that use hazardous chemicals, and facilities that generate, treat, store, or dispose of hazardous wastes.

Climate vulnerability percentile score 32.79

The climate burden score represents a community's risk of drought, flood, extreme heat, and wildfire compared to the rest of the state. The score ranges from zero to 100, the higher the score, the higher the burden.

Sensitive populations percentile score 75.17

The sensitive populations score captures how at risk a community is to environmental exposures and climate impacts related to health. For example, air pollution has a stronger impact on older and younger people and people with chronic conditions such as asthma. The score ranges from zero to 100, with a higher score being higher vulnerability. We calculate the score using data on asthma hospitalization rate, cancer prevalence, diabetes prevalence, heart disease prevalence, life expectancy, low birth weight rate, mental health, population over 65, and population under five.

Demographics percentile score 84.93

The demographics score represents a community's social and economic vulnerabilities. The score ranges from zero to 100, with a higher number representing a higher vulnerability. We calculate it using data on people with disabilities, housing cost burden, educational attainment, limited English proficiency, income, and race and ethnicity.

The pollution and climate indicators section lists the selected census block group's environmental exposures, environmental effects, and climate vulnerability indicator percentile scores. See pages 25 to 31 of the Colorado EnviroScreen technical documentation for the pollution and climate indicator data sources and methodology. The indicator percentile ranking is highlighted in red if it is above the 80th percentile, indicating that the census block group and the selected location have a higher burden based on that indicator than other Colorado communities.

Pollution and climate indicators

Indicator	**Value**	**Unit**	**Percentile**
Air toxics emissions	0.07	distance weighted measure of estimated air toxics emissions	71.19
Diesel particulate matter	0.11	micrograms per cubic meter	31.66
Drinking water regulations	49.02	population weighted duration (in weeks) of resolved and unresolved health based violations from active community public water systems	67.79
Fine particle pollution (PM 2.5)	7.71	micrograms per cubic meter	42.8
Impaired streams and rivers	53.46	average impairment and assessment status of streams	46.79
Lead exposure risk	0.23	percentage of housing units built before 1960, as an indicator of potential exposure to lead	56.4
Noise	42.95	decibles A	32.85
Other air pollutants	0.03	distance weighted measure of estimated other air pollutant emissions	67.31
Ozone	47.53	parts per billion	41.94
Proximity to hazardous waste facilities	1.16	distance weighted count of hazardous waste facilities within 10 km	50.53
Proximity to mining locations	3.85	distance weighted measure of the total number of active coal, hard rock, and construction materials mining permits	97.36
Proximity to National Priorities List sites	0	distance weighted count of proposed or listed NPL sites within 10 km	0
Proximity to oil and gas sites	19.83	distance weighted measure of the total number of active oil and gas locations	54.79
Proximity to Risk Management Plan sites	0.54	distance weighted count of RMP facilities within 10 km	54.32
Traffic proximity and volume	686471.16	amount of vehicular traffic nearby, and distance from roads	35.32
Wastewater discharge indicator	232.59	toxic chemical concentrations in stream segments per km	18.26
Drought	30.27	sum of weekly total percent of an area experiencing a severe, extreme, or exceptional drought	43.62
Extreme heat days	23.75	average number of high heat days between May and September from 2019 to 2023	41.89
Floodplains	3.28	percentage of each geographic area where there is at least a one percent chance of flooding annually	57.15
Wildfire risk	251.74	mean wildfire hazard potential within each geographic area as determined by the US Forest Service, 2023	13.13

The health and social indicators section lists the selected census block group's sensitive populations and demographics percentile scores. See pages 36 to 52 of the Colorado EnviroScreen technical documentation for the health and social Indicators data sources and methodology. The indicator percentile ranking is highlighted in red if it is above the 80th percentile, indicating that the census block group and the selected location have a higher burden based on that indicator than other Colorado communities.

Health and Social Indicators

Indicator	Value	Unit	Percentile
Asthma hospitalization rate	56.37	rate of hospitalization per 100,000 people	75.23
Cancer index	57.79	percent of adults	57.39
Diabetes index	52.06	percent of adults	45.63
Heart Disease index	43.81	percent of adults	34.49
Life expectancy	80.2	years	44.69
Low birth weight	12.21	percent of singleton births	84.54
Mental health indicator	19.9	percent of adults	89.58
Population over 64 years of age	6.1	percent of total population	14.01
Population under five years of age	16.76	percent of total population	98.07
Disability	10.3	percent of total population	47.12
Housing cost burdened	21.57	percent of households	26.79
Less than High School education	48.21	percent of total population	99.34
Linguistic isolation	17.89	percent of total population	92.95
Low income	48.52	percent of total population	88.61
People of color	83.4	percent of total population	97.11

Understanding the Data

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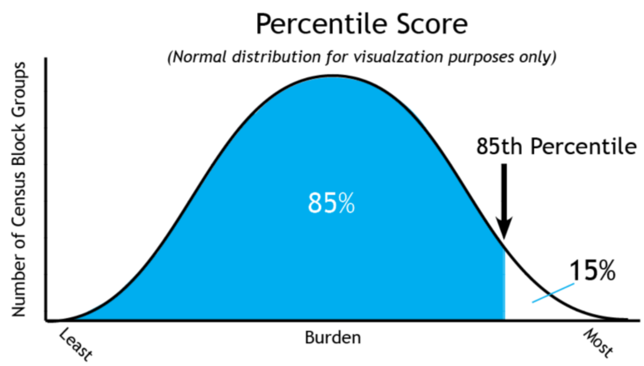

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-Provide information about non-human health or ecosystem risks.

Disproportionately impacted community definition criteria

Criteria	Yes/No	Value
Low-income population above 40%	Yes	48.52%
People of color population above 40%	Yes	83.4%
Linguistically isolated households above 20%	No	17.89%
Housing cost-burdened population above 50%	No	21.57%
Area under tribal jurisdiction	No	N/A
Colorado EnviroScreen percentile score	No	78.21
Within a Justice 40 census tract	Yes	N/A

The table above lists the disproportionately impacted community criteria outlined in Colorado Revised Statute 24-4-109. CDPHE released the most recent version of the disproportionately impacted community map in November 2024.

Demographic data are from the Census Bureau American Community Survey 2018-2022. Colorado EnviroScreen Percentile Score comes from Colorado EnviroScreen version 2.0, released November 2024. Areas identified as "within a Justice 40 Census Tract" are flagged as "Disadvantaged" by the Climate and Economic Justice Screening Tool released in November 2022, which aims to identify communities for the Justice40 Initiative.

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Additional Resources

CDPHE Office of Environmental Justice

Colorado EnviroScreen version 2.0 Reports, Guides, and Resources folder

Some elementary physics of climate change

George Rinker
2024/12/01

Introduction

These notes describe a simple model of Earth's surface and atmosphere I put together as an exercise to improve my own understanding of climate stability and change. I wanted to see if fundamental physical law and simple analysis could say anything useful about our climate's future, unburdened by the complex details of what to most of us is a confusing collection of measurements, calculations, and politics we have little insight into, whose conclusions we have to believe or not without knowing what assumptions drive them or what the sources of their uncertainties are, or perhaps more important, what political pressures have constrained them.

My model is based on conservation of energy as incorporated in the physical theories of classical thermodynamics and radiative energy transfer, expressed in terms of global parameters that are fitted to extrinsic climate data and represent the collective effects of the underlying processes that determine climate conditions.

The parameter values are related to these underlying processes through physical descriptions of Earth's surface and atmosphere that attempt to identify and analyze the most important elements and their mutual interactions while avoiding those that don't materially affect the results or simply track the dominant driving forces.

The model is developed and justified in the text and in the appendices, with particular attention paid to its underlying assumptions and approximations with their associated errors and uncertainties. Some numerical calculations are presented and their implications described.

The validity of this approach is supported by the fit obtained to existing data with physically justified parameter functions and values, as well as by the consistency of its results with the far more sophisticated model predictions carried out by the international climate science community. How accurate its extrapolations into the future are is hard to judge, since it ignores or only crudely approximates effects that are nonlinear and could conceivably become dominant in years to come. Its main success is in showing that at present, at least, a very simple picture can describe the gross features of our climate's current warming trend and provide a framework for understanding what drives it and how it's likely to proceed in the near future.

1. Physical structure of the model

Energy balance and surface temperature

Earth's surface[1] and atmosphere form a closed thermodynamic system that exchanges energy with its surroundings almost entirely through the emission and absorption of electromagnetic radiation. No other mode of heat exchange or internal generation is significant or potentially relevant so far as human activity is concerned.

The principal source of electromagnetic energy is our sun, whose radiation arrives at wavelengths and intensities characteristic of its surface temperature ~5778K.

The primary mode of energy loss is thermal radiation from Earth's surface at wavelengths and intensities characteristic of its mean temperature ~287K.

The mean surface temperature is governed by the difference in the rates this energy is absorbed and emitted. This can be expressed as

$$C \frac{\mathrm{d}T}{\mathrm{d}t} = P_A - P_E \quad , \tag{1}$$

where C is the effective heat capacity of the surface, T is its absolute temperature, $\mathrm{d}T/\mathrm{d}t$ is the instantaneous rate of change of T at any particular time t, and P_A and P_E are the rates thermal energy (heat) is absorbed and emitted at that same time.

The left side of Eq.(1) represents net energy flow in terms of temperature and requires both a well defined heat capacity and a well defined temperature. Such definitions are problematic for a complex body like Earth, which consists of many distinct systems at different temperatures that interact in various ways to store and transport energy, all enclosed in a thermal blanket that leaks energy into space. But so long as the internal properties and interactions are accounted for consistently, Eq.(1) must be satisfied for appropriate mean values of C and T, by the surface as a whole or by any sufficiently isolated part of it.

1 By *surface* we mean the physical upper surface of the land or water that lies immediately below the atmosphere. This is not to be confused with the effective surface defined in some approaches that put it in the upper atmosphere where the density is low enough that most thermal photons escape into outer space and temperatures correspond more closely to those of black body emission. The temperatures and parameters of such an effective surface have somewhat different interpretations than here, though the physical results are equivalent.

Absorption

The solar radiation that heats Earth's surface reaches the upper atmosphere at wavelengths ~5x10^{-7}m characteristic of the sun's surface temperature ~5778K. The total rate of incident energy is well known and easy to calculate from the measured solar luminosity and elementary geometry:

$$P_S = \frac{L r^2}{4 R^2} = 1.736 \times 10^8 \mathrm{GW} = 5.478 \mathrm{x} 10^{15} \mathrm{GJ y^{-1}} \quad , \qquad (2)$$

where $L = 3.828 \times 10^{15} \mathrm{GW}$ is the total power (energy per unit time) emitted by the sun over all wavelengths and directions, $r = 6.371 \times 10^3 \mathrm{km}$ is the planet's radius, $R = 1.496 \times 10^8 \mathrm{km}$ is its orbit radius, and the factor 4 in the denominator arises from the fact that the insolation cross section is the area of the projection of a sphere onto a disk, not the area of the sphere itself. This constant energy flux is distributed over the surface by Earth's daily rotation and yearly orbit, with an irradiating power density averaged over time and latitude of $340.3 \mathrm{W m^{-2}}$.

Not all of this energy is absorbed as heat. Some is reflected back into space by clouds or the surface without depositing energy or otherwise interacting significantly, and some is converted[2] to potential energy by processes such as phase transitions and chemical reactions. We will include these losses in one or more *absorptivity* parameters α, whose values lie between 0 and 1 and depend on the character of the absorbing surface and the atmosphere above it, as will be discussed below.

Emission

Earth's surface is cooled almost entirely by thermal radiation emitted into space at wavelengths ~10^{-5}m and intensities characteristic of its surface temperatures ~287K.

If the surface were a perfect emitter at uniform surface temperature T, it would radiate energy according to the Stefan-Boltzmann law of thermal radiation:

$$P_B = 4 \pi r^2 \sigma_B T^4 \quad , \qquad (3)$$

where $\sigma_B = 1.789 \mathrm{MJ y^{-1} km^{-2} K^{-4}}$ is the Stefan-Boltzmann thermal radiation constant. This radiation occurs at much longer wavelengths than does the incoming solar radiation because Earth's surface temperature is far lower than that of the sun.

2 This potential energy is eventually released as heat over time scales ranging from seasonal to geological, and so long as the surface changes little over those periods, the gross thermal balance is unaffected.

Since the earth is not a perfect emitter, this emission rate is reduced, by a factor we represent by one or more *emissivity* parameters ε. As with absorption, their values necessarily lie between 0 and 1 and depend on the character of the emitting surface and the atmosphere above it.

Heat capacity

Obtaining an appropriate value for C is simplified by the fact that the global ocean accounts for the absorption, storage, and transport of more than 90% of all the solar energy absorbed by the planet and its atmosphere. As will be justified later, the ocean's total heat capacity C_O provides a reliable upper bound for for the effective heat capacity C, which we will represent in the form

$$C = \eta C_O = \eta \, \mathrm{x} \, 5.874\mathrm{x}10^{15}\,\mathrm{GJK}^{-1} \quad , \tag{4}$$

where η is a dimensionless parameter whose value lies between 0 and 1 and $5.874\mathrm{x}10^{15}\,\mathrm{GJK}^{-1} = 1.404\mathrm{x}10^{9}\,\mathrm{Gt}\,\mathrm{x}4.184\mathrm{x}10^{6}\,\mathrm{GJK}^{-1}\mathrm{Gt}^{-1}$ is the product of the ocean's total mass and the specific heat of water. Because C multiplies the time derivative, it acts as an overall time scale factor that affects the form of the solutions only to the extent that the other parameters follow different time scales, directly or indirectly through feedback. The actual value of C represents the thermal inertia of the system and is of interest mainly in determining the inherent time delay in temperature response to changes in absorption or emission.

The ocean's total heat capacity C_O appears only in the ratio P_S/C_O, which has the constant value $P_s/C_O = 0.933\,\mathrm{Ky}^{-1}$, conveniently close to $1\,\mathrm{K}\,\mathrm{y}^{-1}$ for time measured in years.

Temperature change rate

Inserting these expressions into Eq.(1) and rearranging yields the following formulas for the rate of surface temperature change:

$$\frac{\eta C_O}{\alpha_e P_S}\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{\alpha}{\alpha_e} - \frac{\varepsilon}{\alpha_e}\left(\frac{T}{T_B}\right)^4 = \frac{\alpha}{\alpha_e} - \frac{\varepsilon}{\varepsilon_e}\left(\frac{T}{T_e}\right)^4 \quad , \tag{5a}$$

where

$$T_B = \left(\frac{L}{16\pi R^2 \sigma_B}\right)^{1/4} = 278.3\text{K} \tag{5b}$$

is the equilibrium temperature for the blackbody condition $\alpha=\varepsilon$, a planetary constant that depends only on the sun's luminosity and distance and not on any particular properties of the planet itself; and

$$T_e = \left(\frac{\alpha_e}{\varepsilon_e}\right)^{1/4} T_B \tag{5c}$$

is the equilibrium temperature for any pair of values α_e, ε_e such that the right hand sides of Eq.(5a) are zero.

Equation(5a) describes the overall exchange of energy between Earth's surface and its external surroundings, converted to a temperature change rate by the heat capacity ηC_O . All the internal complications and material details of the underlying processes are gathered into the three quantities η, α, and ε , which appear as parameters whose values all lie between 0 and 1 and can be estimated or calculated as accurately or approximately as needed without affecting the overall validity of the equation.

All of these parameters are constant in time when the surface is in steady state equilibrium, but they can vary with time as well as temperature when conditions change. So long as they do not depend explicitly on any time derivative of the temperature, Eq.(5a) is a first order ordinary differential equation for temperature as a function of time. It is also nonlinear and inhomogeneous, and even with constant parameter values, the only analytic solutions (that I know of) are for the uninteresting cases $\alpha=0$ or $\varepsilon=0$. But it is computationally stable and trivial to solve numerically for any well behaved set of parameters and initial conditions, and it has simple approximate solutions in some limiting cases.

Quasistatic solutions

When all three parameters are constant in time or nearly so (quasistatic), Eq.(5a) can be written in dimensionless form as

$$4 \frac{d}{d(t/\tau)}\left(\frac{T}{T_e}\right) = 1 - \left(\frac{T}{T_e}\right)^4 , \tag{6a}$$

with

$$\tau = \frac{\eta C_O T_e}{4\alpha P_S} \tag{6b}$$

a characteristic physical time scale. For temperatures T close to equilibrium T_e, we can linearize Eq.(6a) by changing variables to $\delta = (T/T_e) - 1$ and expanding the binomial to first order in δ to get

$$\frac{d\delta}{d(t/\tau)} = -\delta \ , \tag{6c}$$

which provides the solution for the initial condition $T = T_i$ at $t = t_i$

$$T = T_e + (T_i - T_e)e^{-(t-t_i)/\tau} \ . \tag{6d}$$

Equation(6d) shows that any small parameter change that shifts T_e will be followed by a temperature adjustment in the direction to re-establish equilibrium, acting on a time scale of order $\tau = (\eta C_O T_e)/(4\alpha P_S) \approx (\eta/\alpha) \times 77\,\text{years}$. This is essentially a minimum response time that delays the effects of any climate changing adjustments in conditions, whether natural or human made.

The new equilibrium temperature $T_e = T_i + \delta T$ corresponding to a small parameter change $\alpha_e = \alpha_i + \delta\alpha$, $\varepsilon_e = \varepsilon_i + \delta\varepsilon$ is easily obtained from Eq.(5c):

$$\frac{\delta T}{T_i} \approx \frac{1}{4}\left[\frac{\delta\alpha}{\alpha_i} - \frac{\delta\varepsilon}{\varepsilon_i}\right] \ , \tag{6e}$$

where we have required both sets of parameters and temperatures to satisfy Eq.(5c) and expanded logarithms to first order in δ. Equation (6e) displays the close connection between α and ε as well as the fact that a fractional change in either produces a fractional change in equilibrium temperature T_e one fourth as large. For example, a one percent decrease in ε produces an equilibrium temperature increase $\delta T \approx 0.0025\,T_i = 0.72\,\text{K}$ for $T_i = 287\,\text{K}$.

Some other properties of Eq.(5a) worth mentioning or repeating are

1. The equilibrium temperature of the surface is independent of its heat capacity and depends on its absorptivity and emissivity only through their ratio and not their absolute values, so that a small change in either parameter affects the rate of temperature change in a way that is essentially equivalent to an equal change of

opposite sign in the other. This connection between α and ε provides a certain amount of flexibility in what we take to be the surface and its temperature, a choice that is otherwise complicated by the diffuse nature of our atmosphere with its range of radiating temperatures and densities (see footnote 1).

2. The solutions of Eq.(5a) are stable whenever both α and ε are independent of T. In that case, there are no feedbacks, overshoots, or runaway temperature excursions even if their ratio somehow changes or fluctuates with time. Any such change in α or ε from equilibrium values generates a monotonic temperature adjustment that follows and continues until the corresponding new equilibrium temperature is reached.

3. If either α or ε depends on temperature, any change in conditions can be amplified or diminished through nonlinear feedback effects that can persist even after the original source is removed. Such persistence begins at what is generally called a tipping point and terminates only after the sources of feedback are exhausted or extinguished or overall conditions change enough to make the feedbacks irrelevant.

2. Physical systems

Earth's surface properties

To apply Eq.(5a) requires an appropriate physical description of the atmosphere and surface. Neither of these is simple. Each contains a variety of distinct systems and components and interacts with electromagnetic radiation in complicated sequences of interrelated steps. The atmosphere contains a mixture of several different circulating gases and particulates. The surface includes the global ocean, the exposed land areas with their varying vegetative cover, and the sheets of ice and snow that cover polar and high altitude regions, all with their associated internal complexities and feedback cycles.

It turns out that most of these complications aren't quantitatively important, and those that are can be addressed separately because the different physical systems play different roles in the global processing of heat energy.

Atmosphere

The global atmosphere serves as (a) the primary vehicle for heat transport over land, which it does efficiently by convection; and (b) a thermal blanket over the global surface, preventing some of the heat it radiates from escaping into outer space. It contributes relatively little to global heat storage because its mass $(5.184\text{x}10^6 \text{Gt})$ and heat capacity are much smaller than those of the global ocean. Its main role with respect to energy balance lies in its selective transmission of electromagnetic radiation of different wavelengths.

Land surfaces

The land surfaces are limited in their ability to store and transport heat by the low absorptivity and thermal conductivity of rock. Depending on the type, the absorptivity of rock per unit mass is typically less than half that of water. The low thermal conductivity means that heat penetrates slowly, so that the upper crust acts more as a thermal insulator than a conductor on time scales relevant to climate, and only a thin top layer participates in solar heat storage or transport.

This limitation is illustrated by the significant daily temperature swings that occur on land, in particular in desert areas where these swings are large and the surface properties consistent. The average total solar energy incident on one square meter of surface is approximately $15\,\mathrm{MJ}$ per half day. If this surface absorbs a fraction α of this energy and undergoes a temperature change ΔT in that half day, then its effective heat capacity is approximately $15\alpha/\Delta T\ \mathrm{MJK^{-1}}$. The specific heat of typical rock is approximately $2\,\mathrm{MJK^{-1}m^{-3}}$, so the total heat capacity of a volume of rock one meter in area and *h* meters thick is $h\,\mathrm{x}\,2\,\mathrm{MJK^{-1}}$. Equating this to the above effective heat capacity with $\alpha=0.3$ and $\Delta T=30\,\mathrm{K}$ yields $h=0.075\,\mathrm{m}$, for an effective volume of about $10^{12}\,\mathrm{m^3}$ and total heat capacity $2\mathrm{x}10^{9}\,\mathrm{GJK^{-1}}$ integrated over all land areas. This is more than six orders of magnitude smaller than the heat capacity of the global ocean.

A more realistic accounting of heat absorption by land could be made by solving the heat diffusion equation for the entire crust, bounded below by the mantle and above by the atmosphere. But that's hardly necessary at the levels of accuracy pursued here, and we will neglect the contributions of land areas to the global heat capacity.

What's most important about land areas is that the relatively rapid daily and yearly surface heating cycles act primarily as weather generators, in that the local surface absorbs radiant heat during the day and releases it at night, thereby pulsing the atmosphere with localized injections of energy in cycles that promote convection and distribution of atmospheric conditions over the entire planet.

Global ocean

The global ocean serves as the planet's principal heat absorber, reservoir, and transport system because (a) it covers most of the surface and absorbs almost all of the radiant energy that falls on it, at all wavelengths; (b) it has far greater thermal mass and heat capacity than either the exposed land surfaces or the atmosphere; and (c) it transports heat by convection, by far the most efficient such mechanism that exists. That it does all this efficiently is evidenced in part by the remarkably uniform temperature of the deep ocean (276±4K from pole to pole).

Energy flow sequence

The consequence of all this is that we can find most of what we're looking for in the following sequence:

(1) Solar radiation reaches the upper atmosphere and is either (a) reflected elastically back into space by water vapor that has condensed or frozen into clouds; or (b) passed through to the surface. What reaches the surface is either reflected back through the atmosphere, absorbed and converted to heat, or stored as potential energy.

(2) Of the fraction that is not reflected away by the atmosphere, almost all is absorbed by the open ocean and distributed throughout its extent by convection.

(3) The heat energy absorbed by the ocean is either consumed by melting sea ice to produce water, evaporation to produce water vapor, or re-radiated upward at thermal wavelengths characteristic of the ocean's surface temperature.

(4) The water vapor in the atmosphere quickly condenses and returns its heat of vaporization to molecular motion and its condensed molecules to the surface as rain or snow.

(5) Thermal energy radiated by the ocean or the atmosphere either passes out into space or is absorbed by the greenhouse gas molecules in the atmosphere and re-emitted in random directions, so that much of the energy traveling upward is trapped and eventually re-radiated back toward the surface, either immediately or after being transported to other areas of the planet by atmospheric convection.

3. Parametric representation

All three parameters η , α , and ε are constant in time when the climate is in thermal equilibrium. Any change in α or ε disturbs this equilibrium and causes the temperature to change accordingly, at a rate largely determined by η . Such parameter changes can occur either directly as consequences of imposed changes in the physical properties of the atmosphere or surface, or indirectly as feedbacks, consequences of the resulting changes in temperature. Some points worth noting are

1. The effects of both direct and indirect changes in parameter values persist until some new thermal equilibrium is reached, which can be long after the parameter themselves have stopped changing. This is because the time to equilibrium is governed by η, independent of whatever is causing α or ε to change.

2. Feedbacks can become their own dominant driving force once they have been triggered and can drive themselves until they have exhausted whatever source fuels them. Sea ice cover, for example, can continue to shrink so long as the temperature remains elevated and there is any ice to melt, stopping only when the ice is all gone, at which point its melting ceases to be a climate driver and its presence no longer a temperature moderator.

Numerical values

We will use general arguments and basic data to obtain initial values for each of the parameters separately and then adjust these values as needed to fit the resulting solutions of Eq.(5a) to known quantities. Because the parameter values are linked to each other in nontrivial ways, the adjustments need not be small. We will use data from the period 1980-2020 and assume the climate was close to equilibrium in 1980.

We will use parameter sets that fit existing data satisfactorily to investigate future conditions under various assumptions about possible public remedies. To the extent that different parameter sets are found that fit available data equally well, any differences in their predictions must be taken as measures of their potential errors.

Heat capacity C

The total heat capacity of the global ocean provides an upper bound on C, since it assumes implicitly that heat is distributed evenly throughout the ocean's volume on time scales short compared with changes in heat content and temperature. This can hardly be the case, since different layers of ocean water participate in circulation and transport on different time scales, some of which can be much longer than that. This reduction is described here by the parameter η, whose value must be positive and less than 1, probably around 0.2 according to current measurements.

In principle, the ocean heat capacity C_o can vary with time as feedback arising from (a) a change in the total mass of ocean water due to melting or evaporation; or (b) changes in circulation. The former is not zero because the specific heat of vapor or ice is only about half that of liquid water; however, the corresponding change in C_o is too small to be a concern here, less than one percent even if all the present surface ice melts and atmospheric vapor doubles. Changes in circulation are harder to predict, and we will not attempt to account for them here beyond absorbing them as uncertainties in the overall time scale and noting that at present, rising temperatures appear to be increasing stratification and thereby reducing the effective volume of water available to store heat, reducing the effective heat capacity as a positive temperature feedback.

We will fix appropriate values for η as we fit to measured global temperatures.

Absorptivity α

Absorptivity varies from equilibrium values almost entirely through feedbacks arising from changes in the phases of water in the atmosphere and on the surface. The fundamental mechanisms underlying these changes are well understood, but their application to the global ocean and atmosphere is burdened by the complexities of nonlinear fluid dynamics and is less clear.

Increased humidity in the atmosphere reduces both absorptivity and emissivity, the former through increased cloud formation and reflection of incoming sunlight and the latter through increased absorption of outgoing thermal radiation from the surface. That these two effects largely cancel each other is not in dispute, but there seems to be no consensus at present whether the net effect is positive, negative, or neutral. We will assume that whatever it is, the net effect varies slowly from year to year and is compensated for implicitly when we fit to equilibrium conditions.

A less ambiguous feedback involves melting and freezing of surface ice and snow, which we account for in the following way.

We represent the mean absorptivity α in terms of four surface categories: ocean or land, ice covered or not, each with its characteristic absorptivity:

$$\alpha = F_S\left(F_{OI}\alpha_{OI} + F_{OU}\alpha_{OU} + F_{LI}\alpha_{LI} + F_{LU}\alpha_{LU}\right) , \qquad (7a)$$

where

F_S = fraction of sunlight reaching the surface (0.77)
F_{OI} = fraction of surface covered by ocean ice
F_{OU} = fraction of surface covered by open ocean
F_{LI} = fraction of surface covered by land ice
F_{LU} = fraction of surface covered by bare land

α_{OI} = absorptivity of ocean ice (0.20)
α_{OU} = absorptivity of deep ocean (0.94)
α_{LI} = absorptivity of land ice (0.20)
α_{LU} = absorptivity of land surfaces (0.35) , (7b)

and where the numerical values listed are nominal and subject to adjustment and the fractions are understood to be yearly averages.

The area fractions require correction from their values as measured on Earth's spherical surface in order to account for the fact that surface ice is concentrated near the poles, where the low angle of solar incidence reduces the effective insolation and the surface reflectance.

The mean insolation can be corrected by projecting Earth's three dimensional sphere onto the two dimensional disk that intercepts incoming sunlight. A simple way of doing this is to assume each type exists only in a polar cap above a particular latitude. This describes the important time dependent boundaries between ice and ice free areas accurately enough in spite of its misplacement of the continents, whose boundaries are static and therefore absorbed in the equilibrium parameter values.

The surface area fractions F_{3d} and F_{2d} for a sphere and disk respectively are related to corresponding latitudes Φ by

$$2F_{3d} = 1 - \sin(\Phi) \quad (8a)$$
$$2\pi F_{2d} = \pi - 2\Phi - \sin(2\Phi) \ . \quad (8b)$$

The global ocean covers an area of about $361 \times 10^6 km^2$, a fraction 0.708 of Earth's surface of approximately $510 \times 10^6 km^2$. The latitude corresponding to this 3d fraction is $-0.136\pi(-24.6^o)$ according to Eq.(8a). Equation (8b) gives a corresponding 2d fraction 0.757, slightly larger than for 3d.

The land ice covering Antarctica and Greenland totaled about $15.7 \times 10^6 km^2$ in 1980, a 3d surface fraction 0.0308 corresponding to a latitude $-0.388\pi(-69.8^o)$ and 2d fraction 0.0091.

Sea ice near the poles totaled about $20 \times 10^6 km^2$ in 1980 averaged over the seasons, a 3d fraction 0.0392 corresponding to a latitude $+0.373\pi(+67.2^o)$ and 2d fraction 0.0130.

These polar ice sheets are melting at the present time, though the surface area covered is shrinking significantly only for sea ice, where the ice packs build up from relatively thin drift ice each winter and melting is accelerated by currents that bring warmer water from nearer the equator. Sea ice cover is shrinking now by about 0.47% per year, a decrease by a factor 0.828 over the 40 years from 1980 to 2020 to a 3d fraction 0.0325 corresponding to a latitude $0.384\pi(+69.2^o)$

The melting process itself is beyond the scope of this model, and we will not attempt to describe it in any detail, or to analyze the melting volume, which is important for sea level rise due to melting of land ice. We will simply assume that the rate of change of effective snow/ice surface area is proportional to that area itself and to the difference in temperature from equilibrium:

$$\frac{\mathrm{d}F(t)}{\mathrm{d}t} = -F(t)\left[T(t)-T_e\right]/s_m \quad , \tag{9a}$$

which integrates to

$$F(t) = F(t_0)\mathrm{e}^{-\int_{t_0}^{t}\mathrm{d}t'\left[T(t')-T(t_0)\right]/s_m} \quad , \tag{9b}$$

where s_m is a parameter to be fitted to existing melt rate data.

Emissivity ε

The emissivity ε varies with greenhouse gas load according to Eq.(B2):

$$\varepsilon(t) = \varepsilon(t_0)\prod_k \mathrm{e}^{-(N_k(t)-N_k(t_0))/s_k} = \varepsilon(t_0)\mathrm{e}^{-\sum_k \delta N_k/s_k} \quad , \tag{10}$$

where the product and sum are over all contributing species k , $N_k(t)$ is the abundance of species k at time t , and s_k is the corresponding mean absorption depth in the same units as $N_k(t)$, averaged over Earth's emission spectrum.

Absorption depths are intrinsic molecular properties that can be accurately measured in the laboratory for any particular gas and spectrum, though not so accurately in the global atmosphere with all its varying conditions. We will represent them here in terms of their CO_2 equivalent and write

$$\sum_k \frac{\delta N_k}{s_k} = \frac{1}{s_{CO_2}} \sum_k \left[\frac{s_{CO_2}}{s_k}\ \delta N_k\right] = \frac{\delta N}{s_{CO_2}} \quad , \tag{11}$$

where the ratios s_{CO_2}/s_k are known laboratory values and δN is the equivalent CO_2 gas load. For conditions close to equilibrium, Eq.(5a) becomes

$$\frac{\eta C_O}{\alpha_e P_S}\frac{\mathrm{d}T}{\mathrm{d}t} = 1 - \mathrm{e}^{-\delta N/s_{CO_2}} \quad , \tag{12}$$

where we have used Eq.(5c) to eliminate ε_e , T_e and T_B .

We can invert Eq.(12) to express s_{CO_2} in terms of known loads and temperatures at two different times:

$$s_{CO_2} \approx -\delta N/\ln\left(1-\frac{\eta C_O}{\alpha_e P_S}\frac{\delta T}{\delta t}\right) \quad . \tag{13}$$

Values for the reference years 1980 and 2020 are $\delta N = 152\text{ppm}$, $\delta T = 1\text{K}$, and $\delta t = 40\text{y}$.

Natural greenhouse gas loss

Each greenhouse gas decays out of the atmosphere at a rate proportional to its abundance:

$$\frac{\mathrm{d}N_k(t)}{\mathrm{d}t} = - N_k(t)/\tau_{dk} \quad , \tag{14}$$

where τ_{dk} is a characteristic decay time scale for species k , related to its half life by $t_{1/2} = \tau_{dk}\ln(2)$. Equation (14) integrates to

$$N_k(t) = N_k(t_0)\mathrm{e}^{-(t-t_0)/\tau_{dk}} \quad , \tag{15}$$

where t_0 is any convenient time when $N_k(t_0)$ is known.

The characteristic decay time for CO_2 is hundreds or thousands of years, for CH_4 around ten years, and H_2O a few days. Since CH_4 converts to CO_2 in the atmosphere, a corresponding small increase in the latter occurs as CH_4 decays.

Anthropogenic contributions to greenhouse gas loads

In 1980 the total atmospheric loads of CO_2 and CH_4 were about 300ppm and 0.75ppm, respectively. By 2020 they had increased to about 417ppm and 1.87ppm, at increasing rates that had reached 7.7ppm/year and 0.05ppm/year.

Because these 2020 rates were substantially greater than the mean rates of 3ppm and 0.03ppm over that period, and because little was being done at the time to change them, it's likely that they were following the exponential growth of human population and activity. In that case, the atmospheric loads have the form

$$N_k(t) = B_k + V_k(t) = B_k + V_k(t_0) e^{(t-t_0)/\tau_{vk}} \quad , \tag{16}$$

where B_k is the constant natural background and $V_k(t)$ the varying contribution. Knowing the total loads at two different times and the rate of change at one of these times is sufficient to determine the constants B_k and τ_{vk}, which can be obtained using any convenient numerical method for solving transcendental equations. The human contribution $H_k(t)$ to $V_k(t)$ is then extracted by noting that

$$e^{(t-t_0)/\tau_{vk}} = e^{(t-t_0)/\tau_{dk}} e^{(t-t_0)/\tau_{hk}} \quad , \tag{17a}$$

or

$$\frac{1}{\tau_{hk}} = \frac{1}{\tau_{vk}} - \frac{1}{\tau_{dk}} \quad . \tag{17b}$$

4. Representative results

Calculated results are shown in the figures below for a representative parameter set over the period 1980-2100 under four human response scenarios:

(1) Greenhouse gas loads continue to rise after 2020 at the same exponentially increasing rates observed during the period 1980-2020 (Figs.1a-1c);

(2) Greenhouse gas loads continue to rise at constant rates equal to those observed in 2020 (Fig.2);

(3) Anthropogenic production of greenhouse gases ceases entirely in 2030 and does not resume (Fig.3); and

(4) Anthropogenic production of greenhouse gases ceases entirely in 2050 and does not resume (Fig.4).

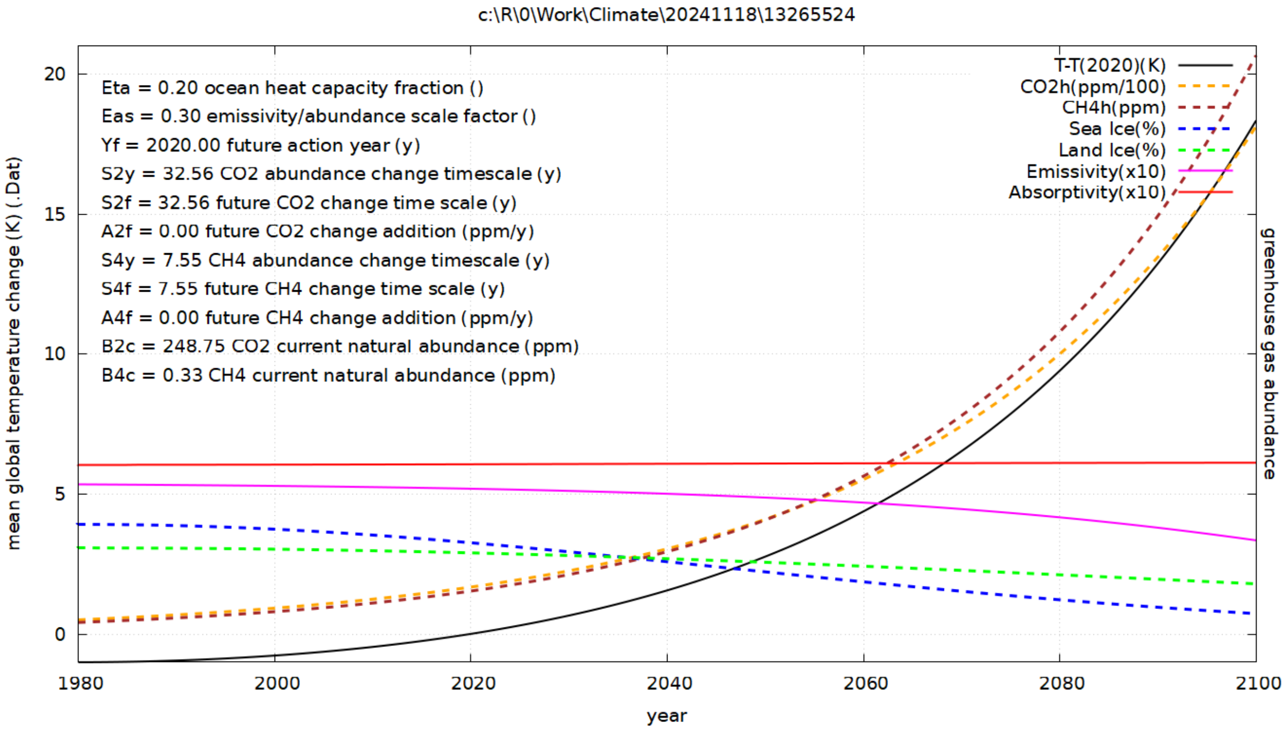


Figure 1a. Temperatures, greenhouse gas loads, ice cover for scenario 1.

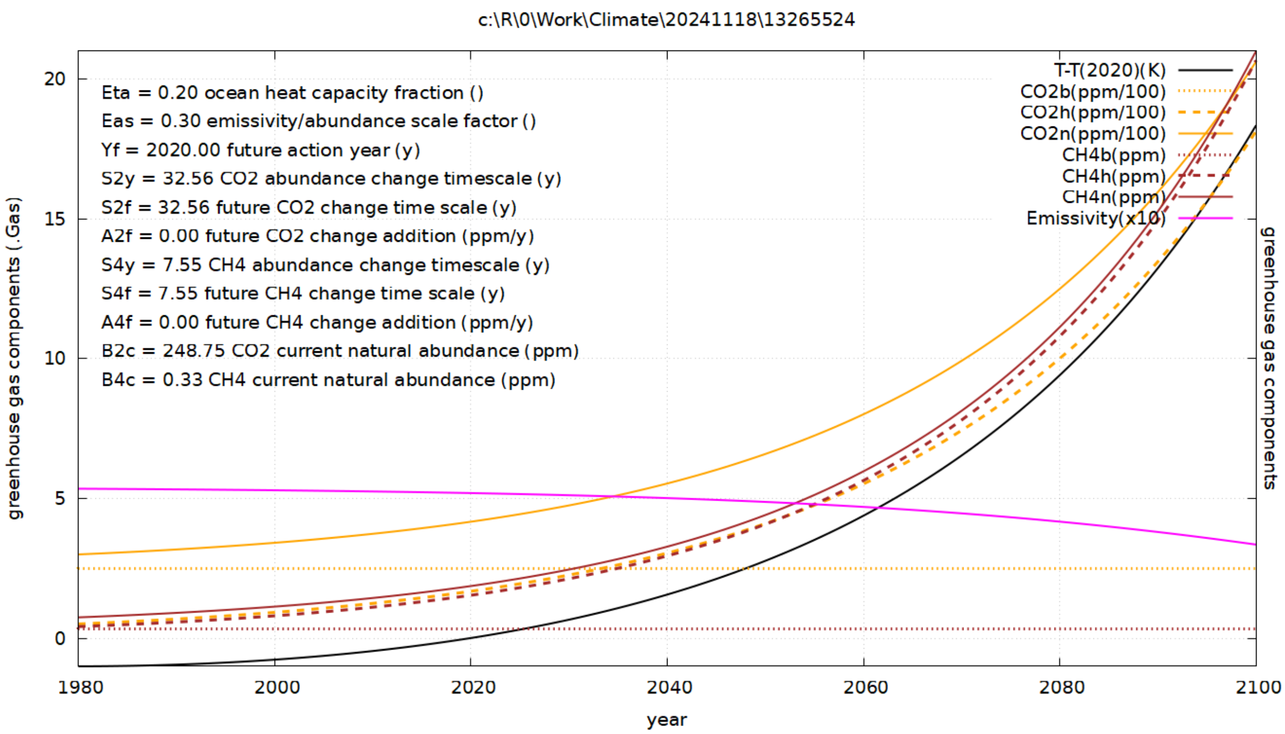


Figure 1b. Greenhouse gas loads for scenario 1.

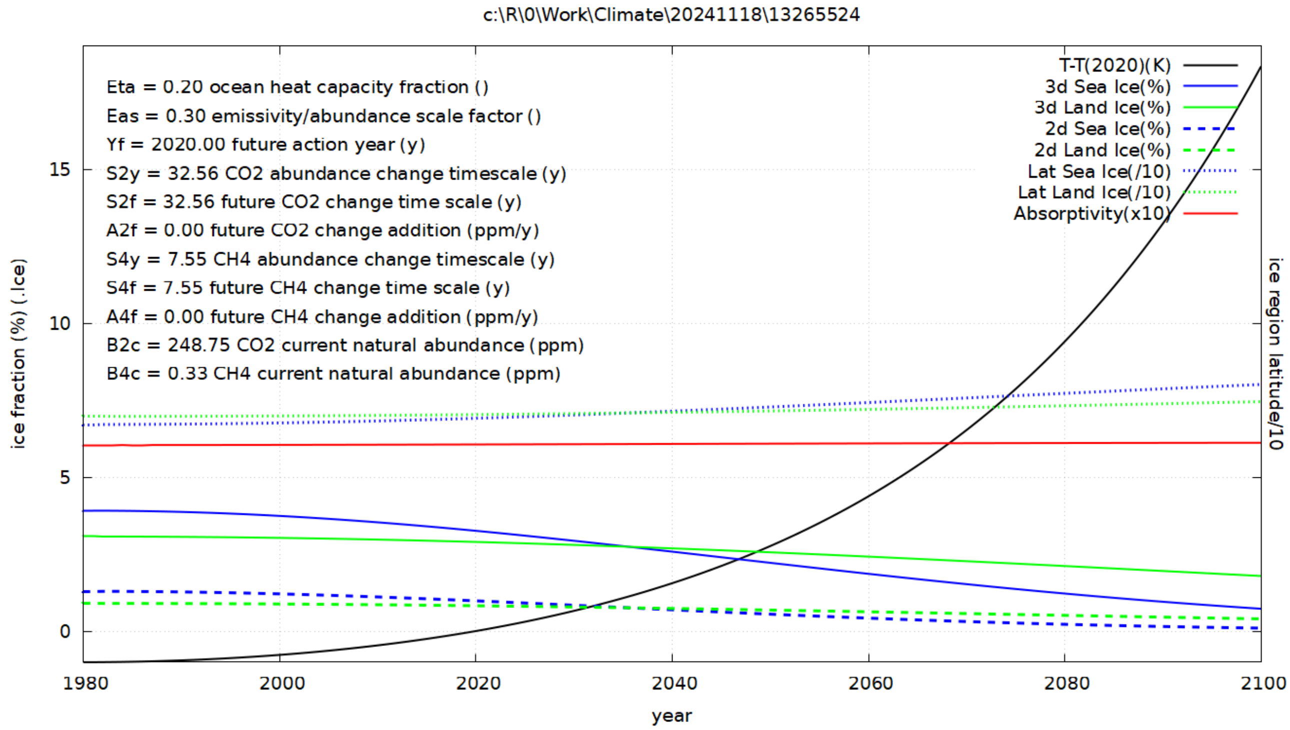


Figure 1c. Surface ice cover for scenario 1.

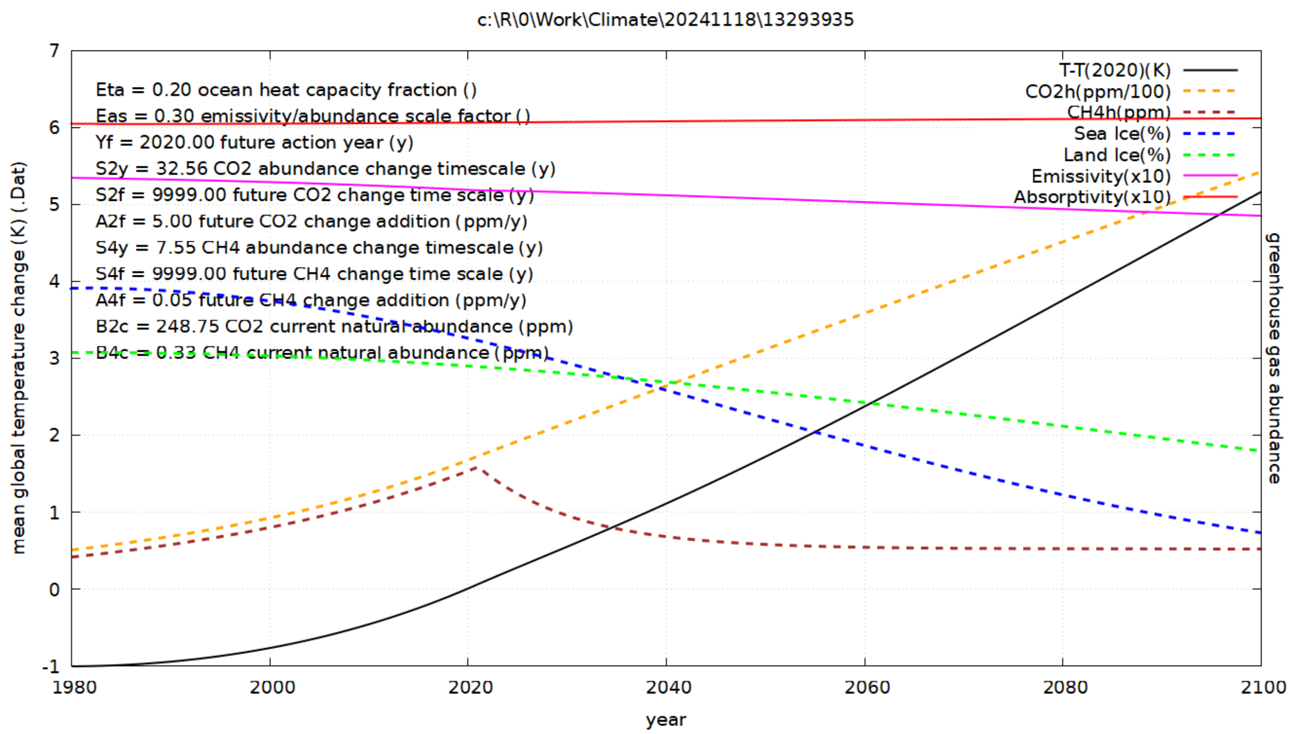


Figure 2. Temperatures, greenhouse gas loads, ice cover for scenario 2.

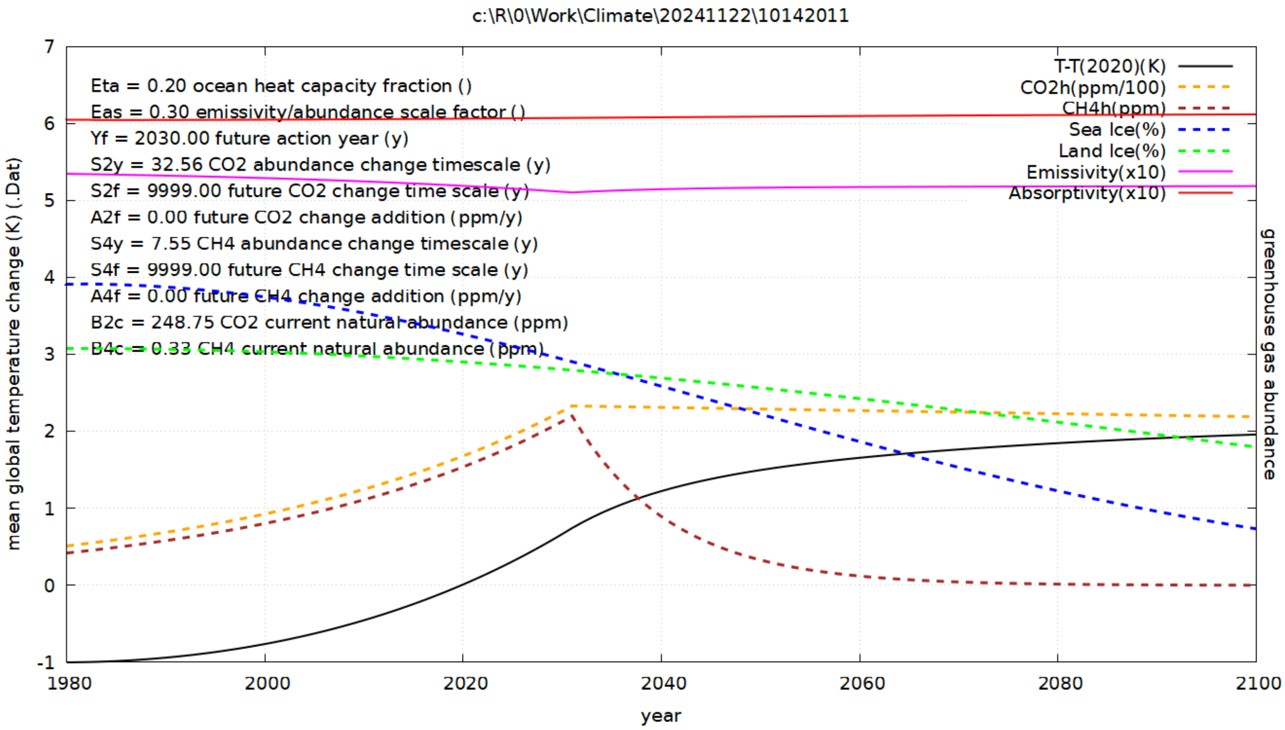


Figure 3. Temperatures, greenhouse gas loads, ice cover for scenario 3.

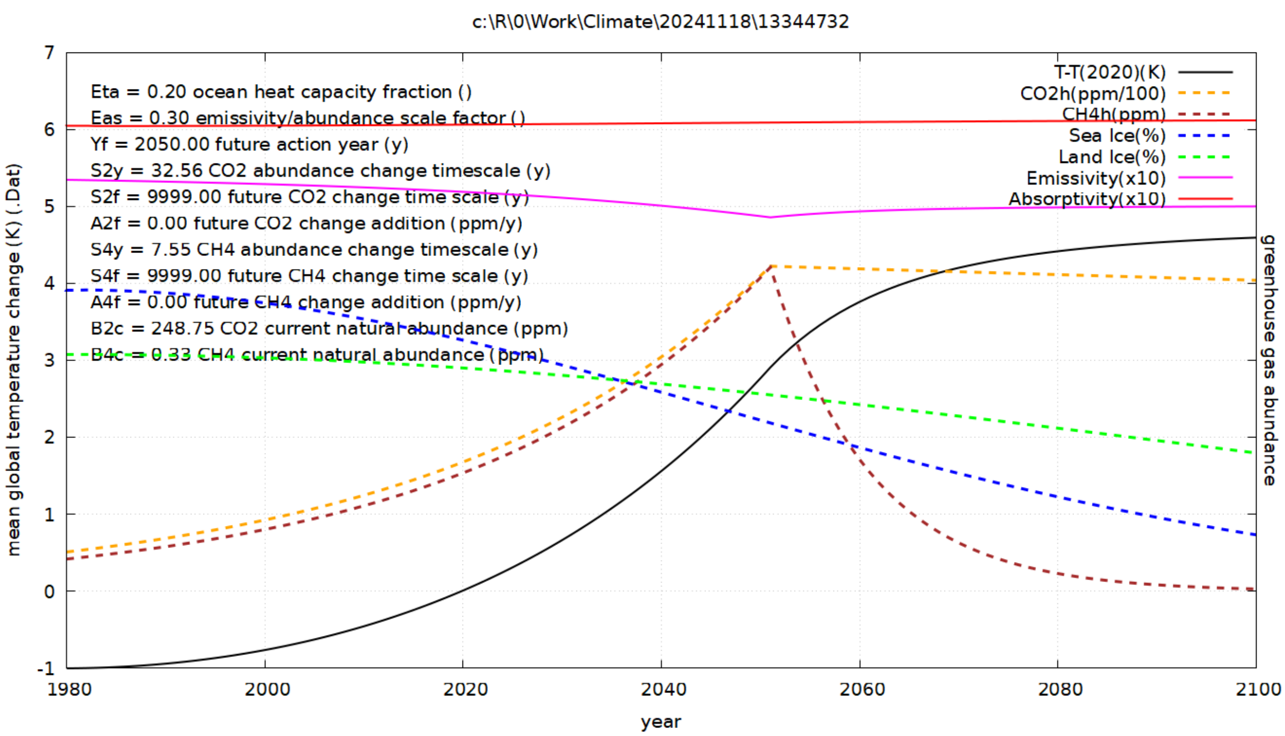


Figure 4. Temperatures, greenhouse gas loads, ice cover for scenario 4.

5. Discussion and conclusions

(1) Figures 1a-1c summarize some important consequences of maintaining the status quo, with rates of greenhouse gas production continuing to increase as they have over the past 40 years. The most notable consequence is the increase of mean global temperature by around 18K (32F) by the end of the century. This is not realistic, but only because our current style of living and means of production can hardly be expected to survive that long under such conditions.

Figures 1b and 1c show details of the corresponding greenhouse gas loads and ice surface cover under this scenario.

(2) Figure 2 shows the same information as Fig.1a following the second scenario, in which greenhouse gas production is stabilized at the current rate as of 2020. In this case, the CO_2 load increases almost linearly with time and the CH_4 load quickly falls to background levels, since the natural CO_2 lifetime is much longer than its production rate while that of CH_4 is much shorter. In this scenario, the global temperature rise by 2100 is only around 5K (9F).

(3) Figure 3 shows the same information as Figs. 1a and 2 for scenario 3, in which net zero is achieved for both CO_2 and CH_4 in 2030. The CO_2 load remains nearly constant after that and the CH_4 load decreases rapidly to background levels by natural decay. The temperature rise between 2020 and 2100 is only about 2K (3.6F).

(4) Figure 4 corresponds to scenario 4, which is the same as scenario 3 except that net zero is achieved 20 years later in 2050. In that case, the temperature rise from 2020 to 2100 is about 4.5K (8F), 2.5K more due to the 20 year delay in taking action.

Which of these scenarios will turn out to be closer to the truth is not easy to predict, given the vagaries of human nature and the capricious political atmosphere that seems everywhere around us. As a consequence, any quantitative prediction of future temperature change is subject to wild uncertainty, not because the science is questionable but because human nature is not well equipped to deal with it.

The science of temperature prediction is straightforward. Even such a simple model as this tells us the same things the most careful and sophisticated treatments do, with little variation due to different parameter choices so long as they fit the data already available. So far as I've been able to discover at least.

It must be emphasized, however, that the connection between greenhouse gas load and emissivity in these calculations is fit to temperature data and not somehow derived independent of it, and as a consequence, one cannot use these results as proof that greenhouse gas loads are causing current global temperatures to rise. That's a built in assumption, whose main defenses are that it fits the data and is consistent with the most careful analyses currently available. A further defense is that the fundamental interactions underlying this assumption (opacities of gases) have been carefully studied since long before global warming made the news, and it's highly unlikely that significant errors have been made on that account.

The main virtue of the fitting procedure used here is that it incorporates all the secondary phenomena associated with rising gas loads and temperatures (such as melting permafrost, for example) without having to address them explicitly.

Global consequences

Most of the global consequences of rising temperatures are matters of speculation involving human response and will not be discussed here.

As individuals, most of us could tolerate a simple 5K(9F) rise in average temperature; however, that's roughly equivalent to temperatures 700 miles closer to the equator for anyone not already in the tropics (Denver to San Antonio for example). Our population as a whole could survive that much displacement, in principle. Whether it would is another question. Of critical importance are the time scales involved, since slower rates of change are easier to adapt to. With the parameters used here, changes in temperature lag behind changes in gas load by at least 25 years [Eq.(6b)].

One consequence of rising temperatures that is not so speculative has to do with loss of polar ice. All scenarios considered here show large losses of sea ice by 2100, probably enough to open north polar routes to regular shipping. Absorptivity would increase, but not so much as it would for the same areas at lower latitudes where insolation is more direct.

Sea level rise due to melting of land ice is probably more important. Greenland contains enough ice to raise the mean global sea level by 8m (25 feet), and Antarctica enough to raise it by 75m (240 feet). There is no doubt about this. But how soon it might happen is hard to say, depending as it does on actual temperatures and the complicated details of the melting processes, which affect ice volume somewhat differently than ice cover area.

A consequence of rising temperatures that could turn out to benefit plant and animal life in the long run arises from the fact that the vapor pressure of water is strongly temperature dependent, so that average humidity and precipitation will rise with temperature so long as there's water in the global ocean available to evaporate. That creates problems during transition in the form of extreme weather events that will persist until temperatures stabilize, but ultimately it could improve the productivity of large areas of land that are now too arid to grow much.

Acknowledgements

I was prompted to look into this subject by discussions I participated in as a member of the Environment and Science Advisory Board of the Larimer County (CO) Commissioners, when I realized I didn't understand it well enough to defend the substance of what was by then the overwhelming consensus of the international science community. I'd hoped to come up with something straightforward enough to be obvious to anyone, but as so often happens, there's more to it than first meets the eye. No physicist will have trouble following what I've said here, but others may. The mathematical language is an unfortunate necessity, but it can't be avoided because the answers depend on how much, not just what.

Appendix A: Numerical values

Required:	
Measured:	
Stefan-Boltzmann constant	$5.670 \times 10^{-8}\,Wm^{-2}K^{-4}$
solar luminosity	$3.828 \times 10^{26}\,W$
Earth orbit radius	$1.496 \times 10^{11}\,m$
Earth orbit period	$3.15576 \times 10^{7}\,s$
Earth sphere radius	$6.371 \times 10^{6}\,m$
ocean heat capacity	$5.875 \times 10^{24}\,JK^{-1}$
ocean surface area fraction	0.708
ocean ice area fraction 1980	0.0392
ocean ice area fraction 2020	0.0325
ocean ice area fraction melt rate 2020	$0.009\,y^{-1}$
land ice area fraction 1980	0.0308
land ice area fraction 2020	0.0290
land ice area fraction melt rate 2020	$0.003\,y^{-1}$
atmospheric CO_2 abundance 1980	300ppm
atmospheric CO_2 abundance 2020	417ppm
atmospheric CO_2 change rate 2020	$5\,ppm\,y^{-1}$
atmospheric CH_4 abundance 1980	0.75ppm
atmospheric CH_4 abundance 2020	1.87ppm
atmospheric CH_4 change rate 2020	$0.05\,ppm\,y^{-1}$
mean surface temperature 1980	287K
mean surface temperature 2020	288K
ratio CH_4/CO_2 thermal absorption	$31\,molecule^{-1}$
sunlight fraction to surface 1980	0.77
sunlight fraction to surface 2020	0.77
Estimated:	
open ocean absorptivity	0.94
bare land absorptivity	0.35
ocean ice absorptivity	0.20
land ice absorptivity	0.20
atmospheric CO_2 decay time	$10^{3}\,y$
atmospheric CH_4 decay time	$10\,y$
Adjusted:	
ocean heat capacity fraction	0.2
emissivity/abundance scale factor	0.3

Related:

Land ice:

Antarctic ice volume			$26.5\text{x}10^{15}\,\text{m}^3$
/ ocean surface area	$36.1\text{x}10^{13}\,\text{m}^2$	=	$73.4\,\text{m}\,(241\,\text{feet})$
Greenland surface ice volume			$2.86\text{x}10^{15}\,\text{m}^3$
/ ocean surface area	$36.1\text{x}10^{13}\,\text{m}^2$	=	$7.92\,\text{m}\,(26\,\text{feet})$

Atmosphere:

total mass	$5.184\text{x}10^{18}\,\text{kg} = 5.184\text{x}10^{6}\,\text{Gt}$
total molecules	$1.078\text{x}10^{44} = 1.790\text{x}10^{20}\,\text{mol}$
mean molecule mass m_{avg}	$28.964\,\text{u} = 4.810\text{x}10^{-26}\,\text{kg}$
CO_2 molecule mass	$44.009\,\text{u} = 7.308\text{x}10^{-26}\,\text{kg} = 1.5194\,m_{avg}$
CH_4 molecule mass	$16.043\,\text{u} = 2.664\text{x}10^{-26}\,\text{kg} = 0.5539\,m_{avg}$
H_2O molecule mass	$18.153\,\text{u} = 3.015\text{x}10^{-26}\,\text{kg} = 0.6267\,m_{avg}$
mean abundance conversion	$1\,\text{ppm}_{\text{mol}}(\text{avg}) = 5.184\text{x}10^{12}\,\text{kg}$
CO_2 abundance conversion	$1\,\text{ppm}_{\text{mol}}(CO_2) = 7.877\text{x}10^{12}\,\text{kg}$
CH_4 abundance conversion	$1\,\text{ppm}_{\text{mol}}(CH_4) = 2.871\text{x}10^{12}\,\text{kg}$
H_2O abundance conversion	$1\,\text{ppm}_{\text{mol}}(H_2O) = 3.249\text{x}10^{12}\,\text{kg}$

Appendix B: The greenhouse effect

Earth's greenhouse effect is produced by trace gases in the atmosphere that interact with outgoing thermal radiation more strongly than they do with incoming sunlight.

This selective interaction is a type of inelastic scattering that occurs because the molecules of these particular gases have low lying excited states that can easily absorb low energy thermal photons from the earth's surface but not the much higher energy photons from the sun. The absorbed photon energy is released whenever an absorbing molecule returns to its ground state, but because the released photons are emitted in more or less random directions while absorption comes mostly from below, the net result is that about half the radiant energy per interaction returns to the surface rather than continuing on into space.

To account for these effects, consider a beam of photons passing upward through a volume of absorbing gases. The power absorbed from this beam between elevation z and $z + \text{d}z$ is

$$\text{d}P(z) = -P(z) \sum_k n_k(z)\ \text{d}A\ \text{d}z \int_0^\infty \text{d}\lambda\ a_k(\lambda)\quad , \qquad \text{(B1)}$$

where $P(z)$ is the beam power at elevation z, $n_k(z)$ is the number of gas molecules of species k per unit volume at elevation z, $\mathrm{d}A$ is the area of the beam perpendicular to its direction of propagation, and $a_k(\lambda)$ is the probability that a photon of wavelength λ will be returned to earth by any process that involves a single molecule of species k. (Since we will take $\mathrm{d}z \to 0$, we need not consider more than one interaction for any given photon.) This expression integrates over all wavelengths and coordinates to give

$$P_t = P_r \mathrm{e}^{-\sum_k N_k/s_k} = P_r \prod_k \mathrm{e}^{-N_k/s_k} = P_r \varepsilon_s \quad , \tag{B2}$$

where P_t is the power transmitted through the atmosphere and radiated into space, P_r is the power radiated from the surface, s_k^{-1} is the probability $a_k(\lambda)$ integrated over all wavelengths, N_k is the total number of molecules of species k in the atmosphere, and ε_s is the emissivity factor arising from scattering in the atmosphere.

For any set of changes $N_k \to N_k + \delta N_k$, Eq.(B2) gives for the change in the scattering emissivity factor

$$\delta\varepsilon_s = -\varepsilon_s \sum_k \delta N_k / s_k \quad . \tag{B3}$$

These results are useful because they describe the functional relationship between the overall photon transmission rate and the quantity of absorbing gas present without requiring knowledge of the underlying interaction or transport details. The parameters s_k can be fitted to empirical data and thereby include both direct and indirect processes, including feedbacks that amplify or diminish the overall effect.

It's convenient because N_k can represent any linear measure of molecule count so long as the associated scale depth s_k is adjusted appropriately, expressed in the same units. Mass, for example, can be used so long as the molecular masses are accounted for properly.

Appendix C: Principal greenhouse gas properties

Of all the gases in the atmosphere that interact strongly with thermal radiation, the most important for climate regulation are water vapor (H_2O), carbon dioxide (CO_2), and methane (CH_4). These three gases have very different properties from each other, and they affect the climate in very different ways.

All of these gases occur naturally, in the sense that they are produced and removed independent of human activity in concentrations that are stable over the time periods of interest here. They also occur to varying degrees as consequences of human activity.

Water (H_2O)

The most important short-term greenhouse gas is H_2O. It is by far the most abundant of the three, comprising on average about 0.25% of all atmospheric molecules (mole fraction) at any particular time. It also has a high thermal photon interaction rate. But its molecules remain in the atmosphere for only a few days because they stick together to form droplets or crystals that quickly become heavy enough to precipitate out as rain or snow. So long as the surface temperature is below its boiling point, water remains present in the atmosphere long enough to affect our climate only when it is continually replenished.

Water enters the atmosphere naturally by evaporation from the planet's water surfaces, sublimation from snow and ice, and other processes such as transpiration from plants and animal excretions.

Human activity affects atmospheric water concentrations also through higher order effects that are consequences of human induced temperature changes, at rates that are relatively insignificant but generally greater than those generated directly (e.g., as combustion products).

Carbon dioxide (CO_2)

The most important long term greenhouse gas is CO_2. It absorbs less energy per molecule than H_2O or CH_4, but it is abundant enough (417ppm mole fraction in 2022) and long lived enough (years to centuries to millennia, depending on altitude and weather) to affect the climate permanently so far as human time scales are concerned.

Most of the CO_2 in the atmosphere enters near the surface and is transported upward by convection or diffusion, some of it rising as far as the stratosphere. It does not precipitate out as water does because its molecules don't stick to each other. But it dissolves in water, so some of it returns to earth in rain or snow. The remainder either returns eventually by atmospheric convection and absorption by plants or surface water, or remains until it decomposes or reacts with other atmospheric chemicals.

About half of the CO_2 in our atmosphere at present is natural, much of it an essential part of the carbon cycle that maintains living animals and plants through oxidation and photosynthesis, which continuously convert O_2 to CO_2 and back again. When these conversion rates are in balance, these natural processes establish and maintain surface temperatures that can remain stable for many millions of years.

The remaining CO_2 is produced by human activity, primarily through the burning of hydrocarbon fuels that release CO_2 and H_2O through the elementary reaction

$$2CH_2 + 3O_2 \rightarrow 2CO_2 + 2H_2O + \text{heat}. \quad \text{(C1)}$$

Around 90% of this CO_2 enters the atmosphere near the surface and is subject to the same transport mechanisms as natural CO_2. The remaining 10% is injected directly into the stratosphere by hydrocarbon fueled jet air traffic.

Removing this excess CO_2 from the atmosphere on time scales useful for human society is problematic at least partly because the processes involved in Eq.(B1) are exothermic and thermodynamically irreversible. Reversing the combustion process requires external energy input, which occurs naturally in processes such as photosynthesis driven by sunlight but is problematic by artificial methods.

Methane (CH_4)

The least abundant of the three major greenhouse gases is CH_4, which occurred at about 1.87ppm mole fraction in 2022. It's a stronger greenhouse gas than CO_2, absorbing approximately 31 times as much energy per molecule. But it remains in the atmosphere for only a few years, mainly because it is more reactive than the others. In the presence of O_2, for example, it is converted to the other two through the same oxidation process as combustion, *i.e.*, the reaction $CH_4+2O_2 \rightarrow CO_2+2H_2O$, and so has direct long term effects only as a minor part of the sequence that produces them. This direct contribution to the greenhouse effect is most important during the intermediate period before it decomposes. Like H_2O, CH_4 contributes directly to the long term greenhouse effect only when it is continually replenished.

Methane is probably most important for climate change as a trigger and driver for the melting of sea ice, which feeds back into Eq.(5a) as an increase in absorptivity arising from the associated change of surface area from highly reflecting to highly absorbing. This effect is nonlinear, and at the moment is accelerating at a rate that may already be past its tipping point.

As the simplest hydrocarbon molecule, methane is generated in numerous processes both natural and anthropogenic. Natural processes include the decomposition of dead organic matter, which provides positive feedback through the melting of permafrost and the subsequent exposure of methane bearing soil to the atmosphere. Human sources include the mining of fossil fuels and the livestock industry, where there exist opportunities to control or contain it that have traditionally been neglected.

Appendix D: Some elements of hydrocarbon fuel chemistry

Hydrocarbon fuel molecules are built around a core of carbon and hydrogen atoms bonded together. They burn by breaking the carbon-hydrogen bonds and attaching oxygen atoms to the fragments, as in the basic subreaction

$$2CH_2 + 3O_2 \rightarrow 2CO_2 + 2H_2O + \text{energy(heat)} \ . \qquad \text{(D1)}$$

This reaction is exothermic because the total molecular binding energy on the right hand side is greater than that on the left. The reverse reaction is endothermic, *i.e.*, energy must be added from an external source to drive it.

The simplest hydrocarbon fuel is methane (CH_4), a gas that burns according to

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{heat} \ . \qquad \text{(D2)}$$

Because CH_4 is a more powerful greenhouse gas than CO_2 , burning it is better than dumping it into the atmosphere so far as climate change is concerned. The same is true of the other light hydrocarbons that exist as gases under standard conditions (*e.g.*, ethane, propane, butane).

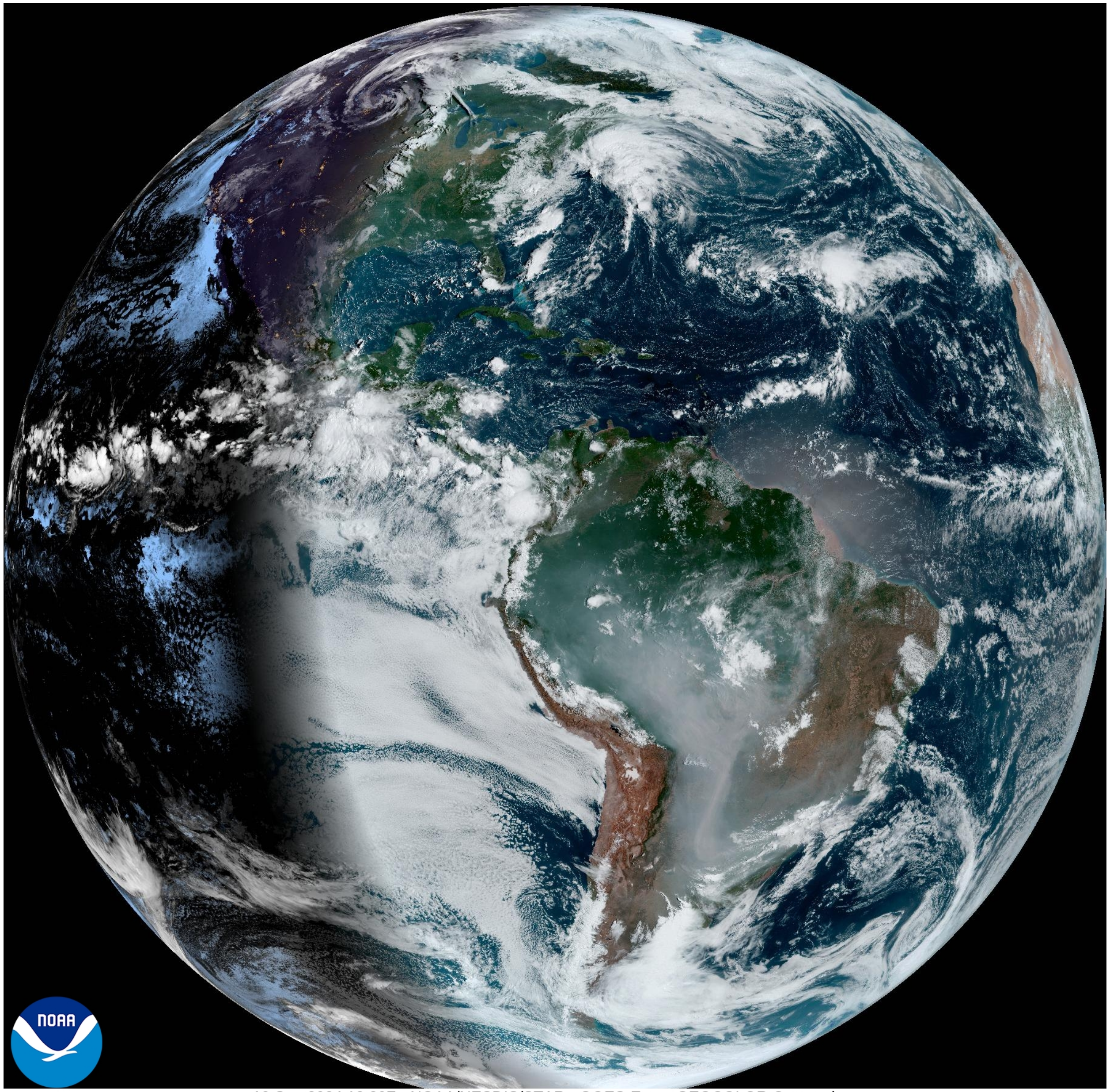
A major constituent of gasoline is octane (C_8H_{18}), a liquid that burns according to

$$2C_8H_{18} + 25O_2 \rightarrow 16CO_2 + 18H_2O + \text{heat} \ . \qquad \text{(D3)}$$

Molecular masses for this reaction are

$$228 + 800 \rightarrow 704 + 324 \ , \qquad \text{(D4)}$$

which shows that for every mass unit of C_8H_{18} burned, $704/228 \approx 3$ mass units of CO_2 are produced. Since gasoline has a density of about 6.3 pounds per gallon, this means that every gallon of gasoline you burn generates about 19 pounds of carbon dioxide. If you get the current international average of around 22mpg, that's almost a pound per mile. If there are one billion vehicles on the road, each driven 10,000 miles per year with that mileage, that's 4Gt per year, about 10% of the total CO_2 load humans are adding as of 2020.



19 Sep 2024 13:20Z - NOAA/NESDIS/STAR - GOES-East - GEOCOLOR Composite

Notes:

1. Solar radiation is visible
   =>light areas reflect
   dark areas absorb

2. Thermal radiation invisible
   =>what you see is not
   what you get

3. Polar illumination angle is
   always low
   =>average insolation is
   reduced

4. Fires in South America

5. Looks like a complicated mess
   to analyze

Address complexity by averaging over day and year:

Energy balance: heat capacity * temperature change rate
= rate energy absorbed – rate energy emitted

$$\eta C_O \frac{dT}{dt} = \alpha P_S - \varepsilon S \sigma_B T^4$$

$0<\eta<1$ = fraction of global ocean that absorbs and distributes heat

C_O = global ocean heat capacity (JK^{-1})
= global ocean mass * specific heat of water

T = absolute temperature of surface (K)

t = time (years)

$0<\alpha<1$ = absorptivity
= fraction of incident energy absorbed
= fraction not reflected * fraction absorbed at surface

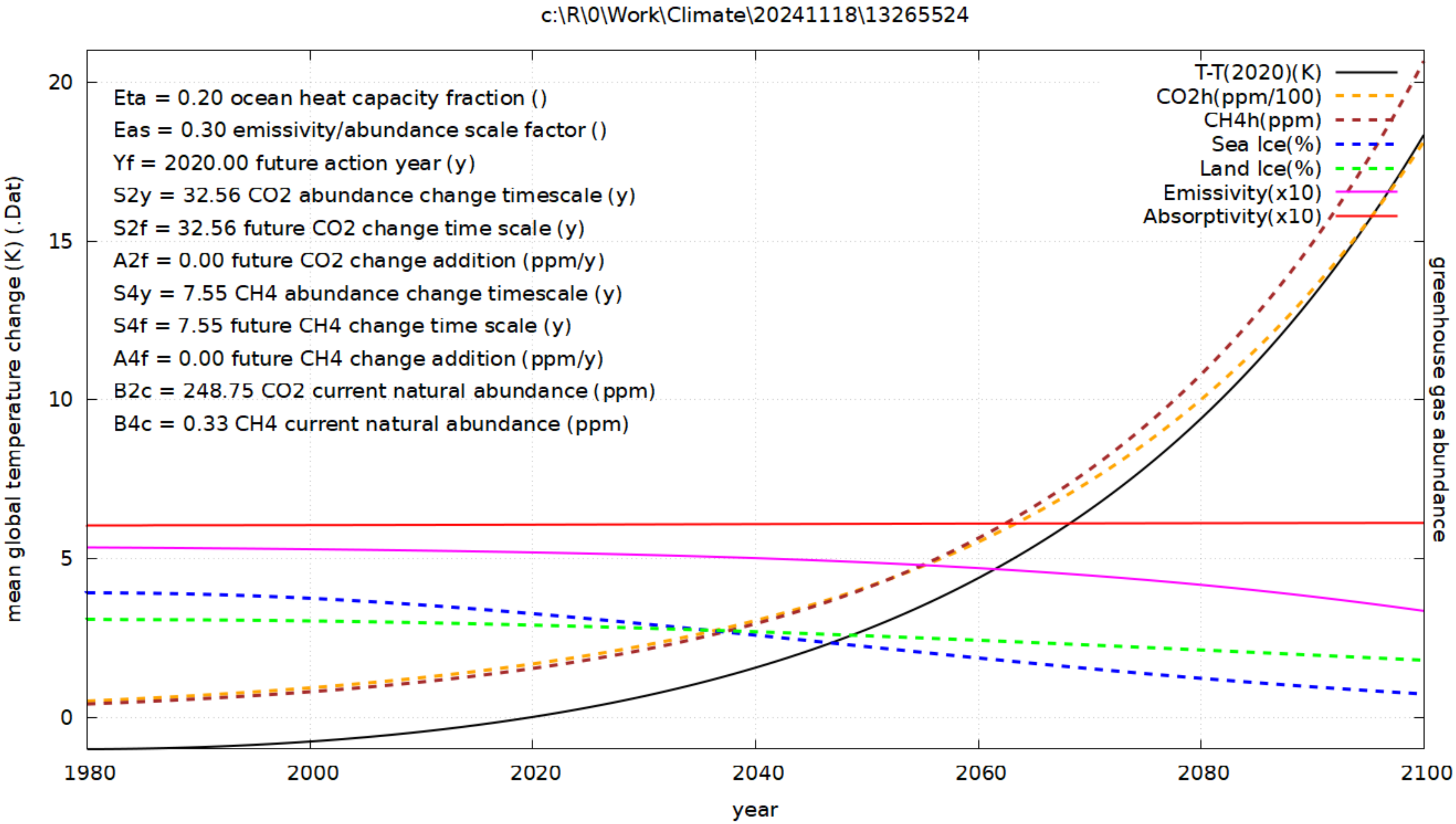
$P_S = \frac{L r^2}{4 R^2}$ = rate of incident energy
= solar luminosity (J/year) * geometrical factor (¼)

$0<\varepsilon<1$ = fraction of blackbody radiation emitted
= fraction emitted from surface * fraction not returned

$S = 4\pi r^2$ = Earth surface area

σ_B = Stefan-Boltzmann blackbody radiation constant
= $5.67 \times 10^{-8} Js^{-1}m^{-2}K^{-4}$ * s/year

NOTE: *This equation must be obeyed for suitable average values no matter how complicated the internal details might be*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B4c = 0.33 CH4 current natural abundance (ppm)
T-T(2020)(K)
CO2h(ppm/100)
CH4h(ppm)
Sea Ice(%)
Land Ice(%)
Emissivity(x10)
Absorptivity(x10)
mean global temperature change (K) (.Dat)
greenhouse gas abundance
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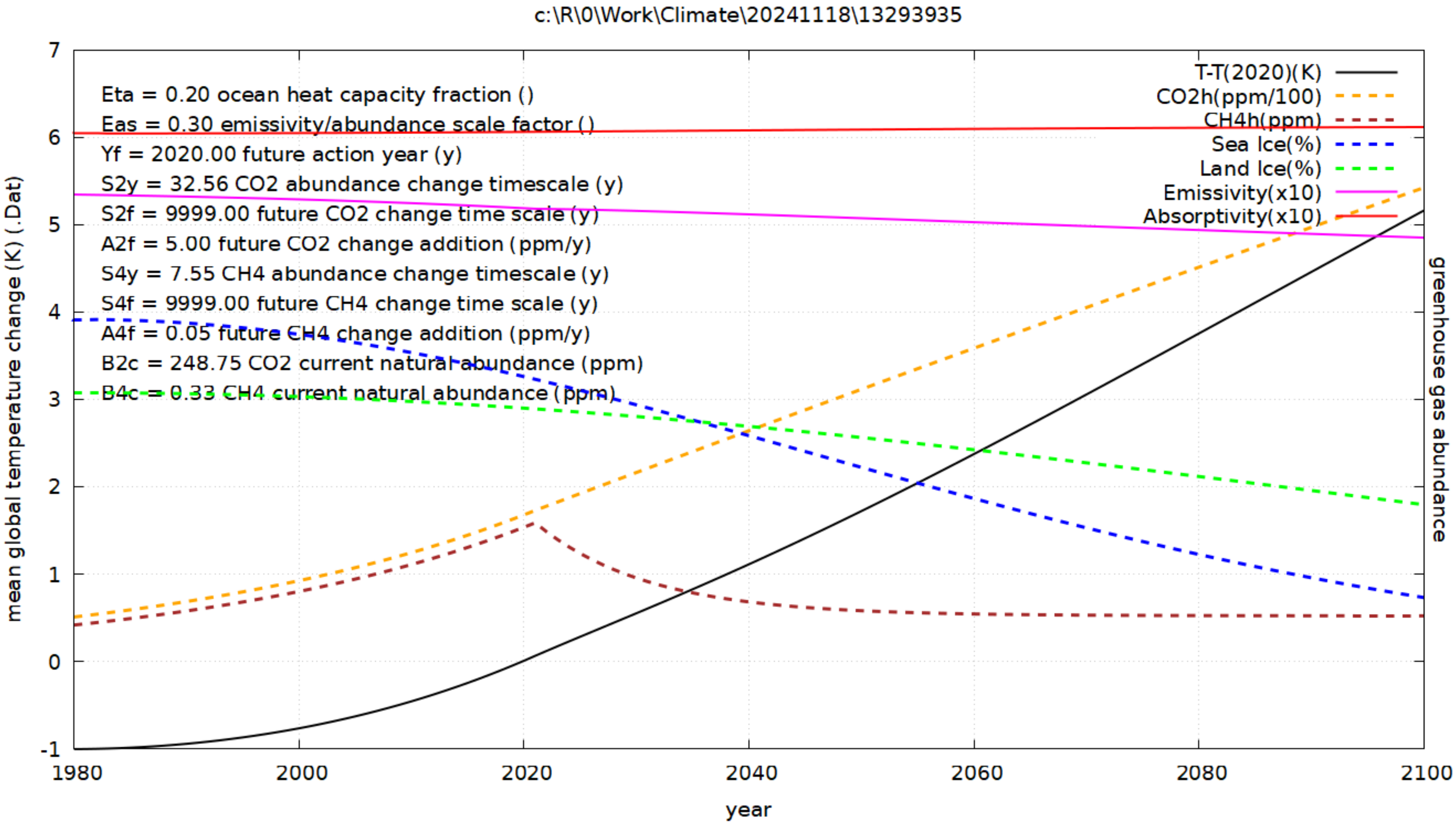
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CH4h(ppm)
Sea Ice(%)
Land Ice(%)
Emissivity(x10)
Absorptivity(x10)
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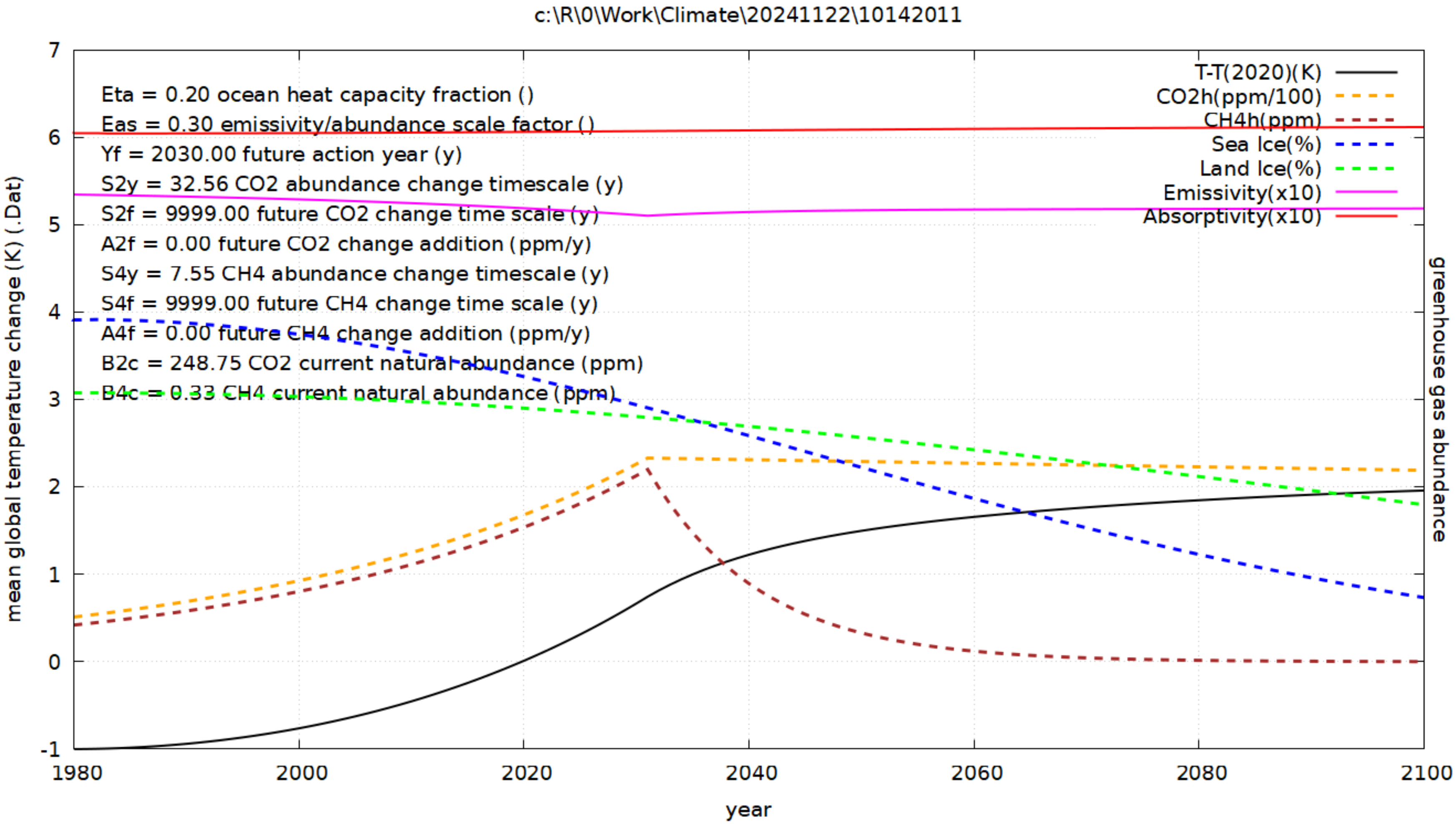
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Land Ice(%)
Emissivity(x10)
Absorptivity(x10)
mean global temperature change (K) (.Dat)
greenhouse gas abundance
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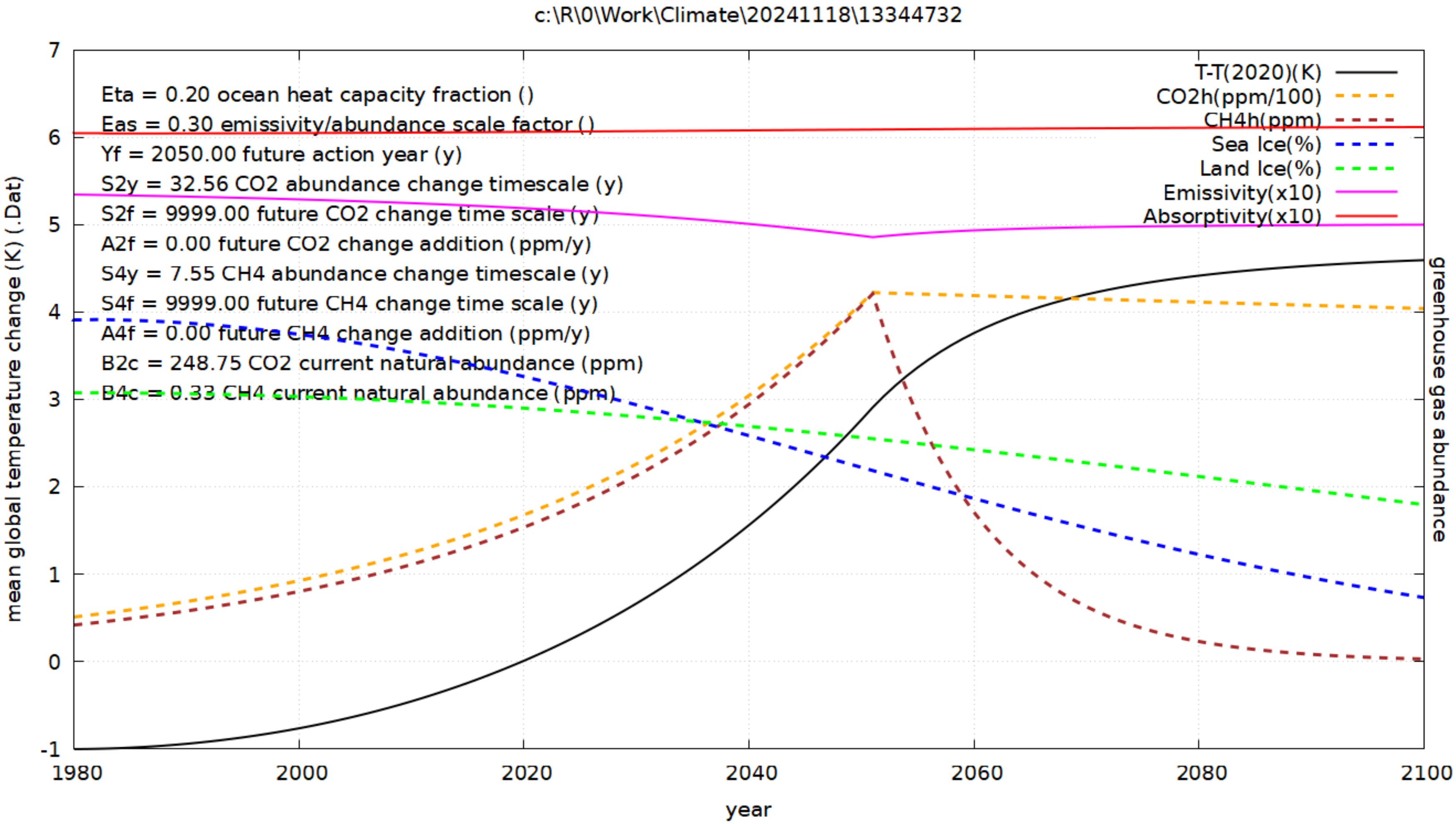
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S4f = 9999.00 future CH4 change time scale (y)
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