Economics of Climate Change in the Face of Uncertainty [1]

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Overview

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Basic Heat Balance Model

The Basic Heat Model as in North et al. ('NCC') (1981) is:

$$\begin{aligned}
\sigma_0(1-\alpha_p)\pi R^2 &= 4\pi R^2 \sigma T_R^4 \\
\sigma_0 &= 1340 W/m^2 \\
\sigma &= 0.56687 \times 10^{-7} W/m^2 K^4 \\
\alpha_p &= \int_{-1}^{1} S(x)\alpha(x)dx \\
T_R &= \text{ equilibrium global temperature}
\end{aligned} \tag{1a}$$

where σ is the Stefan Boltzman constant.

$$\begin{aligned}
S(x) &= 1 - 0.477 P_2(x) \quad , P_2(x) = (1/2)(3x^2 - 1) \\
x &= \sin(\text{latitude}) \\
\alpha_p &= \text{ albedo } \approx 0.3
\end{aligned} \tag{1b}$$

Basic Heat Balance Model + Atmosphere I

As in Budyko (1977) and NCC (1981), who approximate (1) with atmosphere effect as:

$$
\begin{aligned}
\underbrace{(\sigma_0/4)(1-\alpha_p)}_{\text{incoming solar radiation}} &= \underbrace{A + BT_g}_{\text{parameterized outgoing long wave radiation}} \\
T_g &= 14.93C + 273.15 = 288.08K \\
T_g &= 14.93 \times 9/5 + 32 = 58.74F \\
A &= 203.3W/m^2, \quad B = 2.09W/m^2C \\
\sigma_0/4 &= 1340/4 = 335W/m^2 \\
1-\alpha_p &= 0.7
\end{aligned} \tag{2}
$$

where T_g is close to Northern Hemisphere temperature and not far off from global temperature.

Important literature on multiple equilibria caused by feedbacks:

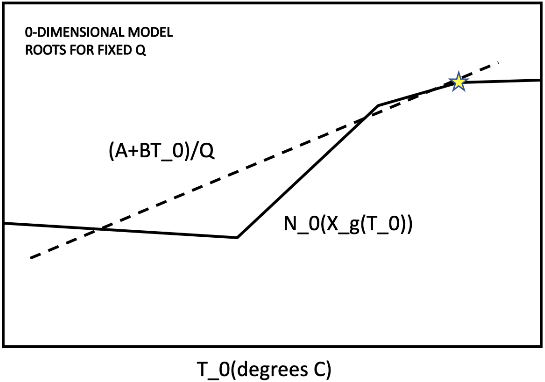


Figure: A cartoon sketch of figure 1 of NCC (1981)

Atmospheric Heat Balance Model + Dynamics and Radiative Forcing I

Additional RF term caused by humans to the atmospheric heat balanced model:

$$\begin{aligned} &d(T_g + T)/dt = (\sigma_0/4)(1-\alpha_F) - (A + B(T_g + T)) + RF \implies \\ &dT/dt = -BT + RF \end{aligned} \tag{3}$$

T is the temperature 'anomaly' ($T \approx 1.1$)

$$RF \approx 5.35 \ln\left(\frac{C_t}{C_0}\right) \text{ (Arrhenius's Law)} \tag{4}$$

C_t is atmospheric content in ppm at date t
($C_{2021} \approx 415$ ppm , $C_{1750} \approx 280$ ppm)
(1 ppm ≈ 2.13 GtC)
Set $dT/dt = 0$ and use Arrhenius's Law:

$$T = (1/2.09)5.35 \ln\left(\frac{415}{280}\right) = 2.105/2.09 = 1.01 \tag{5}$$

Atmospheric Heat Model + Dynamics and Radiative Forcing II

'Averaged across land and ocean, the 2020 surface temperature was 1.76°F (0.98°Celsius) warmer than the twentieth-century average of 57.0°F (13.9°C) and 2.14 °F (1.19 °C) warmer than the pre-industrial period (1880-1900).'

Source: https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature

Matthews' Approximation

Including reaction of biosphere into *RF* term leads to an approximation by Matthews et al (2009):

$$T_t - T_0 \approx \beta \int_0^t E_s ds \tag{6}$$

where:

β is the Cumulative Carbon Response (CCR) or the Transient Climate Response to Cumulative Emissions (TCRE)

E_s is the emissions in gigatons of carbon (3.67 C02 equals one carbon) at time s

There is large uncertainty in β!

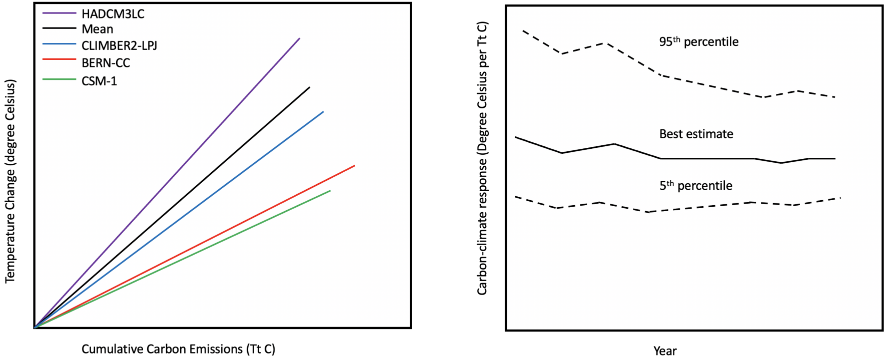


Figure: A cartoon sketch of figure 3 and figure 4 of Matthews et al (2009)

Matthews' Approximation

Nevertheless, Matthews' Approximation is fairly good

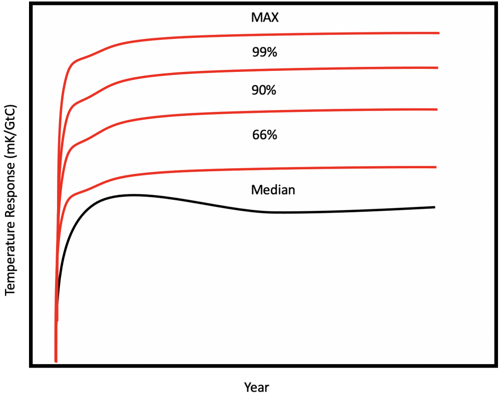


Figure: A cartoon sketch of figure 1 in Ricke and Caldeira (2014)

Cartoon Climate-Economics Model I

We are interested in the interactions between economics and the climate:

$$
\begin{aligned}
&\max_{[E_t]_{t=0}^{\infty}} \int_0^{\infty} e^{-\rho t} U(E_t, T_t) dt = \max_{[E_t]_{t=0}^{\infty}} \int_0^{\infty} e^{-\rho t} \left(\ln(E_t) - \gamma T_t\right) dt \\
&\text{s.t.} \quad dT_t/dt = -BT_t + 5.35 \ln(\frac{C_t}{C_0}), \text{ Given } T_0 \text{ (Arrhenius/ NCC 1981)} \\
&\qquad \text{or} \\
&\qquad dT/dt = \beta E_t, \text{ Given } T_0, \text{ (Matthews et al (2008))} \\
&\qquad\qquad E_t = \text{ Carbon Emissions at time } t \\
&\qquad\qquad T_t = \text{ Temperature Anomaly at time } t \\
&\qquad\qquad C_t = \text{ Carbon in ppm at time } t
\end{aligned} \tag{7}
$$

Simple extensions include adding clean energy

Cartoon Climate-Economics Model II

Key Parameter: $\rho > 0$ is subjective time preference.
Market Discount Rate as the 'Ramsey Rule'
Here C_t is consumption not Emissions

$$r = \rho - d/dt \ln U_{C_t} = \rho - U_{C_t C_t} C_t / U_{C_t} (d/dt \ln C_t) = \rho + \eta g \qquad \text{(R)}$$

where η is elasticity of marginal utility of consumption and g is the growth rate of the economy.

Cartoon Climate-Economics Model IV

- Ramsey and Lord Stern thinks discount rate should be lower than the market rate (Dasgupta (2020) for the debate)
- Stochastic version of (R) is called the 'Stochastic Discount Factor' (SDF) (see Cai, Judd, and Lontzek (2017); Cai and Lontzek (2019); Barnett et al (2020), Hansen (2021))

Cartoon Climate-Economics Model V

Hansen (2021) reviews important contributions that show how the SDF is adjusted for broader notions of uncertainty that go beyond risk (where probabilities are known). Donald Rumsfeld once said:

'Reports that say that something hasn't happened are always interesting to me, because as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns—the ones we don't know we don't know. And if one looks throughout the history of our country and other free countries, it is the latter category that tends to be the difficult ones.'

Source: https://archive.ph/20180320091111/http://archive.defense.gov/Transcripts/Transcript.aspx?TranscriptID=2636

Cartoon Climate-Economics Model V

- CES payoff function: $U(E,T) = (aE^\rho + (1-a)Q(T)^\rho)^{\frac{1}{\rho}}$
  - $Q(T)$ is 'climate quality' and decreases in T
  - $\sigma \equiv \frac{1}{1-\rho}$
- If $\sigma \in [0,1)$, payoff is 'climate limited'
  - If $E \to \infty$ and $Q(T)$ fixed what happens to U?

Usefulness of Matthews' Approximation

- Temperature anomaly is proportional to cumulative emissions β
- However, β varies across AOGCMs $\implies$ useful for model uncertainty.

A Toy Energy-Only Model With HJB Equation I

We reformulate the simple Cartoon Climate-Economics problem into a dynamic programming problem:

$$\rho V(T) = \max_{E} U(E, T) + V_T \beta E = \max_{E} \ln E - \gamma T + V_T \beta E$$
$$\rho(a_0 + a_1 T) = \ln(1/(-\beta V_T)) - \gamma T + \left(\frac{-V_T \beta}{\beta V_T}\right) =$$
$$\ln(1/(-\beta a_1)) - 1 - \gamma T \implies a_1 = -\gamma/\rho, a_0 = (1/\rho)\ln(\rho/\beta\gamma) - 1/\rho \tag{8}$$

A Toy Energy-Only Model With HJB Equation II

We add misspecification concerns about specification of the temperature dynamics, and smooth ambiguity aversion:

$$\rho V(T) = \max_{E} \min_{w_i, i=1,\ldots,J,h} U(E,T) + V_T \left(\sum_{i=1}^{J} w_i \beta_i E + \sigma h \right) + \xi_p h^2/2 + \xi_a \sum_{j=1}^{J} w_j \left(\ln w_j - \ln \pi_j \right) + 1/2 V_{TT} \sigma^2 \tag{9}$$

Equation (9) is an oversimplified cartoon illustration of a small part of Barnett et al (2021), 'Climate Change Uncertainty Spillover in the Macroeconomy'

A Toy Energy-Only Model With HJB Equation III

- Recall that HJB (8) has closed form solution
- How to get closed form solution for HJB (9)?
- Re-scale parameters σ, ξ_p such that:
- $V_{TT}\sigma^2$ vanishes, but...
- $V_T\sigma/\xi_p = -h$ (10) remains

Sources of Feedback Nonlinearities I

- Earth contains multiple nonlinear feedback loops which include:
  - Boreal Forest Dieback
  - Atlantic Deepwater Formation
  - Amazon Rainforest Dieback
  - Sahara Greening
  - Indian Monsoon Chaotic Multistability
  - Permafrost of Tundra Lost
  - Instability of West Antarctic Ice Sheet
- Source: Lenton et al (2019)

Sources of Feedback Nonlinearities II

An interesting phenomenon is the hydrologic cycle:

$$\frac{E' - P'}{E - P} \approx \alpha T'$$

where primes denote the change and

the Clausius-Clapeyron Scaling Factor is

$$\alpha = \frac{L}{R_\nu T^2}$$

where L is the latent heat of vaporization

R_v is the gas constant of water vapor

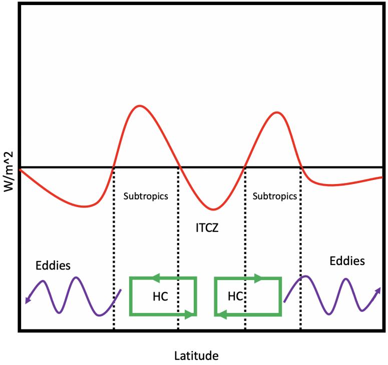


Figure: Cartoon Sketch of Siler et al (2018) Figure 1

Sources of Feedback Nonlinearities III

- Seasonal Cycles/Oscillations such as...
  - Madden Julian Oscillation (MJO, period $\approx$ 50 days
  - El Nino-Southern Oscillation (ENSO, period $\approx$ 2-7 years)
  - North Atlantic Oscillation (NAO, period $\approx$ NA)
- Generate interesting dynamics in the Earth System (see Ghil and Lucarini (2020) for literature review)
- Adds additional challenges for attribution!

Climate Budget I

According to Matthews et al (2009), to stay in the boundaries of 'Paris' 1.5 degrees limit until 2100, given a temperature anomaly at 1.1 degrees, yearly carbon emissions would need to be:

$$\frac{(1.5-1.1)^{\circ}\mathrm{C}}{1.6^{\circ}\mathrm{C}/\ \mathrm{TtC}} = .25\ \mathrm{TtC}\ = 250\ \mathrm{GtC}$$

and within 2 degrees yearly carbon emissions would need to be:

$$\frac{(2-1.1)^{\circ}\mathrm{C}}{1.6^{\circ}\mathrm{C}/\ \mathrm{TtC}} = .5625\ \mathrm{TtC}\ = 562.5\ \mathrm{GtC}$$

But, there is large uncertainties among the AOGCMs!

Climate Budget II

'Accounting for observational uncertainty and uncertainty in historical non-CO_2 radiative forcing gives a best-estimate from the historical record of 1.84 °C/TtC (1.43–2.37 °C/TtC 5–95% uncertainty) for the effective TCRE and 1.31 °C/TtC (0.88–2.60 °C/TtC 5–95% uncertainty) for the CO_2-only TCRE. While the best-estimate TCRE lies in the lower half of the IPCC likely range, the high upper bound is associated with the not-ruled-out possibility of a strongly negative aerosol forcing.'

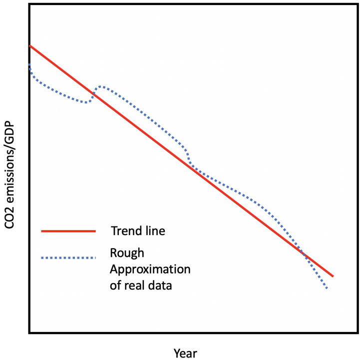
Source: Millar and Friedlingstein (2018)

Climate Budget III

'Based on our best-estimate of the historical effective TCRE (1.84 °C/TtC), assuming a constant effective TCRE into the future would be compatible with a best-estimate 520 GtC remaining budget (approx. 47 years of current emissions—all budgets given to nearest 5 GtC) for 2 °C and 250 GtC (approx. 23 years of current emissions) for 1.5 °C.'

Source: Millar and Friedlingstein (2018).

However, in actual policy making one needs to take into account the preferences including attitudes towards risk and broader notions of uncertainty of the society that the policymaker represents. See Barnett et al (2020, 2021) and Hansen (2021) for this kind of approach to carbon budgeting.



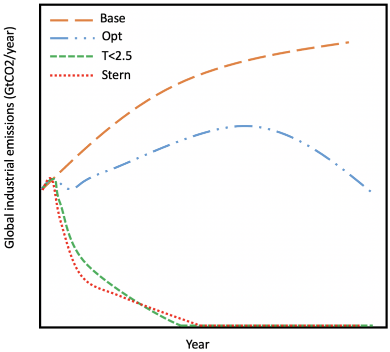


Figure: A cartoon sketch of figure 1 and figure 2 of Nordhaus 2018

Social Cost of Carbon I

The Social Cost of Carbon (SCC) is the optimal carbon tax.
Nordhaus (2017) uses the following function as the SCC:

$$SCC_t = \frac{\frac{\partial U(C_t, E_t, T_t)}{\partial E_t}}{\frac{\partial U(C_t, E_t, T_t)}{\partial C_t}} \tag{10}$$

Optimal carbon taxes under Biden and Obama was around 50 dollars per ton in 2020 dollars.

Cai and Lontzek (2019) wrote that:

‘After converting the SCC to \$/tC, they report that the 5th, 25th, 50th, 75th, and 95th percentile values are \$15, \$33, \$51, \$102, and \$238/tC, respectively.’

'DSICE, however, can also determine the stochastic features of the SCC process. The SCC is the shadow price of a state variable and, as we expect, is approximately a random walk. When we quantify the SCC process, we find that it displays substantial variance. For example, in our benchmark case the median SCC is $286/tC in 2100, but with a 10 percent chance of exceeding $700/tC and a 1 percent chance of exceeding $1,200/tC. In general, the standard deviation of the SCC grows faster than its mean.'

Source: Cai and Lontzek (2019)

Social Cost of Carbon III

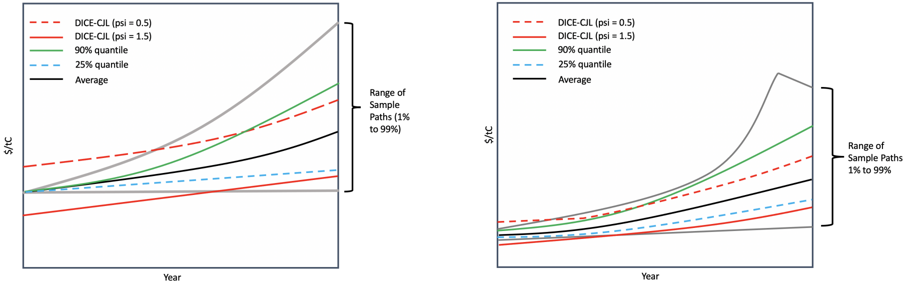


Figure: A cartoon sketch of figure 1 (SCC) and figure 2 (Carbon Tax) of Cai and Lontzek (2019)

Social Cost of Carbon IV

'Figure 1 displays the SCC process for 2005–50. First, note that moving from the DICE-2007 choice of ψ=.5 to our benchmark choice of ψ=1.5 substantially increases the SCC. However, when we add uncertainty with $\gamma = 10$, we see a decline in the SCC to \$61/tC, which is still higher than that implied by DICE-2007 preferences. During 2005–50, we see that the no-risk line (dashed red line) exceeds the average SCC with long-run risk (black line) by about \$50/tC. Therefore, in the next half-century, uncertainty reduces the SCC.We discuss the intuition for this below when we carry out sensitivity analysis. The productivity risk does substantially increase the range of the SCC.'

Source: Cai and Lontzek (2019)

Social Cost of Carbon V

However, Cai and Lontzek (2019), and the earlier important foundation paper, Cai, Judd, and Lontzek (2017), only adjust for risk (where probabilities are known). See Hansen (2021) for approaches that adjust for broad concepts of uncertainty.

Social Cost of Carbon V

- Alternative to carbon tax is 'cap and trade'.
- Professor Chichilnisky's scheme: allocate the bulk of the emissions rights to poorer nations and small allotments to the long-time emitters like G7, U.S., and Canada (Chichilnisky and Sheeran (2009): 'Saving Kyoto').

Space and Heat Poleward Tansport I

- Current frontier of climate economics: Heat Balanced Model + Spatial Components.
- We follow NCC (1981) without endogenous ice line (implies constant co-albedo).
- The equation for the temperature anomaly is:

$$dT(x)/dt = -BT(x) + D\partial/\partial x\left[(1 - x^2)\partial T(x)/\partial x\right] + \beta E \tag{11}$$

where $D, T(x), \beta, E$ are heat diffusion parameter, temperature anomaly at latitude x, TCRE parameter and emissions.
We assume emissions into the atmosphere diffuse rapidly across latitudes.

Space and Heat Poleward Tansport II

Expand temperature by noting that the even-numbered Legendre polynomials $P_n(x)$ form a orthogonal basis set:

$$
\begin{aligned}
T(x) &= \sum_{n(\text{even})} T_n P_n(x) \\
\int_0^1 P_n(x) P_m(x) dx &= \frac{\delta_{mn}}{2n+1}, \quad m, n \text{ even}
\end{aligned}
\tag{12}
$$

The eigenvalue problem is the following:

$$
-\frac{d}{dx}\left(1 - x^2\right)\frac{dP_n(x)}{dx} = n(n+1)P_n(x) \tag{13}
$$

Substitute the orthogonal basis representation of the temperature anomaly into (11):

$$d\left(\sum_{n(\text{even})} T_n P_n(x)\right)/dt =$$

$$-B\sum_{n(\text{even})} T_n P_n(x) + D\partial/\partial x\left[\left(1-x^2\right)\partial \sum_{n(\text{even})} T_n P_n(x)/\partial x\right] + \beta E$$

$$= -B\sum_{n(\text{even})} T_n P_n(x) - D\sum_{n(\text{even})} n(n+1)T_n P_n(x) + \beta E \implies$$

$$dT_0/dt = -BT_0 + \beta E, \quad dT_n/dt = -BT_n - Dn(n+1)T_n$$

$$\{T_n(0)\} \text{ given from } T_0(x) = \sum_{n(\text{even})} T_n(0)P_n(x) \tag{14}$$

Space and Heat Poleward Tansport IV

Why is space and heat transport important?

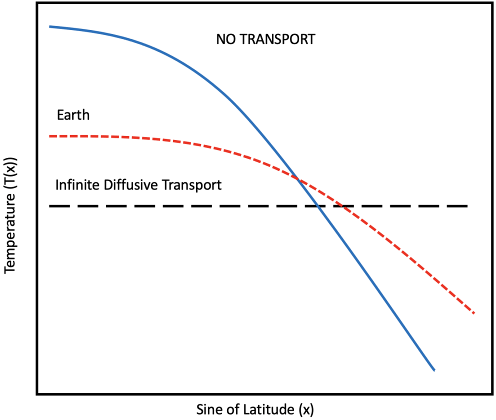


Figure: Cartoon figure 4 of NCC (1981)

Space and Heat Poleward Tansport V

For a very recent work on poleward uncertainty look at Trenberth et al (2019)

Global Welfare Maximization Problem I

We can pose the global welfare maximization problem into:

$$
\begin{aligned}
\max_{[E_t]_{t=0}^{\infty}} \quad & \int_0^{\infty} e^{-\rho t} \int_{-1}^{1} w(x) U(E_t(x), T_t(x)) dxdt \\
\text{s.t.} \quad & dT_t(x)/dt = -BT_t(x) + D\partial/\partial x \left[(1-x^2)\partial T_t(x)/\partial x\right] + \beta E_t \\
& E_t = \int_{-1}^{1} E_t(x) dx \text{ or} \\
& \int_{-1}^{1} \int_0^{\infty} E_t(x) dxdt \leq R_0 \text{ Finite Reserve}
\end{aligned}
\tag{15}
$$

where R_0 is total reserves and $w(x)$ is the weights

Global Welfare Maximization Problem II

Consider a simpler two box heat moisture transport model by Langen and Alexeev (2007) used as a climate dynamics module for an economic model by Brock and Xepapadeas (2017):

$$
\begin{aligned}
& \max_{[E_{it}]_{t=0}^{\infty}} \int_0^{\infty} e^{-\rho t} \sum_{i=1}^{2} w_i U_i(E_{it}, T_{t1}, T_{t2}) dt \\
= & \max_{[E_{it}]_{t=0}^{\infty}} \int_0^{\infty} e^{-\rho t} \sum_{i=1}^{2} w_i (1-\eta_i) \ln(E_{it}) - (1-\eta_i) d_i T_{it} dt \\
\text{s.t.} \quad & \ln \Gamma_i(T_{it}) = d_i T_{it} \\
& dT_{1t}/dt = (-B-\gamma_1-\gamma_2) T_{1t} + \gamma_1 T_{2t} + \beta E_t/2 \\
& dT_{2t}/dt = (\gamma_1+\gamma_2) T_{1t} - (B+\gamma_1) T_{2t} + \beta E_t/2 \\
& T_t \equiv T_{1t} + T_{2t}, \quad dT_t/dt = -BT_t + \beta E_t \\
& \bar{T}_t \equiv (T_{1t} + T_{2t})/2, \quad d\bar{T}_t/dt = -B\bar{T}_t + \beta E_t/2 \\
& T_i(0) = T_{i0}, \quad i = 1, 2
\end{aligned}
\tag{16}
$$

Global Welfare Maximization Problem III

Scovronick et al (2019) extend Nordhaus's Regional Integrated Climate-Economics (RICE) model to include health damages besides climate damages from the world's emissions of fossil fuels. They say:

'Depending on how society values better health, economically optimal levels of mitigation may be consistent with a target of 2 °C or lower.'

However they (and even much of the recent literature in climate economics) do not include uncertainties and dynamics of poleward heat moisture transport much less including the extensive climate dynamics discussed by Ghil and Lucarini (2020). A rich area of future research awaits.

References I

Barnett, M., Brock, W., & Hansen, L. P. (2020).
Pricing uncertainty induced by climate change. The Review of Financial Studies, 33(3), 1024–1066.
https://doi.org/10.1093/rfs/hhz144

Barnett, M., Brock, W., & Hansen, L. P. (2021).
Climate change uncertainty spillover in the macroeconomy. In NBER Macroeconomics Annual 2021, volume 36. University of Chicago Press. https://www.nber.org/books-and-chapters/nber-macroeconomics-annual-2021-volume-36/climate-change-uncertainty-spillover-macroeconomy

Brock W. & Xepapadeas A. (2017).
Climate change policy under polar amplification. (2017). European Economic Review, 99, 93–112.
https://doi.org/10.1016/j.euroecorev.2017.06.008

References II

Budyko, M. I. (1977).
On present-day climatic changes. Tellus, 29(3), 193–204.
https://doi.org/10.3402/tellusa.v29i3.11347

Cai, Y., & Lontzek, T. S. (2019).
The social cost of carbon with economic and climate risks. Journal of Political Economy, 127(6), 2684–2734.
https://doi.org/10.1086/701890

Cai, Y., Judd, Kenneth L., & Lontzek, T. S. (2017).
The Social Cost of Carbon with Economic and Climate Risk. Hoover Institution Work Paper, 1–79.

References III

Cai, Y., Judd, K. L., Lenton, T. M., Lontzek, T. S., & Narita, D. (2015).
Environmental tipping points significantly affect the cost-benefit assessment of climate policies. Proceedings of the National Academy of Sciences, 112(15), 4606-4611.

Cai, Y., Lenton, T. M., & Lontzek, T. S. (2016).
Risk of multiple interacting tipping points should encourage rapid CO 2 emission reduction. Nature Climate Change, 6(5), 520–525. https://doi.org/10.1038/nclimate2964

References IV

- Celine Herweijer, Richard Seager, Michael Winton & Amy Clement (2005)
  Why ocean heat transport warms the global mean climate, Tellus A: Dynamic Meteorology and Oceanography, 57:4, 662-675, DOI: 10.3402/tellusa.v57i4.14708

- Chichilnisky, G., & Sheeran, K. A. (2009).
  Saving Kyoto: An insider's guide to how it works, why it matters and what it means for the future. New Holland.

- Dasgupta, P. (2020).
  Ramsey and intergenerational welfare economics. In E. N. Zalta (Ed.), The Stanford Encyclopedia of Philosophy (Summer 2020). Metaphysics Research Lab, Stanford University. https://plato.stanford.edu/archives/sum2020/entries/ramsey-economics/

Ghil, M., & Lucarini, V. (2020).
The physics of climate variability and climate change. Reviews of Modern Physics, 92(3), 035002.
https://doi.org/10.1103/RevModPhys.92.035002

Hansen, L. P. (2021).
Uncertainty Spillovers for Markets and Policy. https://doi.org/
https://doi.org/10.1146/annurev-economics-082020-

Held, I. M., & Soden, B. J. (2006).
Robust responses of the hydrological cycle to global warming. Journal of Climate, 19(21), 5686–5699. https://doi.org/10.1175/JCLI3990.1

Langen, P. L., & Alexeev, V. A. (2007).
Polar amplification as a preferred response in an idealized aquaplanet GCM. Climate Dynamics, 29(2), 305–317.
https://doi.org/10.1007/s00382-006-0221-x

Lenton, T. M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., & Schellnhuber, H. J. (2019).
Climate tipping points—Too risky to bet against. Nature, 575(7784), 592–595. https://doi.org/10.1038/d41586-019-03595-0

MacDougall, A. H., Swart, N. C., & Knutti, R. (2017).
The uncertainty in the transient climate response to cumulative co2 emissions arising from the uncertainty in physical climate parameters. Journal of Climate, 30(2), 813–827.
https://doi.org/10.1175/JCLI-D-16-0205.1

References VII

Matthews, H. D., Gillett, N. P., Stott, P. A., & Zickfeld, K. (2009).
The proportionality of global warming to cumulative carbon emissions. Nature, 459(7248), 829–832. https://doi.org/10.1038/nature08047

Millar, R. J., & Friedlingstein, P. (2018).
The utility of the historical record for assessing the transient climate response to cumulative emissions. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 376(2119), 20160449. https://doi.org/10.1098/rsta.2016.0449

Nordhaus, W. D. (2017).
Revisiting the social cost of carbon. Proceedings of the National Academy of Sciences, 114(7), 1518–1523.

References VIII

Nordhaus, W. (2018).
Projections and uncertainties about climate change in an era of minimal climate policies. American Economic Journal: Economic Policy, 10(3), 333–360. https://doi.org/10.1257/pol.20170046

North, G. R., Cahalan, R. F.,& Coakley, J. A. (1981).
Energy balance climate models. Reviews of Geophysics, 19(1), 91. https://doi.org/10.1029/RG019i001p00091

References VIII

Scovronick, N., Budolfson, M., Dennig, F., Errickson, F., Fleurbaey, M., Peng, W., Socolow, R. H., Spears, D., & Wagner, F. (2019). The impact of human health co-benefits on evaluations of global climate policy. Nature Communications, 10(1), 2095. https://doi.org/10.1038/s41467-019-09499-x

Siler, N., Roe, G. H., & Armour, K. C. (2018). Insights into the zonal-mean response of the hydrologic cycle to global warming from a diffusive energy balance model. Journal of Climate, 31(18), 7481–7493. https://doi.org/10.1175/JCLI-D-18-0081.1

References IX

Trenberth, K. E., & Caron, J. M. (2001).
Estimates of meridional atmosphere and ocean heat transports.
Journal of Climate, 14(16), 3433–3443.
https://doi.org/10.1175/1520-0442(2001)014¡3433:EOMAAO¿2.0.CO;2

Trenberth, K. E., Zhang, Y., Fasullo, J. T., & Cheng, L. (2019).
Observation-based estimates of global and basin ocean meridional heat transport time series. Journal of Climate, 32(14), 4567–4583.
https://doi.org/10.1175/JCLI-D-18-0872.1