When conflicts get heated, so does the planet: coupled social-climate dynamics under inequality

Jyler Menard¹, Thomas M. Bury¹²³, Chris T. Bauch¹ and Madhur Anand²

¹Department of Applied Mathematics, University of Waterloo, Waterloo, Ontario, Canada, N2L 3G1
²Department of Physiology, McGill University, Montreal, Quebec, Canada, H3G 1Y6
³School of Environmental Sciences, University of Guelph, Guelph, Ontario, Canada, N1G 2W1

Climate dynamics are inextricably linked to processes in social systems that are highly unequal. This suggests a need for coupled social-climate models that capture pervasive real-world asymmetries in the population distribution of the consequences of anthropogenic climate change and climate (in)action. Here, we use evolutionary game theory to develop a social-climate model with group structure to investigate how anthropogenic climate change and population heterogeneity coevolve. We find that greater homophily and resource inequality cause an increase in the global peak temperature anomaly by as much as 0.7°C. Also, climate change can structure human populations by driving opinion polarization. Finally, climate mitigation achieved by reducing the cost of mitigation measures paid by individuals tends to be contingent upon socio-economic conditions, whereas policies that achieve communication between different strata of society show climate mitigation benefits across a broad socio-economic regime. We conclude that advancing climate change mitigation efforts can benefit from a social-climate systems perspective.

1. Introduction

The Yellow Vest movement, protests during the Greek economic crisis, and players of the ultimatum game each reveal how asymmetrical costs and benefits fuel resistance to decision-making outcomes. In the Yellow Vest movement, protesters clearly stated their desire to mitigate climate change but would not support measures that unfairly impacted the working class [1,2], while real-world players of the ultimatum game will not accept offers deemed unfair, even when the Nash equilibrium predicts they should do so [3–6].

Such asymmetries are also pervasive in climate change mitigation and the consequences of climate (in)action, such as: (1) asymmetry of contribution to the problem, wherein those who have benefited most from industrialization have contributed most to causing a climate emergency, (2) asymmetry of impact, wherein the worst consequences of climate change will fall on those least responsible, (3) asymmetry of power or representation, wherein the most affected do not always have the loudest or most heard voice, and (4) the asymmetry of responses to climate change, wherein some groups may be left behind during the transition to a low-carbon economy [7]. For instance, the Yellow Vest movement exemplifies how austerity measures applied to those least responsible and least powerful can exacerbate resource inequality and thereby lead to dissatisfaction.

Models increasingly help us understand the interactions between the carbon cycle, the climate system, human processes, and the impact of policies [8,9]. To ensure those policy decisions are robust to uncertainties, multiple scenarios are often laid out, ranging from carbon emission trajectories (RCPs) [8,10] to socio-economic systems pathways (SSPs) [11]. Influence in these models usually flows in one direction, from socio-economic systems to the Earth system. Yet, two-way feedback mechanisms link climate and social processes: human behaviour changes...
the climate [12], and the climate changes human opinions [13,14] and consequently human behaviour. Coupled human-environment models are already widely applied to study other systems such as fisheries and forests [15–22] and the need for coupled social-climate models has been noted [23–26]. Some integrated assessment models (IAMs) address this limitation by linking economic and climate systems [27,28], but IAMs tend to omit non-market transactions, information asymmetries [27,29], and feedbacks both within social systems and between social and Earth systems.

The need for coupled social-climate models to develop intuition and understanding of how social processes affect climate uncertainty has been raised in the literature [9,23,26]. Specifically, [23,26] point out the need for social-climate models because social processes introduce new uncertainty into climate change projections that may be comparable to uncertainty in the physical climate system. Elsewhere, it has been suggested that evolutionary game theory may be an effective way of modelling social mechanisms as a dynamic process coupled to climate dynamics [25]. Recent social-climate models have explored the implications of emergent social-climate dynamics [23–25,30,31], including the role of our reaction to extreme climate events where human behaviour is described by the theory of planned behaviour [30], and the role of social learning [31] and social norms [30,31], in determining climate trajectories. We furthermore suggest that the asymmetries engendered by having distinct groups with different resource levels could play a significant role in social-climate dynamics and should be addressed in models.

Here, we developed a coupled social-climate model to focus on the asymmetry of impact in the form of resource inequality and how austerity-induced dissatisfaction interacts with both climate mitigation efforts and climate system dynamics [32]. Our objectives are (1) to investigate how population heterogeneity, homophily, and dissatisfaction affect the global average temperature anomaly predicted by an Earth system model, (2) to show how social-climate modelling may provide insights into climate change mitigation against a backdrop of powerful social forces, and (3) to introduce a method of modelling coupled social-climate systems with a heterogeneous social structure.

2. Model overview

To address our objectives, we (1) use evolutionary game theory to develop a coupled social-climate model with heterogeneous population structure, (2) use the model to investigate how population heterogeneity changes social-climate dynamics, and (3) explore how the peak temperature anomaly responds to potential social-climate mitigation pathways across the parameter space. Our model is intended to gain intuition for how nonlinear interactions between the climate system and heterogeneous social systems affect climate trajectories, rather than provide empirically validated projections for policymaking. Hence, we opted to develop a minimal model. Full details of our model appear in the electronic supplementary material Methods.

The population consists of two groups differing with respect to (1) population size, (2) how costly it is for individuals to adopt a climate mitigation strategy, (3) baseline resources available to individuals in the group, and (4) the extent to which the climate change impacts their resources. These differences are intended to capture relevant socio-economic inequalities within populations [7] and we refer to these features collectively as population heterogeneity. We considered a population divided into a ‘rich’ (R) group and a ‘poor’ (P) group (figure 1, left box). Social dynamics within each group are governed by imitation (social learning) dynamics, whereby individuals learn the opinions of their peers and change their opinions according to the group-specific utility functions [33]. Individuals may adopt one of two opinions: mitigate climate change or do not mitigate climate change. The utility functions governing decision-making depend on several factors, including: social norms within the group—an additive term (+δx) incentivising aligning one’s opinion with the group majority opinion; personal cost of (projected) climate change—a
sigmoidal temperature-dependent term with maximum value $f_{\text{max}}$, meant to capture abrupt changes in risk assessment with temperature increases (whether due to tipping points or other effects is left ambiguous); perceived cost of mitigation—a constant term capturing a cost incurred with adopting mitigative behaviour; dissatisfaction among the poor group—a sigmoidal term dependent on temperature and resource inequality with maximum value $d$ that represents dissatisfaction with resource inequality and mitigation efforts by the rich group. We note that unlike the material impacts of climate change, which affect mitigators and non-mitigators alike to similar extents (see electronic supplementary material, Methods 5.2.7), the personal cost of projected climate change may confer benefits and costs through different channels. Eco-anxiety and eco-anger, moral considerations for current and future humans (and biodiversity loss), and other perceived risks of climate change can confer costs on non-mitigators through psychological channels resolvable by adopting mitigative behaviour [34]. In addition, adopting mitigative behaviour may provide private co-benefits: vegetarian diets may have health benefits [35] and have a smaller environmental impact [36]; changing local air quality standards, or residential heating appliances, can have respiratory health benefits and environmental impacts. The ratio $d/f_{\text{max}}$ represents the relative importance of dissatisfaction versus the influence of climate change. Interaction between the two groups occurs via imitation dynamics weighted by homophily in both groups, and dissatisfaction among the poor group. The extent to which individuals imitate and make decisions based on social norms in the other group is governed by the homophily factor $h$. At the extreme values, $h = 1$ recovers no homophily (equal imitation within and across groups), and $h = 0$ resembles pure homophily (imitation only within each group). Homophily captures the extent to which distinct groups are receptive to the opinions of other groups [37], an important factor in whether (and how quickly) mitigation becomes the dominant strategy taken by the total population. As seen with the 2018 ‘Yellow Vest’ movement and the September 2019 global climate strikes, one group (protestors) can express an opinion while a different group (decision-makers) may or may not be receptive to the opinions of the other group. The dissatisfaction term captures the negative effect of resource inequality and inaction of the rich group on the poor group’s incentive to mitigate.

The climate model (right side of figure 1, see electronic supplementary material, figure S1 for finer details) is a simple Earth system model [38] consisting of a carbon cycle and a greenhouse effect. Emissions from the population enter the atmosphere, causing a greenhouse effect, and are then processed through the carbon cycle. Warming due to the greenhouse effect impacts the social dynamics through perceived dangers of climate change (an increase in projected future climate change based on recent trends increases the incentive to mitigate), and through impacting each group’s resources (to different extents—the rich group feels less impact compared to the poor group).

3. Results

(a) Homophily increases the global peak temperature anomaly

We find that homophily increases the global peak temperature anomaly by slowing the spread of mitigative behaviour between groups via imitation (electronic supplementary material, Methods, equation (2)) and social norms (electronic supplementary material, Methods, equation (1)). We generated plots of the global temperature anomaly ($T$, blue), and proportion of poor ($x_p$, red) and rich ($x_R$, black) mitigators versus time, for various values of the strength of homophily ($h$) and the relative importance of dissatisfaction with resource inequality and mitigation efforts by the rich versus climate change impacts ($d/f_{\text{max}}$) in the decision-making process (figure 2). Across the full range of values for $d/f_{\text{max}}$, stronger homophily always increases the peak temperature anomaly by approximately 0.3°C. When homophily is non-existent ($h = 0$), mitigative behaviour spreads readily between the rich and poor groups on account of imitation and social norms, hence both groups adopt widespread mitigation on a rapid and roughly comparable timescale, although the rich group leads the adoption of mitigation when dissatisfaction is high, since the poor group is unwilling to pay the cost of mitigation unless the rich group also does so. On the other hand, when homophily is high ($h = 1$) it prevents the spread of mitigative behaviour between groups and therefore they adopt mitigation at very different timescales, depending on the strength of dissatisfaction. When dissatisfaction is strong (large $d/f_{\text{max}}$), the poor group never adopts mitigation over the simulation time horizon. Whereas, when dissatisfaction is weak (small $d/f_{\text{max}}$), it is the rich group that lags behind on mitigation since the poor group is stimulated to take action on climate mitigation on account of experiencing greater climate impacts. But in both cases, the lack of between-group imitation means that rich and poor groups adopt mitigation to very different degrees and thus the peak global temperature anomaly is higher.

(b) Climate system feedback drives population polarization

The strong divergence of opinions between rich and poor groups when homophily is high ($h = 1$, figure 2) represents a population polarization. However, there are two different mechanisms behind the polarization. The mechanism in operation depends upon the strength of dissatisfaction relative to climate change impacts ($d/f_{\text{max}}$) in the decision-making process, even though the end result is always a higher temperature anomaly. When dissatisfaction is less important than climate impacts ($d/f_{\text{max}} < 1$), the poor group adopts mitigation faster, but homophily partly counteracts the unifying effect of social norms and slows the spread of mitigative behaviour from the poor group to the rich group (figure 2e–c). The mechanism at play here is simply different groups acting independently according to the socio-economic parameters governing their best interest, such that the poor group chooses mitigation rapidly while the rich group lacks behind.

By contrast, when $d/f_{\text{max}} > 1$, the rich group adopts climate change mitigation, but the poor group is much slower to follow—a ‘Yellow Vest’ effect. Initially, the poor group is unwilling to mitigate until the rich group takes the initiative. When the rich group finally adopts mitigation, dissatisfaction declines as a result (equation (17)), but strong homophily slows the spread of mitigative behaviour from the rich group to the poor group (figure 2g–i, electronic supplementary material, figure S1d–f). This problem is compounded by the fact that the initial lack of mitigative behaviour in the rich group causes mitigation in the poor group to decline to very
low levels in the early portion of the model trajectory, making it a strong social norm not to mitigate (figure 2g–i). In the case where homophily is also strong ($h=1$, figure 2i), by the time mitigation becomes established in the rich group, there are so few mitigators in the poor group and so few opportunities for cross-group interaction, that mitigative behaviour recovers only very weakly by the end of the time horizon in most of the model realizations. As a result of dissatisfaction suppressing the timely adoption of mitigation by the poor group, the global temperature anomaly peaks at 3.0°C. The mechanism at play here is a strong synergy between the negative effects of homophily, norms, and dissatisfaction.

The emergence of a polarized population under both mechanisms occurs because climate feedback structures the human population. Our model posits that anticipated climate change induces a population response, and if the population is heterogeneous with respect to socio-economic parameters governing their reaction to climate change, climate change will first trigger a reaction in the groups that are predisposed to respond to it on account of their socio-economic conditions. This reaction will generate both real and anticipated long-term climate change mitigation that in turn reduces the perceived urgency for the other groups to act, which were already predisposed not to act. Hence, there is an inherent tendency for climate feedback to generate a polarized population. We suggest that this is a specific example of a more general mechanism for environmental systems to structure opinion and behaviour in human populations that have pre-existing heterogeneity with respect to socio-economic privilege.

(c) Asymmetric impacts induce polarization despite lack of homophily

Even in the absence of homophily, asymmetry in the impact of climate change on each group’s resources can increase peak polarization between the group strategies. When the rich
group’s resources are mildly affected by climate change, intensifying the impact on the poor group’s resources increases peak polarization (figure 3c); so does increasing how abruptly the poor group’s resources are affected (k_p). Both of these results are driven by increased dissatisfaction, which directly translates into reduced incentive to mitigate in the poor group. Because the effect of dissatisfaction and resource inequality affect primarily the poor group, increasing the size of the poor group results in a significant increase in peak temperature anomaly (electronic supplementary material, figure S8), while shifting people towards the rich group has a much smaller effect on decreasing the peak temperature anomaly. The asymmetry in effect occurs because dissatisfaction can disincentivize a larger proportion of the total population from adopting mitigative behaviour (electronic supplementary material, figure S8). Decreasing homophily can mitigate the impact of dissatisfaction (electronic supplementary material, figure S8), because then mitigative behaviour can spread between groups. This causes the rich group to adopt it faster, directly reducing the amount of dissatisfaction in the poor group.

However, that assumes the relative importance of dissatisfaction and climate change impacts are of similar magnitude; i.e. d/f_{max} ≈ 1. Yet, we find a monotonic relationship between d/f_{max} and peak polarization (figures 4b; electronic supplementary material, S6b). When the intensity of dissatisfaction is less, peak polarization is also less, leading to a reduced peak temperature anomaly (figures 4a; electronic supplementary material, S6a). Conversely, increasing the importance of dissatisfaction increases peak polarization, leading to an increased peak temperature anomaly. Interestingly, a larger peak polarization appears to have a
Figure 4. Increasing the relative importance of dissatisfaction versus climate change influence increases peak temperature anomaly and opinion polarization. Box-and-whisker plots over 500 simulations for (a) peak temperature anomaly and (b) peak polarization versus ratio of dissatisfaction maximum to climate cost function maximum, at zero homophily and minimal impact on rich group’s resources. All other parameter values (excluding those shown) are drawn from triangular distributions defined in electronic supplementary material, table 2. (Online version in colour.)

Univariate sensitivity analysis

Univariate sensitivity analysis with tornado plots suggests climate outcomes depend considerably on social factors ($\alpha$ and $\rho_R$), the ability for the mitigative strategy to spread between groups ($h$), and the relative importance of dissatisfaction and the personal cost of climate change ($d$, $f_{max}$, $T_c$, and $d_1$) (electronic supplementary material, figure S6). Varying dissatisfaction lowers the peak temperature anomaly by up to 0.5°C from the baseline model, and increases mitigative opinion to $\approx 80\%$ of the total population, relative to when dissatisfaction is absent.

Interestingly, in the upper and lower limits of homophily, the parameters with highest sensitivity are different (electronic supplementary material, figure S7). This is because in the absence of homophily the two groups respond to each other and the climate dynamics, while in full homophily they ignore each other and respond only to the climate. The strength of social norms ($d$) is more impactful in the absence of homophily, due to a tightening of how strongly the opinion of one group is tied to the norms of the other group. By contrast, at full homophily, the strength of social norms is much less impactful because it only affects the groups independently of each other. Additionally, uncertainties in climate parameters have higher impact on climate outcomes (the sensitivity of $S$, $\chi$, $A$, and $F_0$ increases)—the two groups stop responding to each other and respond only to the changing climate, making the climate dynamics have higher impact on when the populations shift towards mitigative behaviour.

How quickly the cost of dissatisfaction increases ($d_1$) influences the peak temperature anomaly by changing where the dissatisfaction cost function is most sensitive to temperature. When $d_1$ is lower, the cost of dissatisfaction quickly increases before the perceived cost of climate change can encourage mitigation, hence an increase in $T_c$ and a decrease in $d_1$ both increase the peak temperature anomaly (electronic supplementary material, figures S6 and S9)—the former because climate change is seen to be costly less quickly, and the latter because the poor group becomes non-mitigative more quickly.

Socially driven approaches to climate mitigation

Because social-climate models incorporate both social and climate processes, they provide a method to compare the impacts of social and economic policy interventions through the use of parameter planes, which allows plotting pathways to climate mitigation through pairwise parameter changes. This analysis suggests that climate change might be mitigated most effectively not by economic policies to make mitigative technologies more accessible (although this is still important), but rather by social policies designed to encourage communication between different strata of society.

This prediction is apparent in parameter planes governing the strength of social norms ($d$), cost of mitigation ($d_{25}$ and $d_{50}$), amount of homophily ($h$), and the importance of dissatisfaction relative to climate impacts ($d/f_{max}$) (figure 5). For instance, simultaneously increasing social norms and decreasing homophily strongly reduces the peak temperature anomaly (figure 5d). This is because a stronger social norm maintains
group cohesion, so when homophily is also low, both groups converge to the same opinion. By contrast, homophily has little impact when social norms are weak because social norms are one of the main routes on which homophily operates in our model.

Similarly, reducing homophily or dissatisfaction, or increasing the anticipated impacts of climate change show significant benefits across a broad region of parameter space, whereas the benefits of reducing the cost of mitigation are either weaker or more contingent on the social parameter values (figure 5a,b,d). For instance, reducing the cost of mitigation for the rich group tends to decrease the peak temperature anomaly regardless of the amount of homophily, but not if dissatisfaction is low in the poor group and/or if anticipated climate impacts are high (figure 5a,c). This is because the primary mechanism by which reducing $\alpha_{R0}$ benefits climate change is through uptake of mitigation by the rich group reducing dissatisfaction among the poor group and thus enabling the (more numerous) poor group to adopt mitigation. When dissatisfaction is small (or conversely, anticipated climate change impacts are very large), this mechanism is not necessary to mitigate climate change. Unexpectedly, our model predicts that reducing $\alpha_{R0}$ does very little to reduce the peak temperature anomaly, unless we are willing to make mitigation nearly costless for the poor group and to reduce homophily to extremely small values (figure 5b).

4. Discussion

We introduced a social-climate model based on asymmetric evolutionary game theory with a greater amount of population heterogeneity than existing models. Among other findings, our model predicted that climate feedbacks can structure human populations by driving opinion polarization. Our model also predicted that the benefits of economic policies making mitigation less costly are often contingent upon social and economic conditions, whereas social policies designed to encourage communication between different strata of society exhibit more robust benefits across a broad range of socio-economic conditions.

Political polarization and politics surrounding group identity are growing issues. Digital social media enables individuals to self-sort into homophilous echo chambers. And,
the Yellow Vest movement suggests dissatisfaction with the perceived unwillingness of more resourceful groups to mitigate emissions is one of many factors that can also lead to polarization. Our model demonstrates how homophily, in conjunction with climate-exacerbated dissatisfaction, can lead to polarization in climate responses. Simply having distinct groups does not guarantee that polarization occurs, as different levels of homophily and relative importance of dissatisfaction versus climate change impacts, control the extent to which polarization of climate response occurs. This is just one mechanism by which a worsening climate can deepen or magnify existing problems within social systems [7]. Conversely, because human behaviour then impacts the climate, corroded social systems have the potential to worsen climate anomalies, as our model illustrates. Increased population heterogeneity, homophily, and dissatisfaction can all lead to an increased global temperature anomaly. A worrisome feedback loop thereby suggests itself: more extreme temperature anomalies worsen social systems thereby worsening temperature anomalies. As a human-environment system, social-climate dynamics may warrant more investigation, and may provide an additional method of incorporating work done by social scientists and humanities scholars [39].

The factors by which dissatisfaction becomes dominant are fourfold: (1) homophily disrupts intergroup learning, (2) climate-driven resource inequality creates resentment, (3) lack of action by the resource-rich group generates dissatisfaction, and (4) a small perceived risk of climate change makes the dissatisfaction relatively more important for decision-making. There may be solutions to address each of these mechanisms. For (1), there is some evidence intergroup contact can reduce homophily and lead to spreading of environmental concern [40]; (2) and (3) may be addressed through carbon tax redistribution programs [41] or investments in entrepreneurship and certification programs (to facilitate career change), and (4) may be addressed through increased speed and reliability of attributing extreme events—and other local changes—to climate change.

Climate change is a public goods problem, i.e. there is negligible material benefit to mitigate unless a large proportion of the population also mitigate. Even then, the remaining non-mitigators can ‘free-ride’ on this benefit. This makes the collective transition to mitigation difficult, despite the costs associated with rising temperatures being so large. The issue is that the material costs associated with climate change will be felt by mitigators and non-mitigators alike. This material cost therefore provides no net-incentive to switch strategy in our model. However, there are more personal costs associated with not mitigating through social and psychological channels. For example, the ‘flygskam’ movement in Sweden seeks to stigmatize unnecessary air travel and encourage train travel instead [42,43]. Psychological costs include eco-anxiety and eco-anger [34], moral considerations for current and future humans, and concern after having witnessed extreme weather events [30,44]. It is an open question whether these personal costs of climate are sufficient in reality to overcome all mitigation costs and lead to collective mitigation as figure 2 suggests. Yet, there are reasons to believe that factors such as eco-emotions, co-benefits, and social pressure can motivate individuals towards mitigation behaviour, independent of perceived climate change importance [34,45,46].

As discussed above (and previously [1,2,7]), navigating climate change mitigation when incorporating social processes introduces new difficulties beyond geophysical tipping points; climate-driven social dilemmas also arise and can worsen temperature anomalies. Social-climate models as in [30,31] are capable of introducing population heterogeneity (as done here) in order to model and analyse how these social dilemmas arise and may be prevented. One method future work can use to systematically investigate the circumstances leading to social dilemmas would be to use the social efficiency deficit framework, as discussed in [47–49]. Social efficiency deficit quantifies the difference between a socially optimal solution or payoff, and the evolutionary equilibrium. Along with improved understanding of how social dilemmas arise and may be prevented in social-climate dynamics, social efficiency deficit may also be used to improve climate change mitigation navigation by mapping out parameter space regions leading to extreme social dilemmas or lack thereof.

We opted for a minimal model that nonetheless incorporated a selection of realistic social features such as population heterogeneity and social learning. However, the model’s simplifying assumptions could influence its predictions. Many of our parameters are not directly measurable in experiments or surveys (although they could be inferred by curve-fitting). Our resource model ignores time dependencies. We assume only two groups and only two strategies with respect to climate action. Moreover, we assume only one kind of social learning dynamics: imitation dynamics, wherein a pair of individuals imitate (adopt) the opinion with a larger payoff. Other sensible choices exist, such as the avoidance process and the compromising process [50]. In the avoidance process, an individual changes their opinion after encountering someone with the same initial opinion (similar to a snob effect). While in the compromising process, an individual is convinced their initial opinion is untenable but the persuader’s opinion is also not convincing, thus the individual adopts a third opinion. We assumed the snob effect occurs very rarely in the climate problem and would likely have little effect on our results. However, the compromising process may be important to include. After all, many political decisions result from compromises. In order to include a compromising dynamic, we would need to include more than the two climate responses considered here (mitigation versus no mitigation). Furthermore, the likely results would be the same but on a slower timescale, as initially ‘extreme’ mitigation responses are diluted by compromise, but these diluted responses do not sufficiently mitigate the climate problem, thereby allowing temperatures to continue increasing (albeit at a reduced pace), requiring further mitigation and adaptation down the line. This is similar to how insufficient measures to address the Covid-19 pandemic results in a longer, more lengthy pandemic forcing people and economies to incur a larger cost. These limitations diminish the usefulness of our model for accurate social-climate projections. However, as noted in [23–25,30,31], simple models are still valuable tools to understand processes, attempt new modelling methods, and to explore how the approach could be effective in suggesting policy changes [9]. To this end, our results suggest that social-climate interactions in a heterogeneous population can have nontrivial impacts on both climate trends and opinion dynamics, and thus merit further study. As climate change is driven by social and economic processes, we should not forget that climate change is ‘everything change’—and will require a complementary social change in order for us to mitigate it [51,52].
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