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Homeostatic behaviour in democratic societies under climate change

Bruno Rodrigues

Supervisors: **Prof. dr. ir. Henk Stoof and Prof. dr. ir. Henk Dijkstra**

Institute for Theoretical Physics
Centre for Complex Systems Studies

Utrecht University

Outline

- Motivation
- Opinion formation : Ising-based voter model and properties
- Climate & Economy : The DICE model
- Coupled-DICE : Political parties and coupling equation
- Simulation results
- Conclusions and outlook

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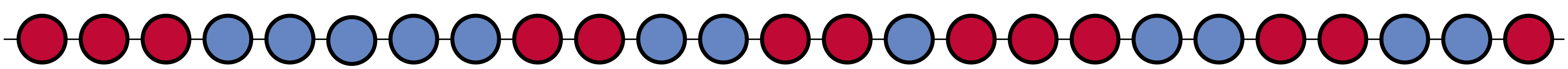
Motivation

- **Homeostasis:** *the tendency towards a relatively stable equilibrium between interdependent elements, especially as maintained by physiological processes, e.g. body temperature.*
- **Gaia hypothesis:** living organisms and their inorganic surroundings form a self-regulating complex system that keeps conditions for life within bounds.
- How do democratic societies and their electoral outcomes affect the average world temperature, when human activity has disturbed the climate system equilibrium?
- Climate ideology of elected parties dictate climate related policies. What’s the impact of human opinion on solving such a long term problem as climate change, when elections are heavily impacted by current concerns?
- Outcomes of US presidential elections from 1920 to present:



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Ising-based model of opinion formation in a complex network of interpersonal interactions

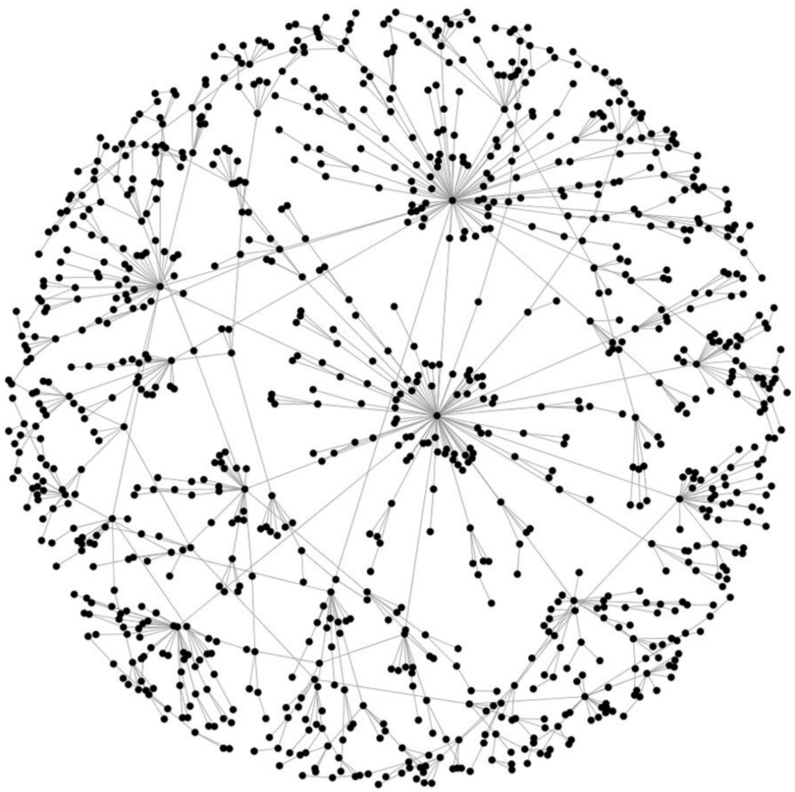
A. Grabowski[a], R.A. Kosiński[a,b,*]

[a]Central Institute for Labour Protection-National Research Institute, 00-701 Warsaw, Poland
[b]Faculty of Physics, Warsaw University of Technology, 00-662 Warsaw, Poland

- 2-D graph built with iterative edge probability rule;
- Ising-like opinion switch mechanism with external stimulation;
- Network properties match real social networks:
    - Scale-free;
    - Hierarchical;
    - Small-worldness.

- LxL lattice,
- $N = L^2$ nodes (individuals)
- Node opinion $S_{ij} = \pm 1$
- Node connectivity k_{ij}
- Node authority A_{ij}

Network properties



[Source: Simon Cockell - Barabassi-Albert network using Cytoascape 2.8.3]

- Network topology built iteratively based on an edge formation probability rule;

- Scale free: connectivity has a power law distribution:

$$P(k) \sim k^{-\gamma}$$

- Hierarchical: Clustering coefficient has power law distribution:

$$C(k) \sim k^{-\beta}$$

(occurs for highly clustered networks $p_c > 0.5$)

Generator algorithm

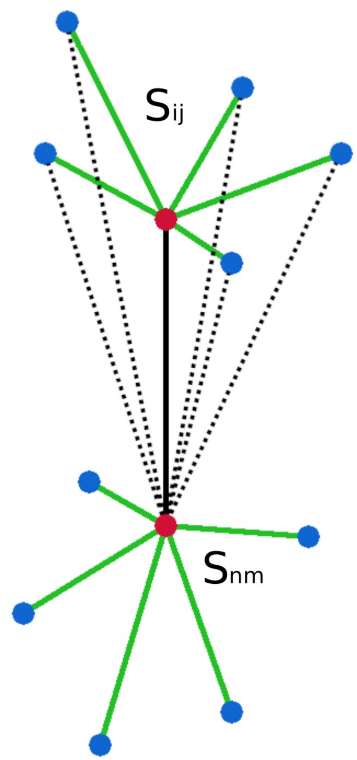
- Edge formation is based on a probability rule that is dependant on the spatial distance l between nodes:

$$P(l) \sim \frac{1}{1 + \exp[(1 - a)/b]} + 0.001\frac{L-1}{L}$$

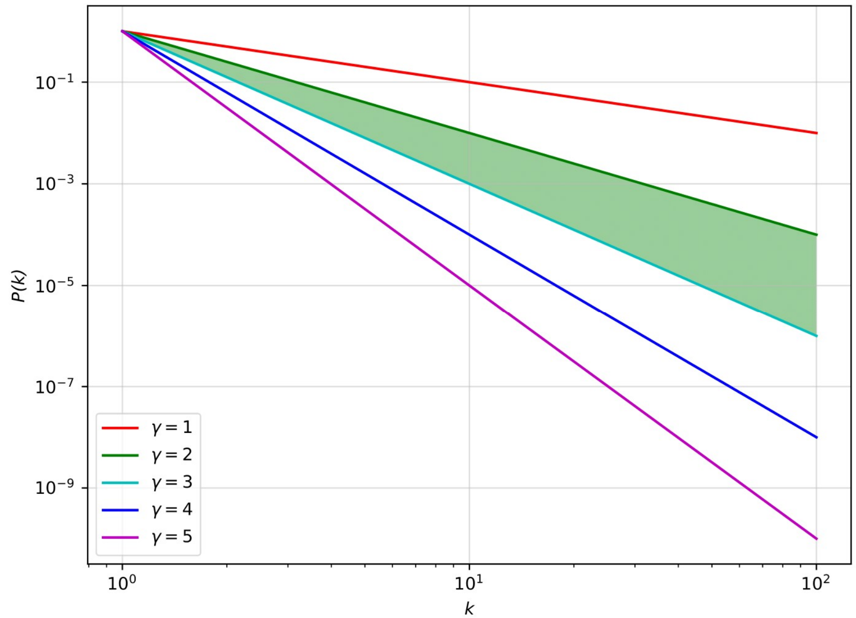
- Lattice grid is split into local groups of $N_G = LG \times L_G$;

- Secondary connections are formed with fixed probability $p_c \in [0,1]$ - affects clustering coefficient:

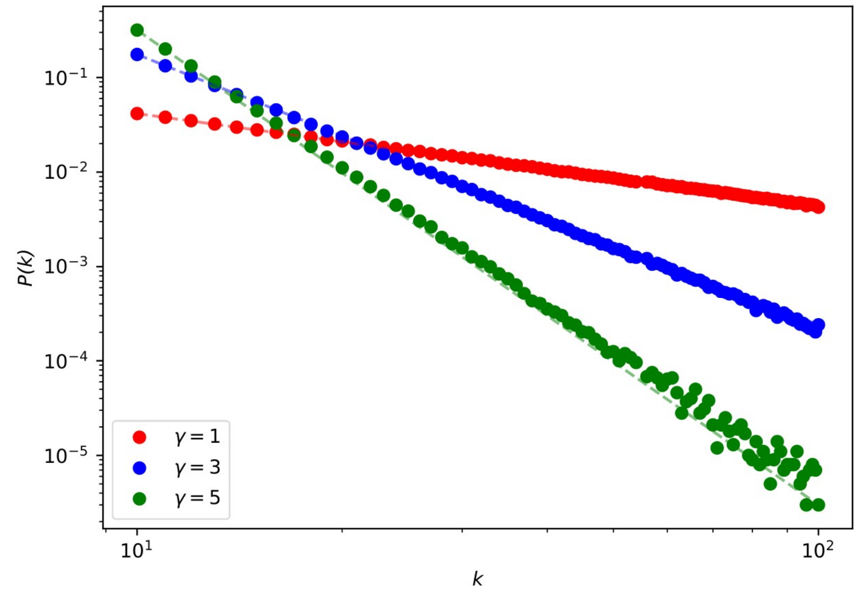
$$C = \left\langle \frac{2E_{ij}}{k_{ij}(k_{ij} - 1)} \right\rangle$$



Distribution of connectivity

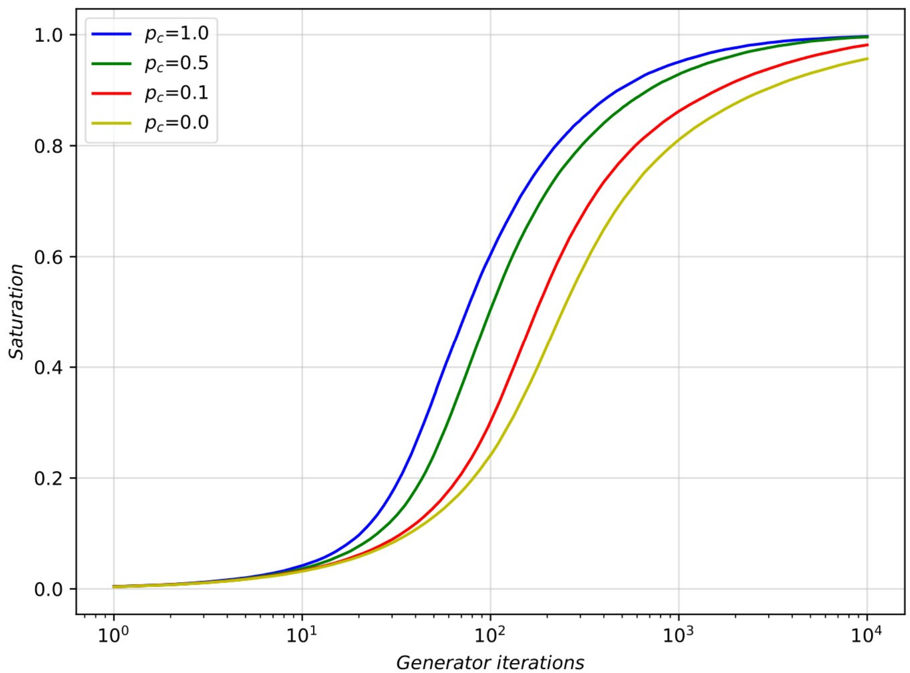


Real world networks have power law distributions with $\gamma \in [2,3]$.
[A. Barabási, R. Albert - 1999]

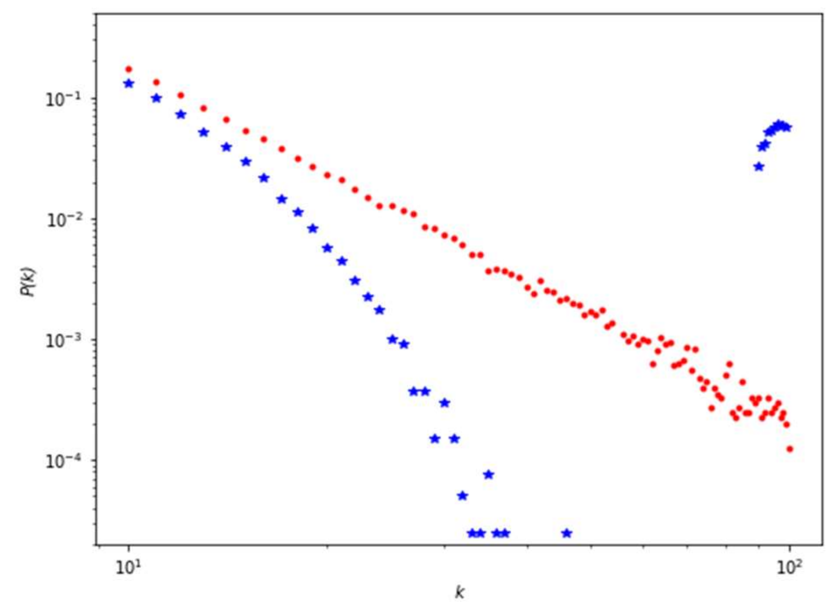


Connectivity distributions of generated networks K_{ij}.
(*N=1000; L_G=20; k_{min}=10; k_{max}=100; p_c=0.5*)

Network formation

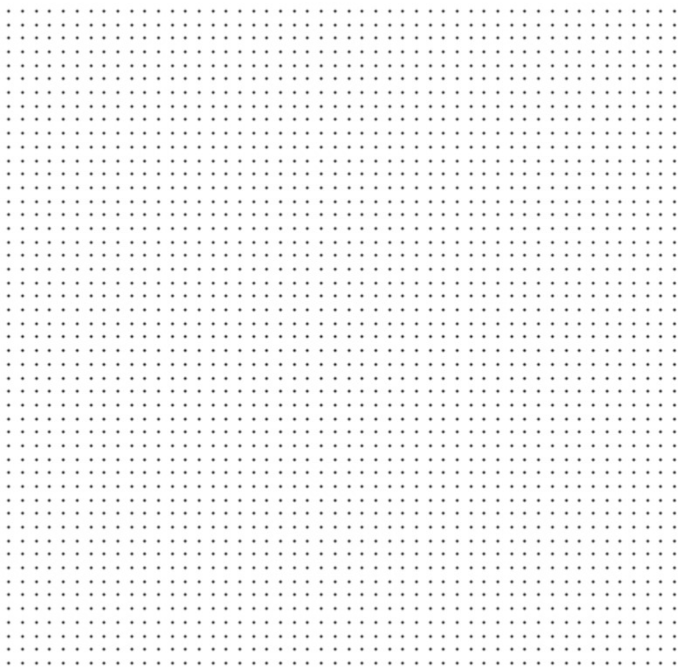


Evolution of network saturation over the algorithm iterations, given by $K_{ij} - kij$.

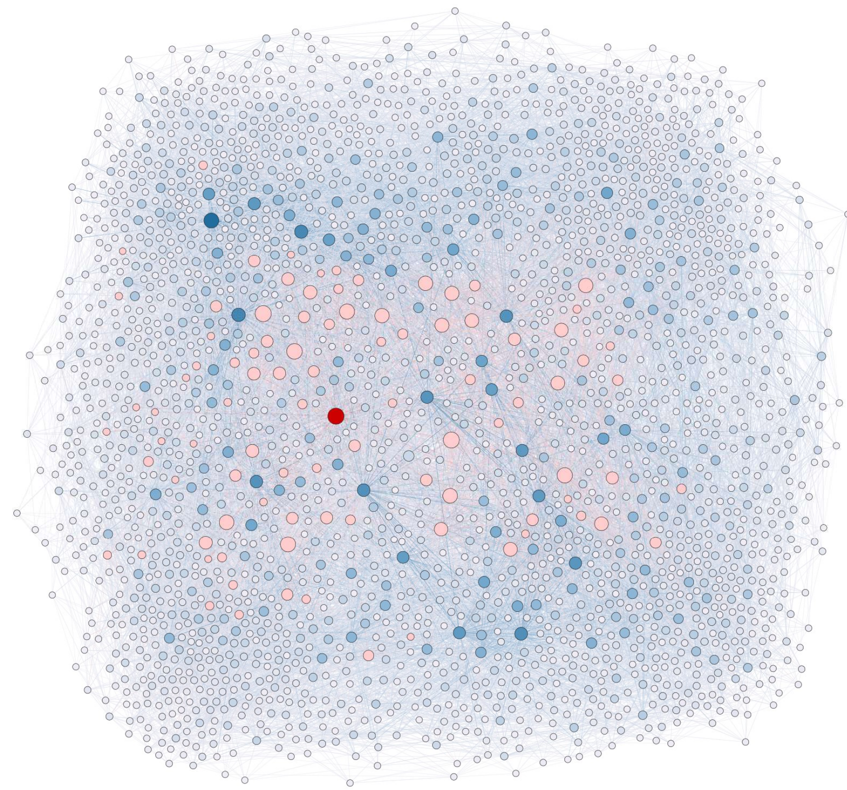


Connectivity distributions of a generated network for 100, 1000 and 10000 iterations of the algorithm.
(*N=100; γ=3;* L_G*=20;* k_{min}*=10;* k_{max}*=100;* p_c*=0.5*)

Network structure



(*N=50; γ=3;* L_G*=20;* k_{min}*=10;* k_{max}*=100;* p_c*=0.5*)



Readjusted visualization (Gephi 0.9.2). Highest connectivity node highlighted.

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Opinion dynamics

- Ising-like mechanism takes on a local field value h_{ij} for each node:

$$h_{ij}(t+1) = \frac{1}{k_{ij}}\left(\underbrace{\sum_{n=1}^{k_{ij}} A_{l(n)m(n)}S_{l(n)m(n)}(t)}_{\text{interpersonal interactions w/ neighbours}} + \overbrace{\frac{1}{N_G}\sum_{n=1}^{N_G} A_{l(n)m(n)}S_{l(n)m(n)}(t)}^{\text{influence of local group}}\right) + \underbrace{I_E}_{\text{external influence}}$$

- Probability rule to switch opinion:

$$p_{ij} = \begin{cases} (1 - A_{ij})\left(1 - \exp\left[(h_{ij}S_{ij})/T\right]\right); & h_{ij}S_{ij} \leq 0 \\ (1 - A_{ij})\exp\left[-(h_{ij}S_{ij})/T\right]; & h_{ij}S_{ij} > 0 \end{cases}$$

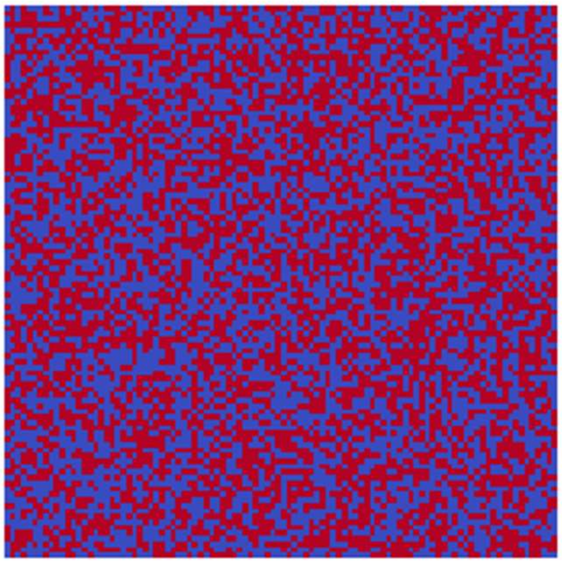
- Authority:

$$A_{ij} \in [0,1]$$

drawn from a truncated Gaussian w/ mean 0 and variance σ

Opinion dynamics - S_{ij}

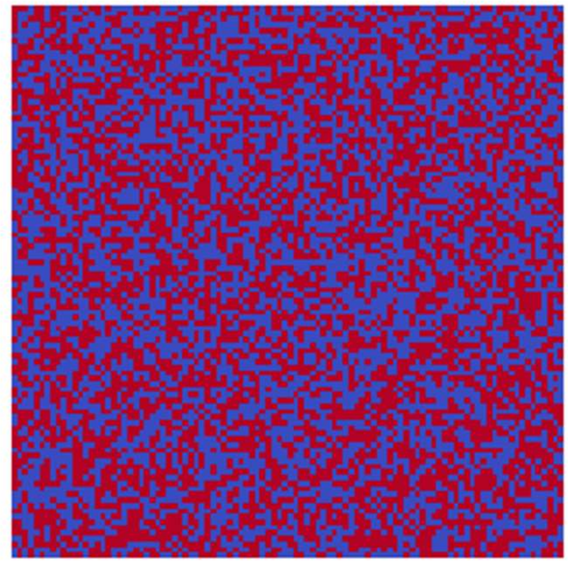
Ferromagnetic at *T = 0* *<S> ≈-1*



One-party rule. Influence of clustered topology visible.

$$\langle S \rangle \equiv \frac{1}{N}\sum_{i,j}^{L} S_{ij}$$

Paramagnetic at *T = 0.15* *<S> ≈ 0*



Two party "balance". Highly divided society at high T.

(*N=100; γ=3;* L_G*=20;* k_{min}*=10;* k_{max}*=100;* p_c*=0.5;* I_E*=0*) - 10^6 MC steps (100 frames)

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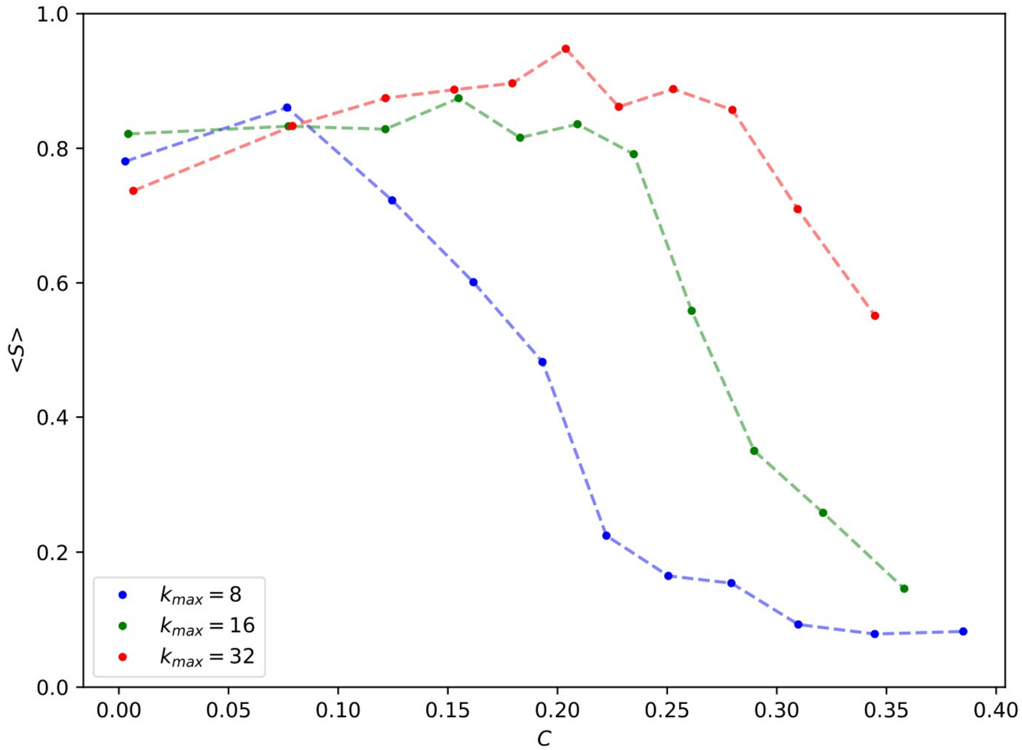
Network clustering

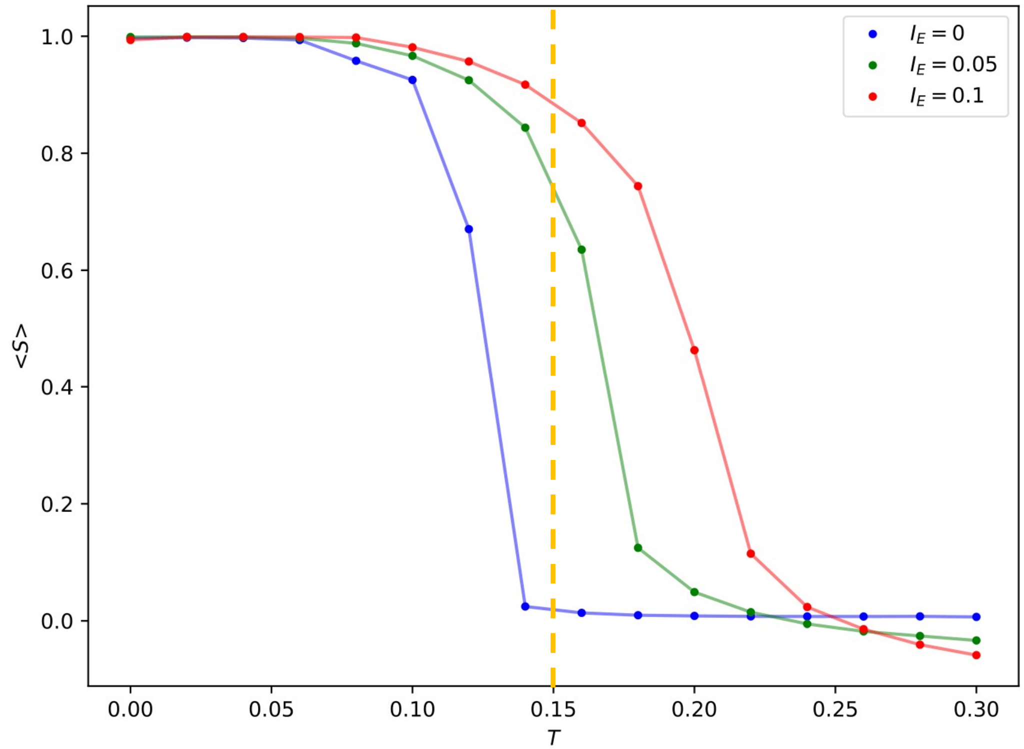


(*N=100; γ=3; L_G=20; k_{min}=8; T=0; – 100 independent simulations*)

- Network parameter p_c directly influences average network clustering *C*;
- System (mostly) tends towards a ferromagnetic state for low clustering;
- Higher clustering results in a paramagnetic state – individuals form small clusters and reinforce each other's opinions;
- Higher connectivity k_{ij} decreases this effect.

External Stimulation

- Under constant external stimulation, the system transitions to paramagnetic state for increasing network temperature;
- Network temperature a measure of “social unrest”;
- The network regime we are interested in is within the region where the phase transition occurs.



(*N=100; γ=3; L_G=20; k_{min}=10; k_{max}=100; p_c=0.5 – 100 independent simulations*)

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The DICE model

(Economics Module)

- Welfare function (quantity to maximize);

$$W = \sum_{t=0}^{T_{max}} U[c(t), L(t)]R(t)$$

discount rate

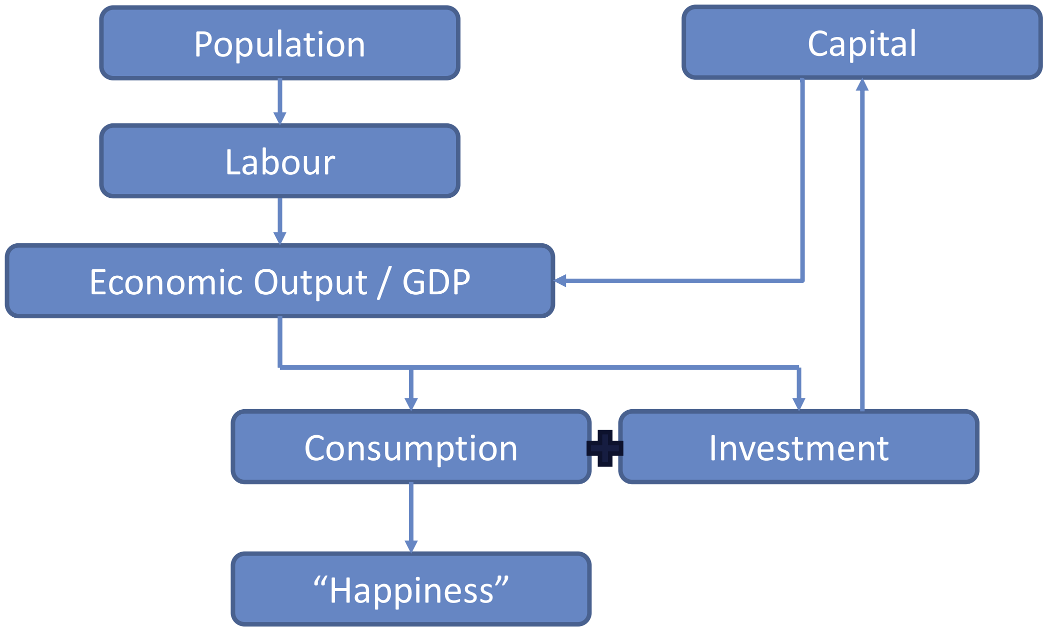
- Economic output:

$$Q(t) = A(t)K(t)^{\gamma}L(t)^{1-\gamma}$$

labour

population

capital



Welfare function – quantity to maximize.

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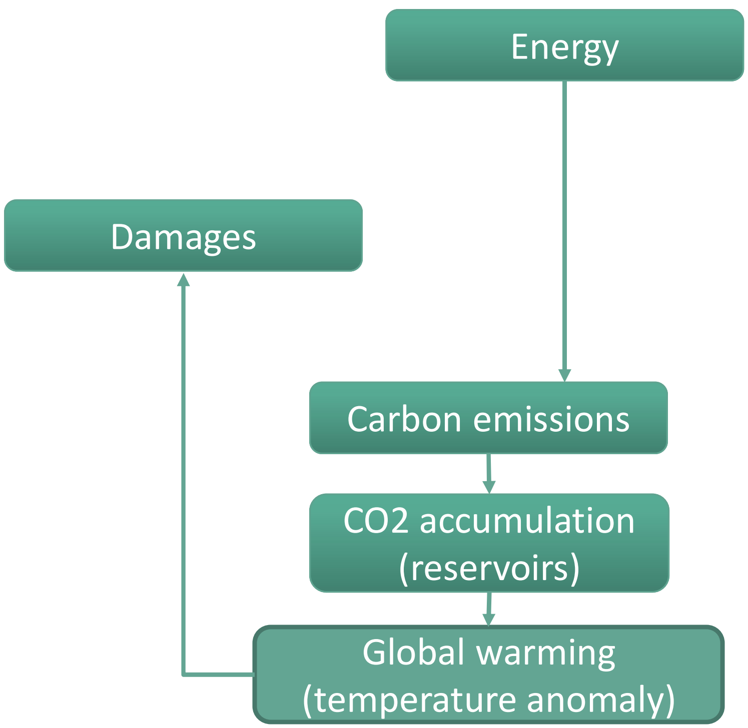
The DICE model

(Climate Module)



- Industrial carbon emissions;

$$E_{ind}(t) = \overbrace{\sigma(t)}^{\text{prescribed}}\, A(t)K(t)^{\gamma}L(t)^{1-\gamma}$$

- Radiative forcing:

$$F(t) = \eta\left\{\ln\left[\frac{M_{AT}(t)}{M_{AT}(1750)}\right]\right\} + \underbrace{\mathcal{O}(t)}_{\text{other greenhouse gases}}$$

The DICE model

(Climate Module)

- Carbon reservoir dynamics;

$$M_{AT}(t) = E(t) + \phi_{11} M_{AT}(t-1) + \phi_{21} M_{UP}(t-1)$$

$$M_{UP}(t) = \phi_{12} M_{AT}(t-1) + \phi_{22} M_{UP}(t-1) + \phi_{32} M_{LO}(t-1)$$

$$M_{LO}(t) = \phi_{23} M_{UP}(t-1) + \phi_{33} M_{LO}(t-1)$$

- Temperature/heat flow dynamics;

$$T_{AT}(t) = TA_T(t-1) + \xi_1\{F(t) - \xi_2 T_{AT}(t-1) - \xi_3[T_{AT}(t-1) - TL_O(t-1)]\}$$

$$T_{LO}(t) = TL_O(t-1) + \phi_4\{T_{AT}(t-1) - TL_O(t-1)\}$$

The DICE model

(Climate-Economy Feedbacks)

- Climate related effects on the economy;

$$\Omega(t) = \phi_1 T_{AT}(t) + \phi_2 T_{AT}(t)^2$$

climate change damages to the economy (Nordhaus' damage function)

$$\Lambda(t) = \theta_1 \mu(t)^{\theta_2}$$

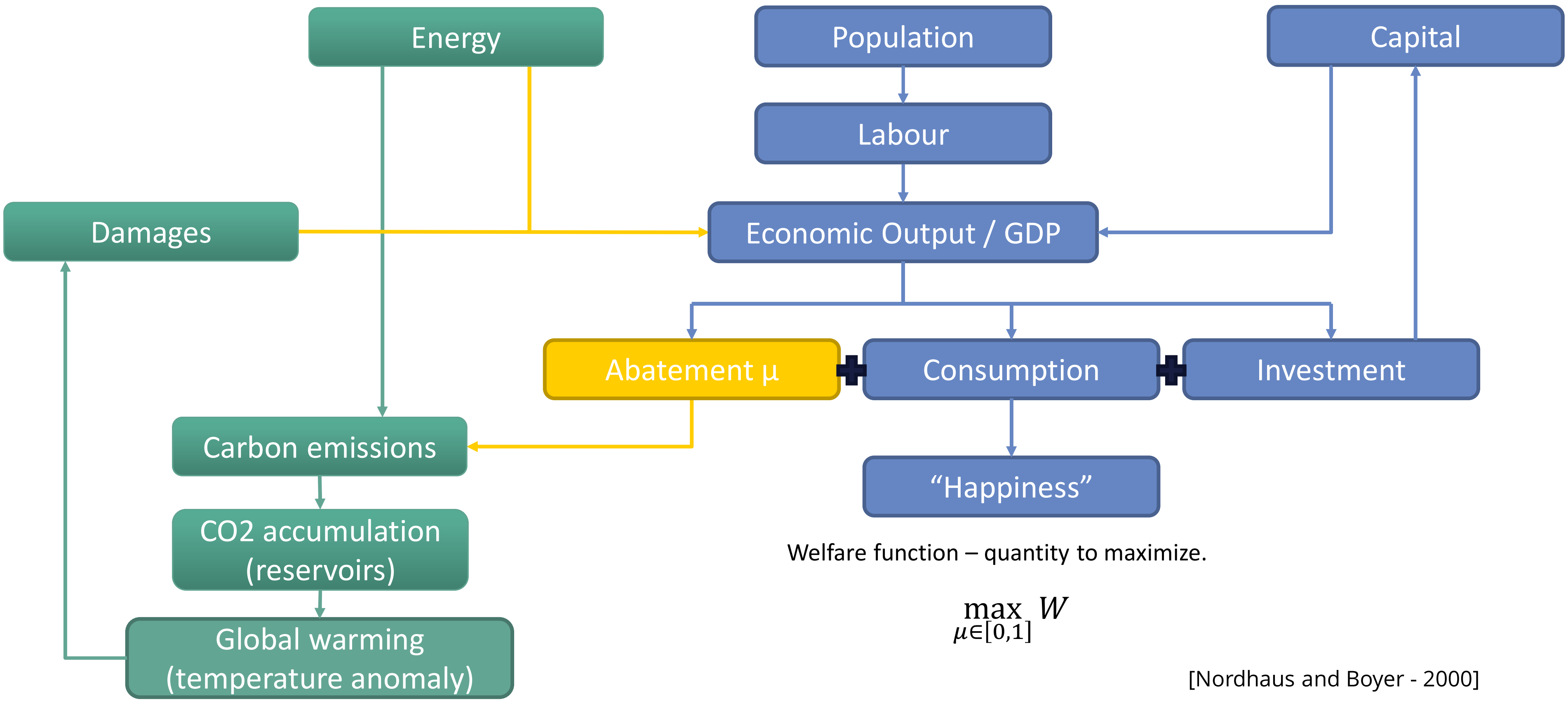
abatement costs (costs of actively reducing CO_2 emissions)

- Abatement μ corresponds to the effective climate policy;

$$Q(t) = \underbrace{[1 - \Lambda(t)]}_{\text{abatement cost}} A(t) K(t)^{\gamma} L(t)^{1-\gamma} \underbrace{\frac{1}{1 + \Omega(t)}}_{\text{damages}}$$

$$E_{ind}(t) = \overbrace{\sigma(t)}^{\text{prescribed}} [1 - \underbrace{\mu(t)]}_{\text{abatement}} A(t) K(t)^{\gamma} L(t)^{1-\gamma}$$

The Dynamic Integrated model of Climate and the Economy



Welfare function – quantity to maximize.

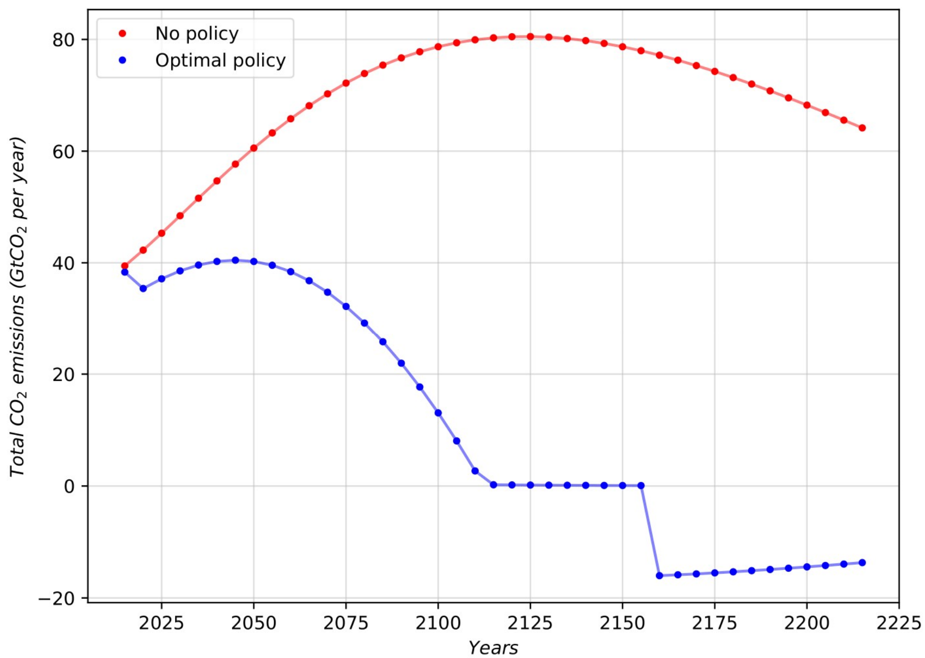
$$\max_{\mu \in [0,1]} W$$

[Nordhaus and Boyer - 2000]

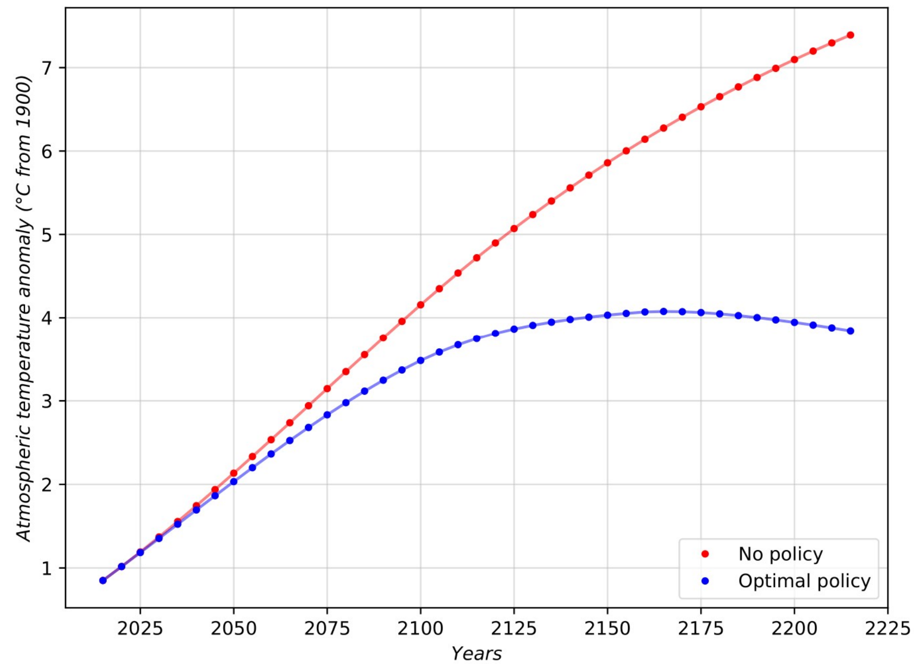
[diagram adapted from: C. Wieners - 2018]

The DICE model

Total CO_2 emissions [no-policy and optimal policy].



Atmospheric temperature anomaly [no-policy and optimal policy].



[Nordhaus - 2013]

(DICE2016 parameters – 500 year run)

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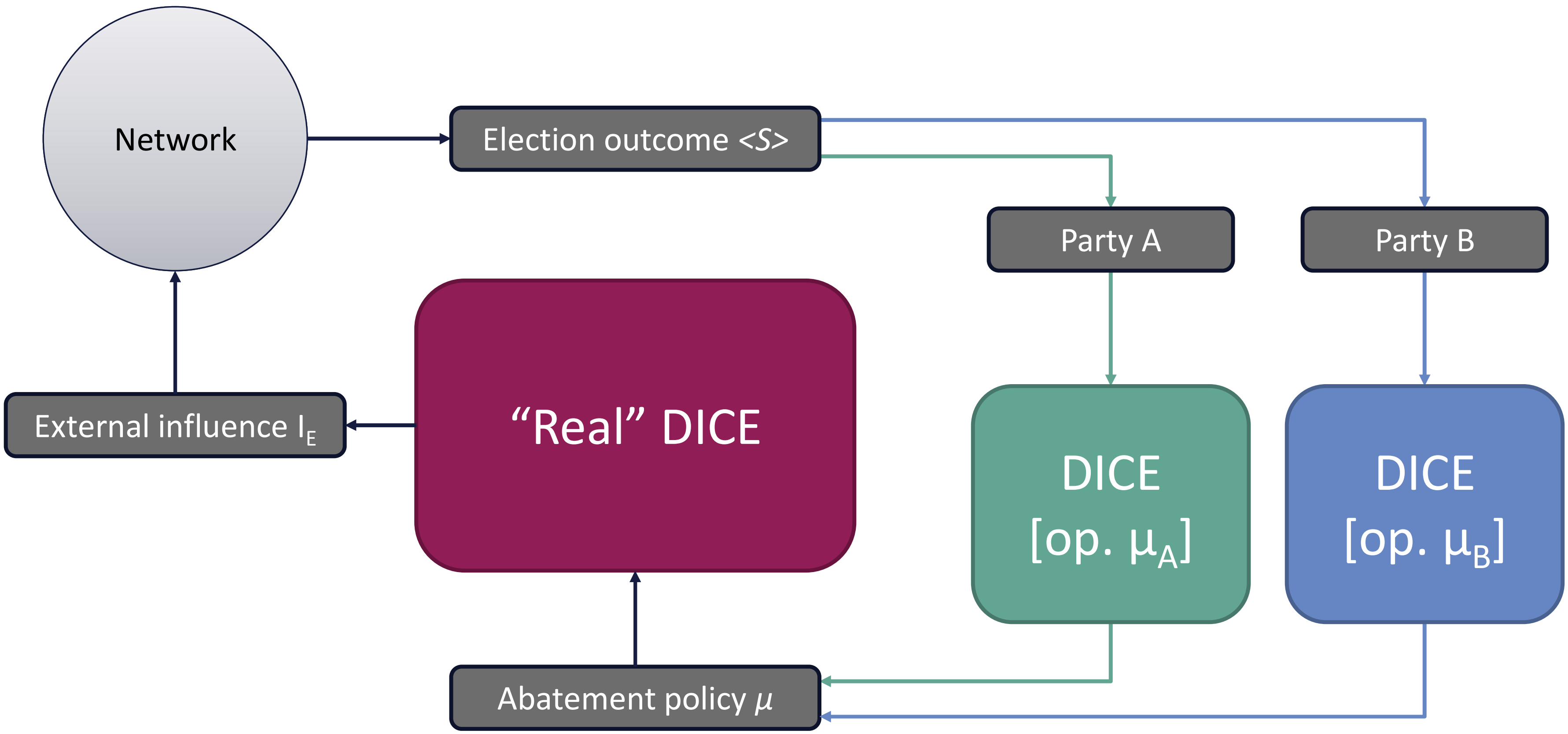
Coupled-DICE



Political Parties – Profiles

- **<u>The Greens</u>**
  - Think climate change is a big problem, but not to the point of hindering economic activity (if it can be avoided).
  - <u>Climate sensitivity</u>: 5K/doubling CO_2

- **<u>The Lukewarmers</u>**
  - Think climate change is a problem, but not so big or urgent that requires drastic measures.
  - <u>Climate sensitivity</u>: 2K/doubling CO_2

[Source: https://www.redbubble.com/ (art by Olaffish)]

Coupling equation

- Proposed (generic) coupling equation:

$$\overline{I_E} = \underbrace{\bar{\alpha} D(t)}_{\text{damages term}} - \overbrace{X(t)}^{\text{taxes term}} + \underbrace{\bar{\omega} F(\hat{T})}_{\text{future “worry”}}$$

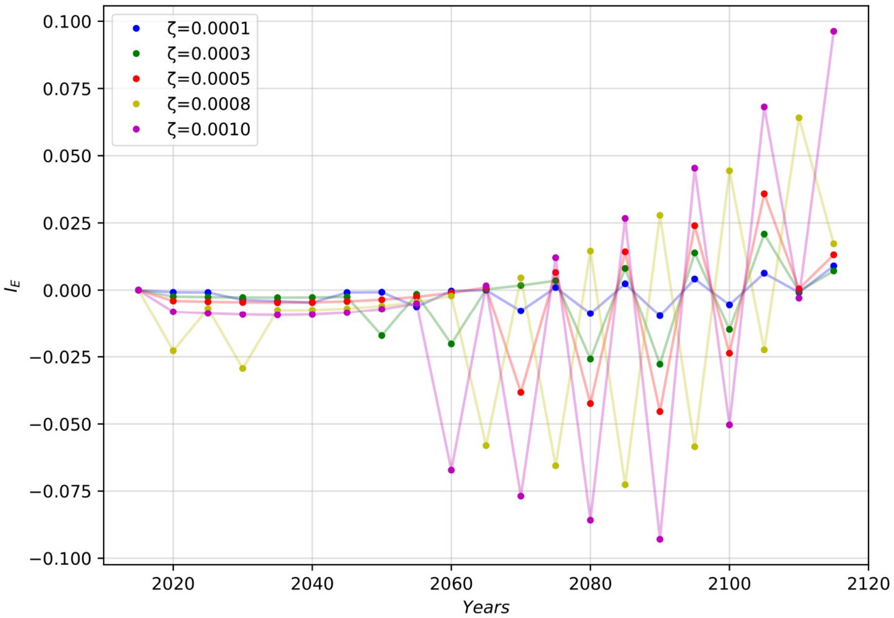
$$I_E(t) = \underbrace{\zeta}_{\text{scale factor}} \left\{ \frac{1}{L(t)} \left[\overbrace{\bar{\alpha} \Omega(t)}^{\text{“awareness”}} - \overbrace{\bar{\mu}}^{\text{marginal abatement cost}} E(t) \right] + \underbrace{\bar{\omega} F(\hat{T})}_{\text{“worry”}} \right\}$$

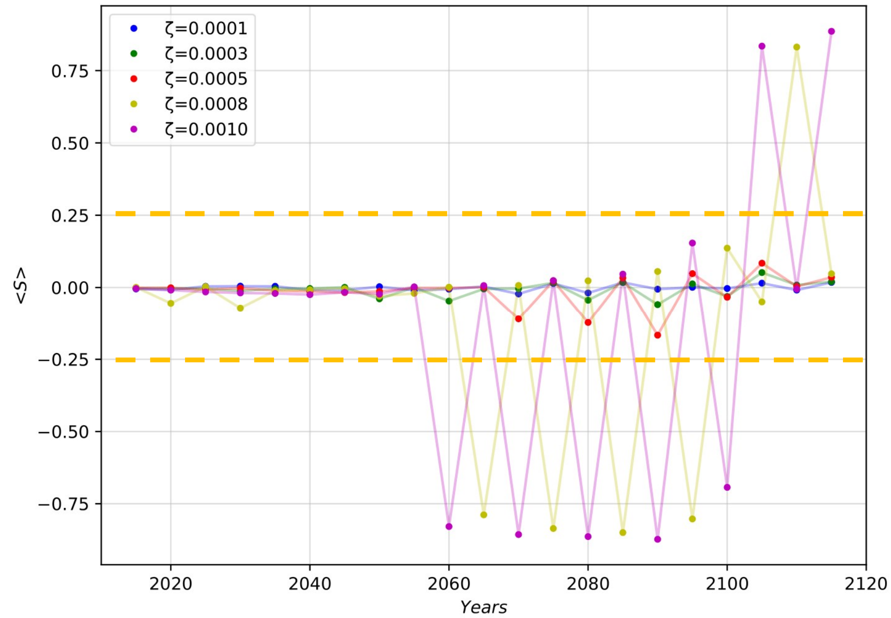
- Taxes are the major factor in the short-term.

- Future “worry”:

$$\hat{T}(\mu) = \underbrace{\gamma_{op} \hat{T}_{op}(\mu)}_{\text{opposition}} + \overbrace{\gamma_{gov} \hat{T}_{gov}(\mu)}^{\text{government}} + \underbrace{\gamma_{sci} \hat{T}_{sci}(\mu)}_{\text{scientists}}$$

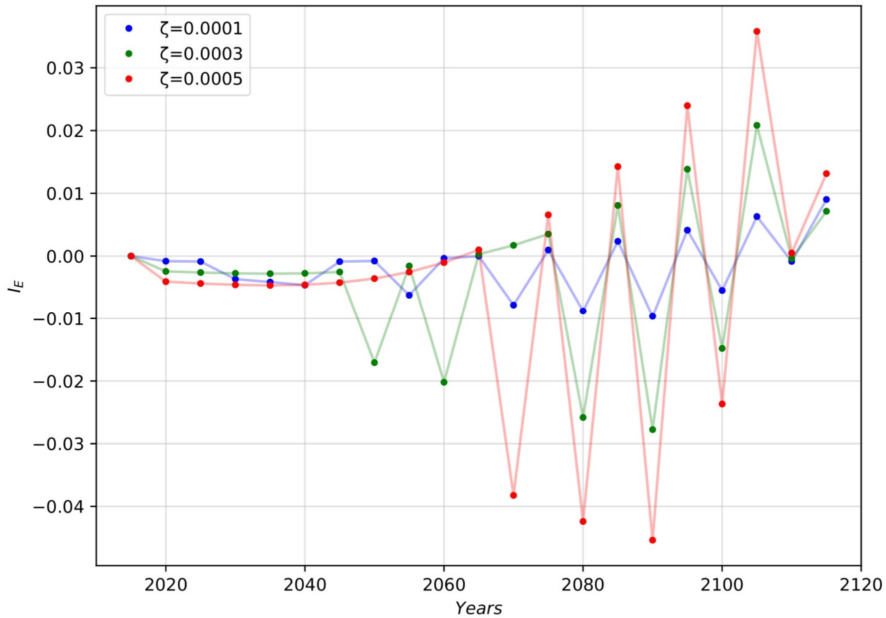
Coupling Equation – Scale

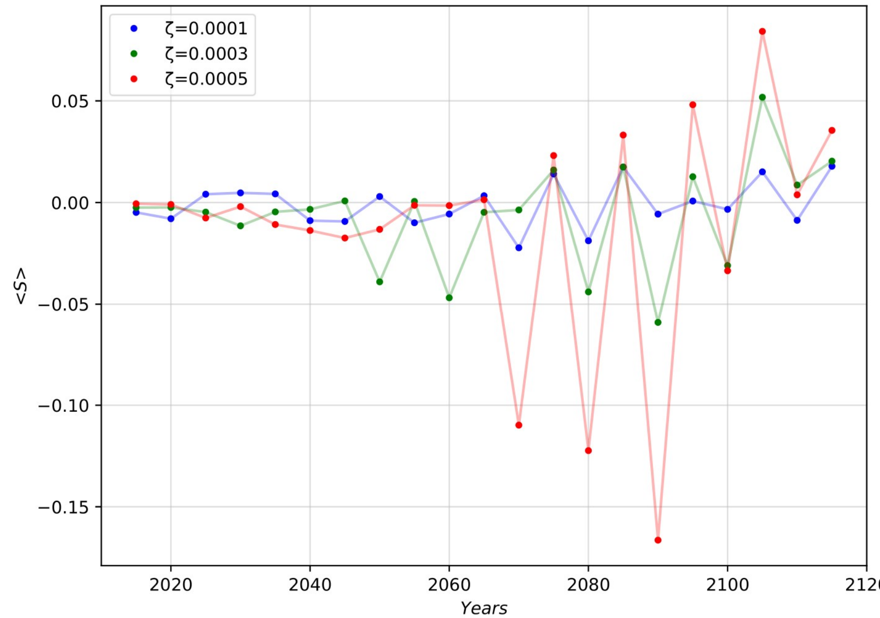




(N=200; γ=3; L_G=20; k_{min}=10; k_{max}=100; p_c=0.5; σ=0.3; T=0.15)

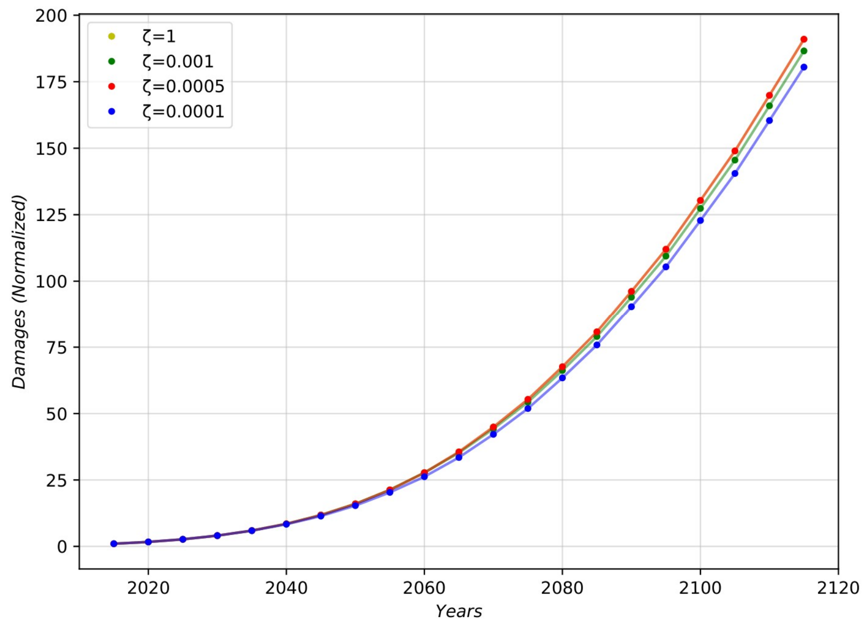
Coupling Equation – Scale



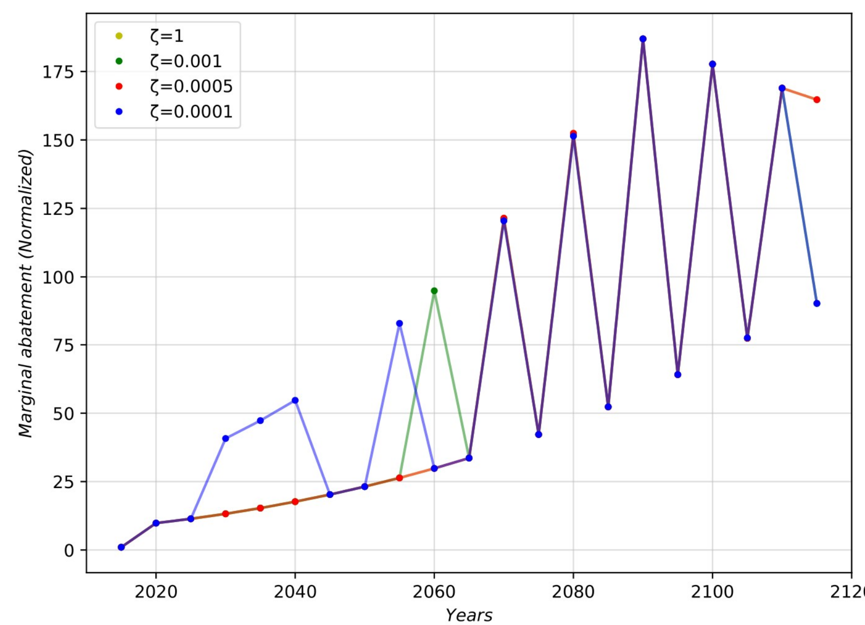


(*N=200; γ=3; L_G=20; k_{min}=10; k_{max}=100; p_c=0.5; σ=0.3; T=0.15*)

Coupling Equation – Bounds



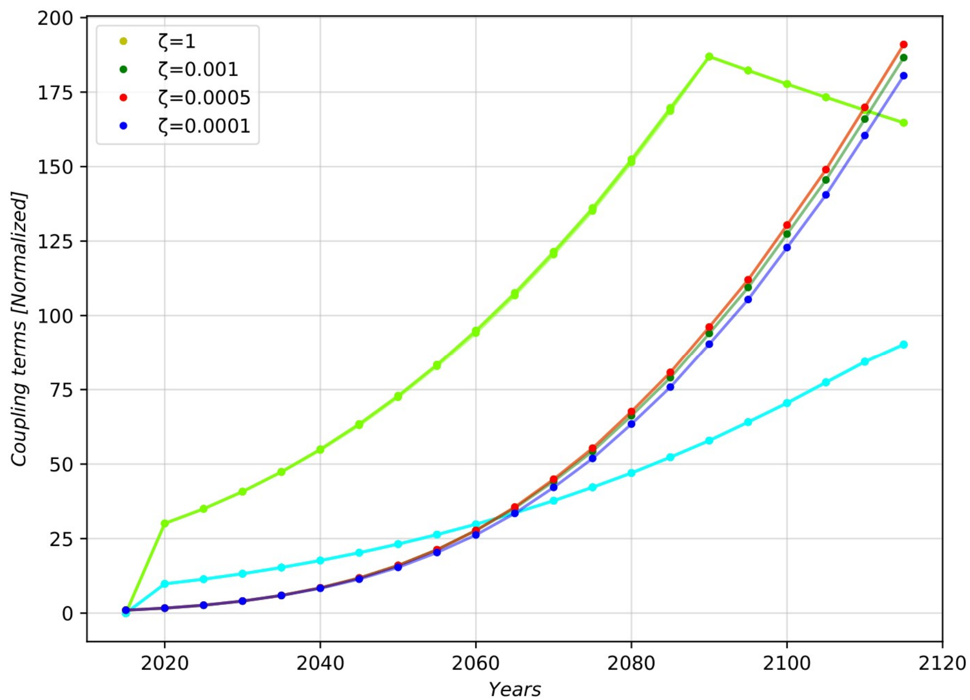
Normalized (dimensionless) damages.



Normalized (dimensionless) abatement costs.

(*$N=200$; $\gamma=3$; $L_G=20$; $k_{min}=10$; $k_{max}=100$; $p_c=0.5$; $\sigma=0.3$; $T=0.15$*)

Coupling Equation – Bounds

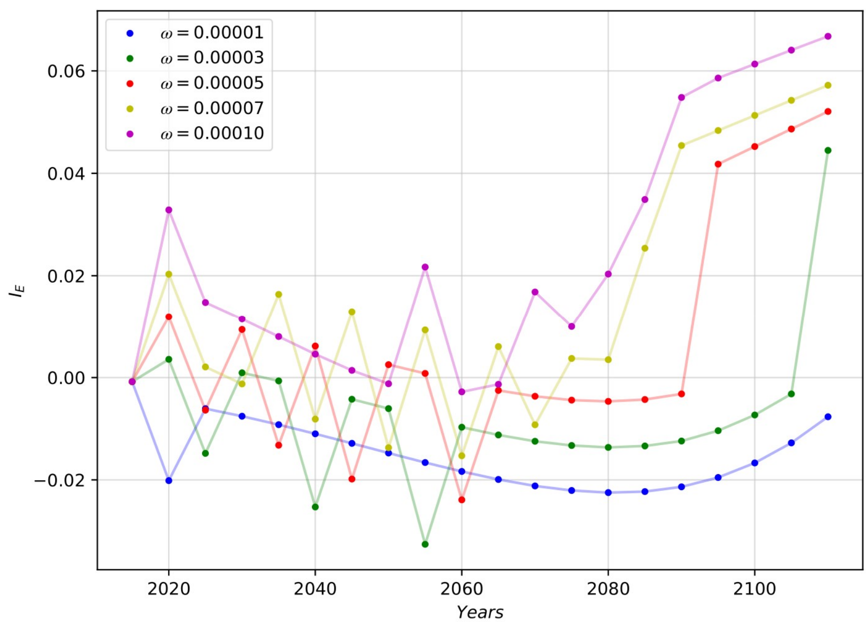


Upper and lower boundaries of the coupling tax terms with climate term for comparison.

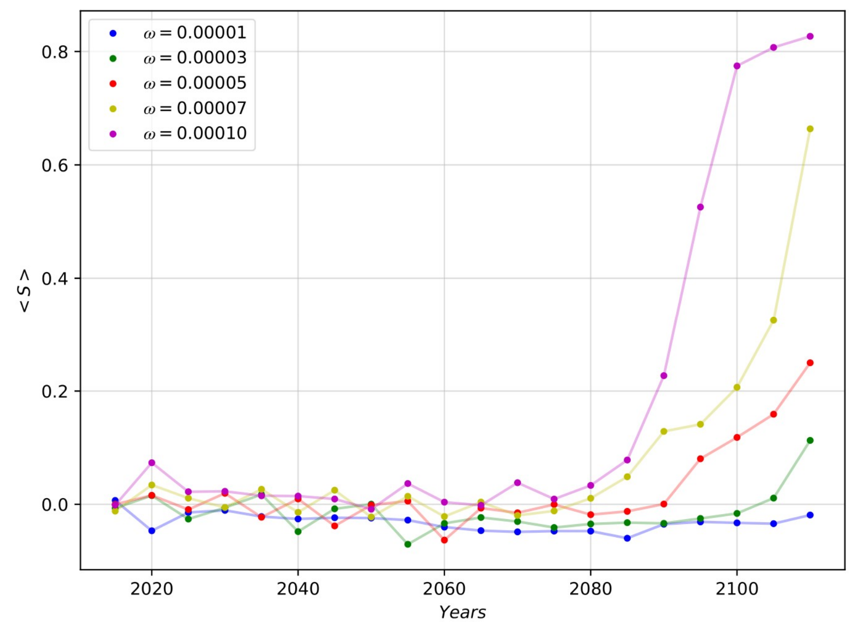
(*N=200; γ=3;* L_G*=20;* k_{min}*=10;* k_{max}*=100;* p_c*=0.5; σ=0.3; T=0.15*)

- Climate damages change very little over different policy scenarios;
- Damages increase over time, but have a minimal impact early on;
- Carbon tax is bound by the optimal policy paths of each party;
- Tax term is the main regulator of I_E.

Coupling Equation – Worry



External influence for different worry parameters.



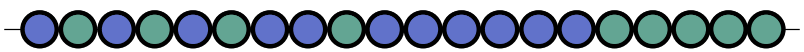
Network opinion for different worry parameters – system transitions to ferromagnetic phase at later years.

($N=200$; $\gamma=3$; $L_G=20$; $k_{min}=10$; $k_{max}=100$; $p_c=0.5$; $\sigma=0.3$; $T=0.15$)

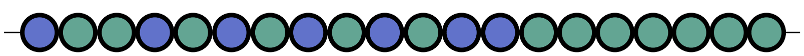
Coupling Equation – Worry

Election results and critical phase transition years (pro-climate)

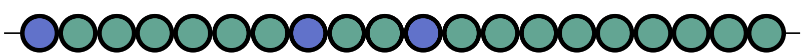
- ω=0.00005



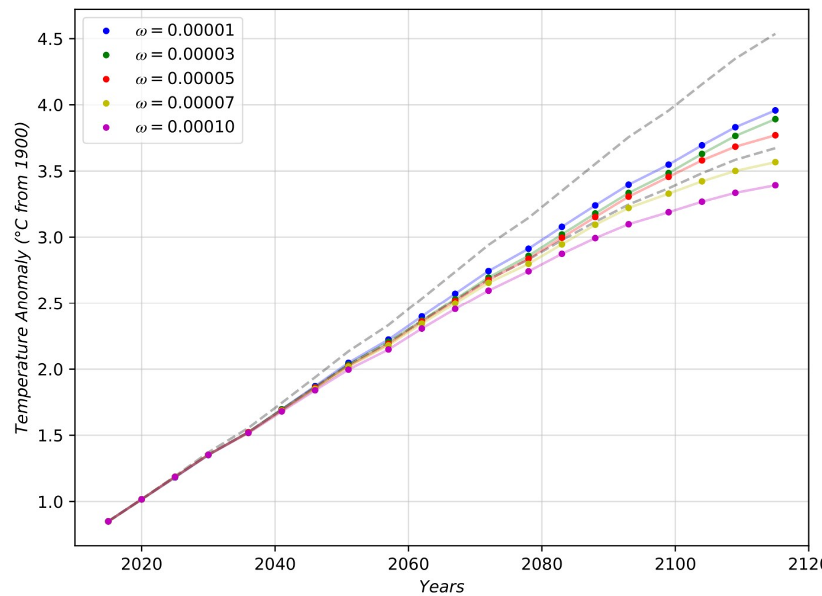
- ω=0.00007 - (2115)



- ω=0.00010 - (2095)



Temperature anomaly – “real” DICE



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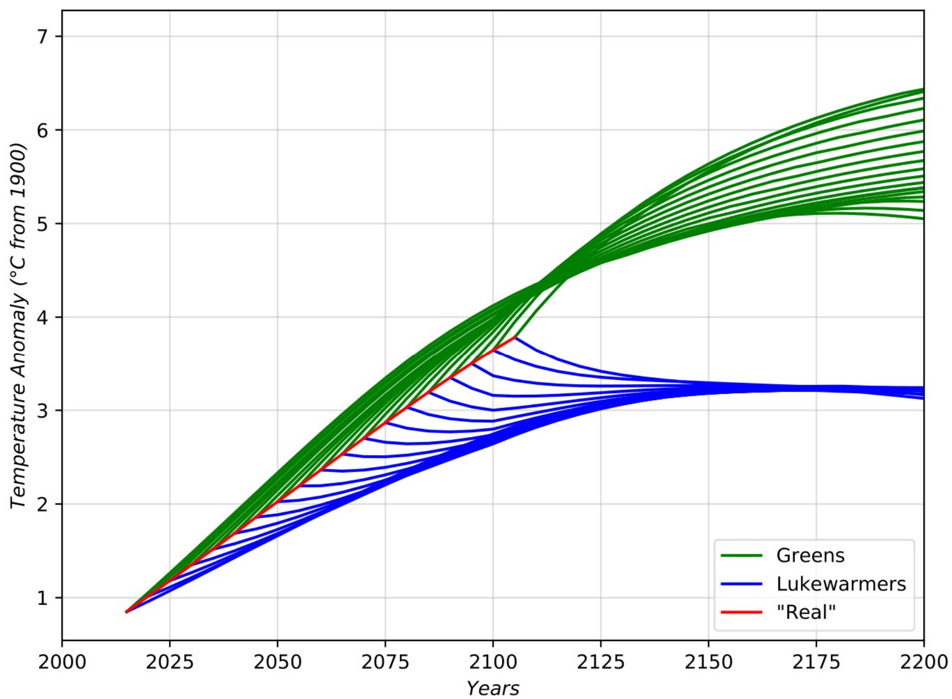
Worry – Peak Temperature



- Project peak temperature diverges considerably over time;
- Affected by the chosen climate sensitivity;
- The difference in temperature outcome sugests a need for a “learning” process;
- Regulation mechanism required.

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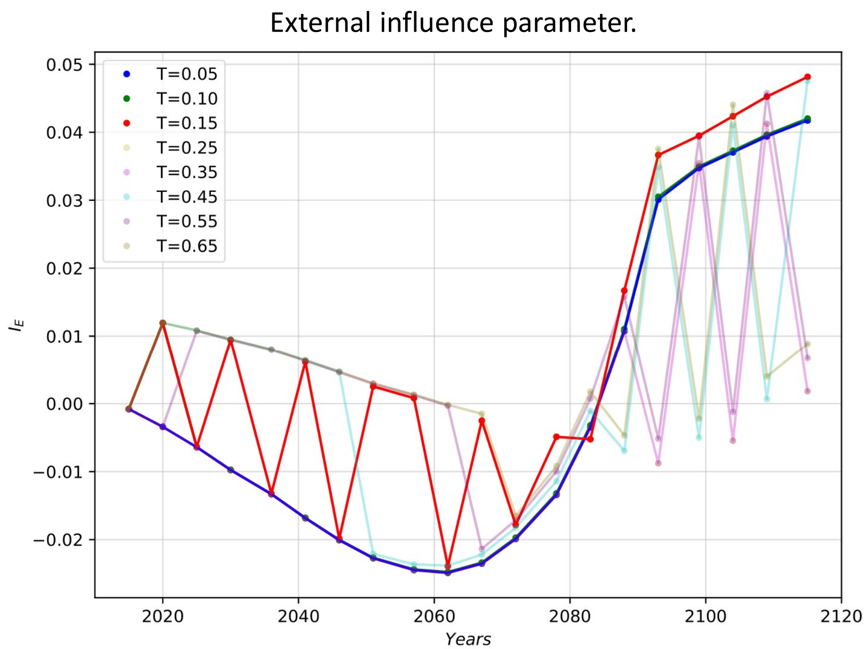
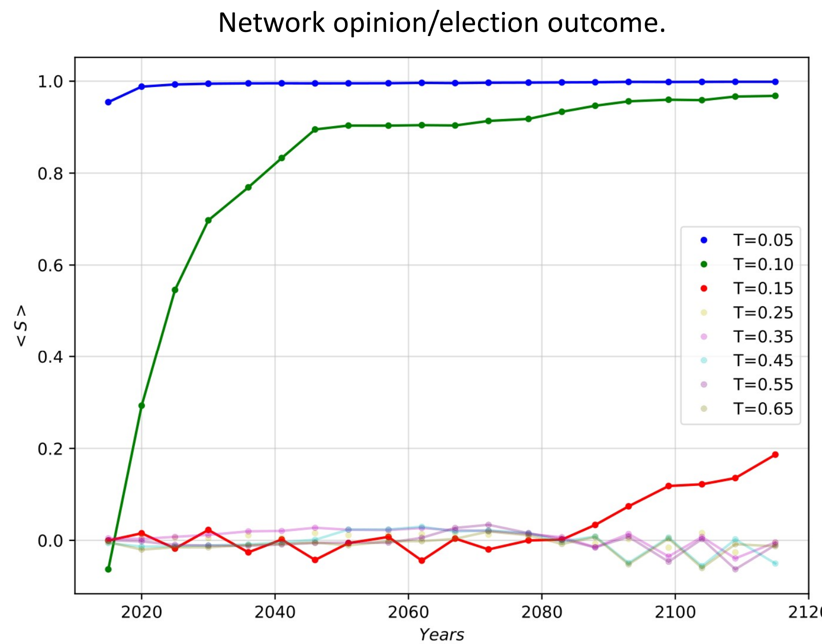
Network temperature





(N=200; γ=3; L_G=20; k_{min}=10; k_{max}=100; p_c=0.5; σ=0.3)

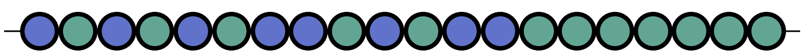
Network temperature

Election results and critical phase transition years (pro-climate)

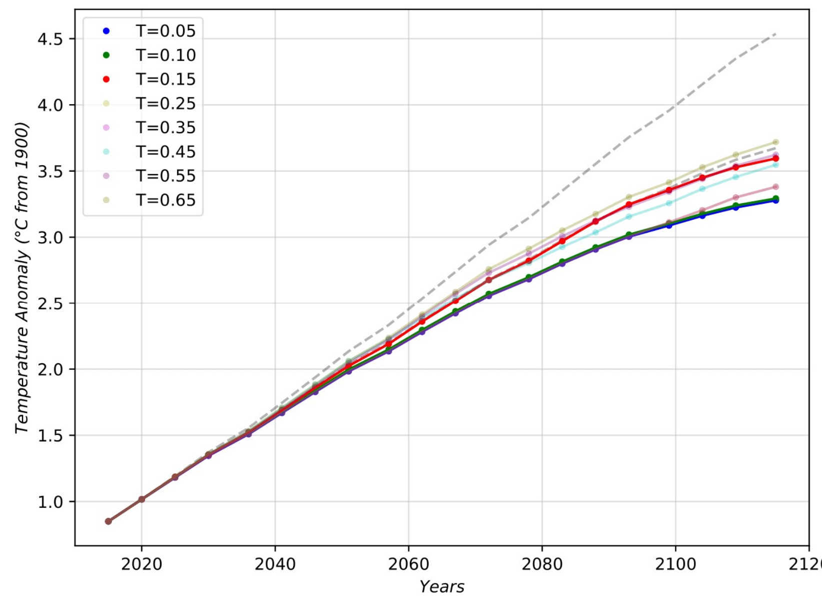
- T=0.05 - (2015)

- T=0.10 - (2020)

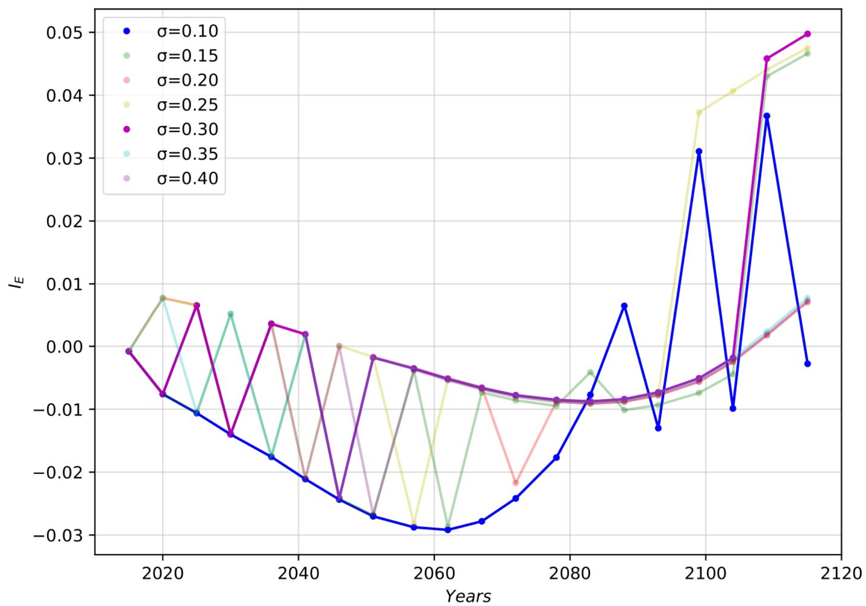
- T=0.15 - (2080)

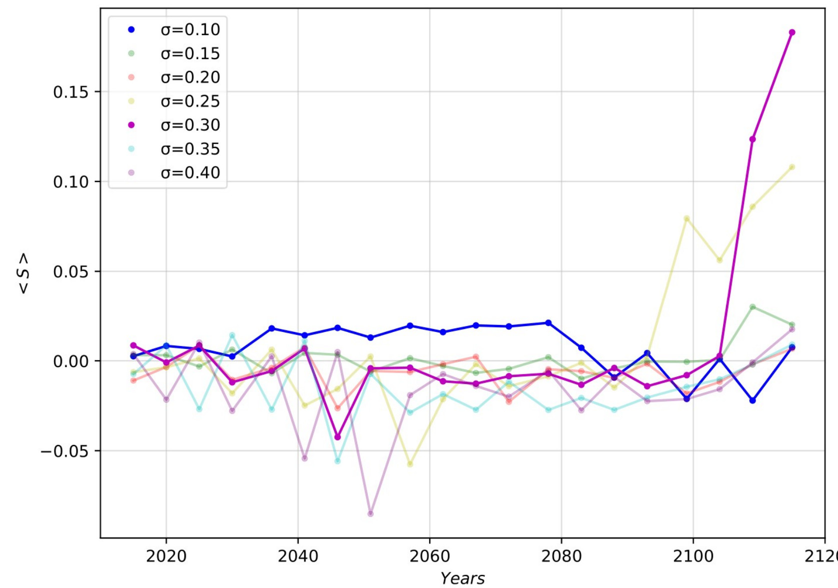


Temperature anomaly – “real” DICE



Network authority





(*N=200; γ=3;* L_G*=20;* k_{min}*=10;* k_{max}*=100;* p_c*=0.5; T=0.15*)

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Conclusions

- Devised a plausible coupling equation that links a climate-economy model to a network that models electoral outcomes;
- Climate damages contribute little to the short term concerns of the population: climate-related tax is more immediate and causes resistance in voting for pro-climate parties;
- When societies are made to care about future impacts of climate change, phase transitions in favor of pro-climate parties can occur.

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Outlook

- Streamline the results to find an analytic description – simplified analytic DICE model;

- Regional version of DICE (RICE model) – world is divided in 12 regions and only some of them are affected by electoral outcomes;

- Make the network graph dynamic: adapt the node size to population growth and account for shifts in authority over time.

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Thank you!

Acknowledgments:
Henk Stoof, Henk Dijstra, Claudia Wieners, Paolo Accordini, Michael Kliphuis and Joris Broere