The Global Water Cycle and Climate Policies in a General Equilibrium Model

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Stylized facts I: emissions and water use

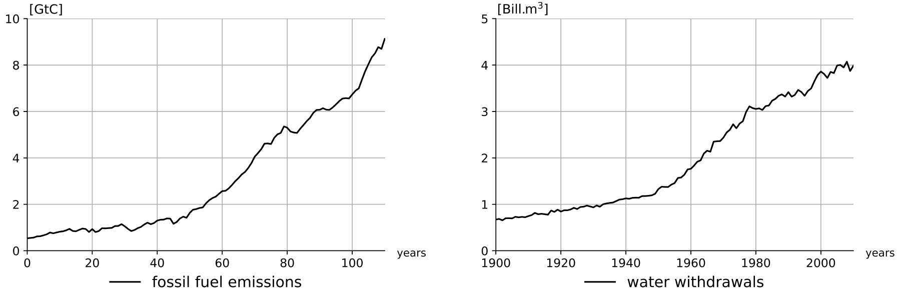


Figure: Fossil fuel emissions and fresh-water withdrawals 1900-2010

Stylized facts II: water stress

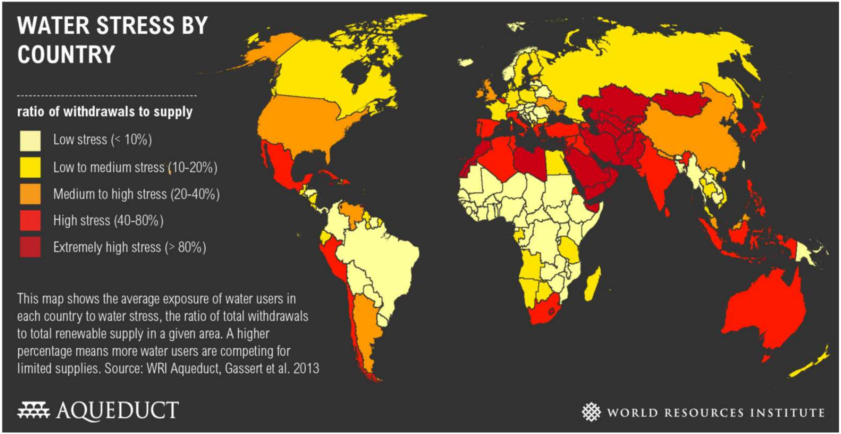


Figure: Water stress levels by country

Stylized facts III: water use in energy production

Energy type	Energy carrier	Water input [m^3/GJ]
FOSSIL FUEL		
	Coal	0.043
	Conventional oil	0.081
	Natural gas	0.004
NUCLEAR		0.105
BIOFUELS		
	Sugarcane (ethanol)	24.550
	Maize (ethanol)	8.090
	Sugarbeet (ethanol)	9.790
	Rapeseed (biodiesel)	19.740
	Soybean (biodiesel)	11.260
HYDROGEN		
	Electrolysis	0.580

Table: Fuel types and water consumption factors

Motivation

- Transition to 'clean' energy essentially implies substitution of fossil fuel by fresh water in energy production
- Studies from natural sciences show that carbon cycle is closely intertwined with water cycle and both are disrupted by global economy
- Trade-off: increasing water use to fight climate change vs. increasing water pollution from climate change
- Research questions centered around climate change and climate policy impacts on water cycle, economy and vice versa, requires a climate-economy model with a global water cycle
- Literature: Golosov et al. (2014), Inglezakis et al. (2016), Archer (2010), Overpeck & Updall (2010), Trenberth et al. (2007) etc.

Model setup

- Deterministic dynamic single-world climate-economy model in infite discrete time with two natural resources
- Model is highly stylized but based on much-used standard assumptions about preferences and technology
- Model features two externalities and is composed of:
  - A. Carbon cycle
  - B. Water cycle
  - C. Economic model

A. Carbon cycle

- Denote fossil fuel X_t, measured in units of CO_2
- We adopt standard three-layer carbon cycle model:
  - Atmospheric carbon M_t^A,
  - Upper oceans M_t^U,
  - Lower oceans M_t^L
- Carbon cycle described by linear three-layer system:

$$M_{t+1}^A = \phi_{11} M_t^A + \phi_{21} M_t^U + \phi_{31} M_t^L + X_t \quad (1a)$$
$$M_{t+1}^U = \phi_{12} M_t^A + \phi_{22} M_t^U + \phi_{32} M_t^L \quad (1b)$$
$$M_{t+1}^L = \phi_{13} M_t^A + \phi_{23} M_t^U + \phi_{33} M_t^L \quad (1c)$$

- Temperature dynamics given by

$$T_{t+1} = T_t + \theta_1 \big(\Delta_t - \theta_2 T_t - \theta_3 (T_t - T_t^L) \big) \quad (2a)$$
$$T_{t+1}^L = T_t^L + \theta_4 (T_t - T_t^L). \quad (2b)$$

- Rising global temperature T_t affects consumer utility

B. Water cycle

- Debote water use Z_t, water circles across three reservoirs:
  - surface and groundwater W_t^F, salt water W_t^O, atmospheric water vapor W_t^A
- Water cycle described by linear three dimensional system:

$$
\begin{aligned}
W_{t+1}^F &= \omega_{11} W_t^F + \omega_{21} W_t^A + \omega_{31} W_t^O - (1-\xi_1) Z_t, & \text{(3a)}\\
W_{t+1}^A &= \omega_{12} W_t^F + \omega_{22} W_t^A + \omega_{32} W_t^O + \xi_2 Z_t, & \text{(3b)}\\
W_{t+1}^O &= \omega_{13} W_t^F + \omega_{23} W_t^A + \omega_{33} W_t^O + \xi_3 Z_t, & \text{(3c)}
\end{aligned}
$$

- Introduce pollution index P_t which measures decline in fresh water quality due to economic activity and climate change
- Water pollution changes over time according to:

$$P_t = \underbrace{(1-\delta)P_{t-1}}_{\text{natural water quality regeneration}} + \underbrace{\chi Z_t}_{\text{direct water pollution}} + \underbrace{\psi T_t}_{\text{indirect water pollution through climate change}} \qquad (4)$$

- Rising water pollution P_t affects consumer utility

C. Economic model

- Consumption:
  - Standard infinitely lived representative consumer
  - Supplies capital and decides about consumption and capital formation and receives profits from all firms and transfers from the government

$$U((C_t, T_t, P_t)_{t\geq 0}) = \sum_{t=0}^{\infty} \beta^t \Big(u(C_t) - v(P_t, T_t) \Big) \tag{5}$$

- Production:
  - Final output commodity Y_t produced using capital K_t and two natural resource inputs X_t, Z_t using standard aggregate production technology:

$$Y_t = F(K_t, X_t, Z_t) \tag{6}$$

  - Standard fossil fuel resource extraction problem with feasibility constraint:

$$\sum_{t=0}^{\infty} X_t \leq R_0. \tag{7}$$

Planning problem

- Consider a planner choosing an allocation $(C_t, K_t, X_t, Z_t)_{t \geq 0}$ which accounts for both externalities in consumer utility
- The planner takes initial capital K_0, fossil resources R_0, initial water pollution P_0, and initial states of the two natural cycles W_0, M_0 as given
- Plannning problem (PP) is constrained optimization problem
- Adopt standard infinite-dimensional Lagrangian approach to obtain explicit conditions which completely characterize the social optimum which is solution to PP
- Beside the 'efficient' solution, we consider two types of constrained policy interventions by social planner:
  - 'Sub-optimal' solution which corrects only for direct but not indirect climate externality and not water pollution externality
  - 'Laissez-faire' solution whithout any environmental policy

Optimal water extraction

Proposition *Let $\hat{v}_t$ denote the (shadow) price for fresh water and $\hat{p}_{z,t} := \hat{v}_{z,t} - c_z$ denote prices net of extraction costs. Then, (PP) has an interior solution*

$$0 < Z_t^* < W_{t+1}^F \quad \textit{for all } \ t = 0, 1, 2, ... \tag{8}$$

if and only if fresh water resource prices satisfy

$$\hat{p}_{z,t+1} = r_{t+1}\hat{p}_{z,t} \quad \forall t \geq 0. \tag{9}$$

In this case, any sequence $(Z_t)_{t\geq 0}$ satisfying (8) is a solution.

(i) *If the water cycle (3) is closed ($\sum_{i\in\{1,2,3\}} \xi_i = 1$), the initial price satisfies $\hat{p}_{z,0} = 0 \quad \Longleftrightarrow \quad \hat{v}_{z,t} = c_z$.*

(ii) *If the water cycle (3) is semi-closed ($\sum_{i\in\{1,2,3\}} \xi_i \leq 1$), the initial price satisfies $\hat{p}_{z,0} > 0 \quad \Longleftrightarrow \quad \hat{v}_{z,t} > c_z$.*

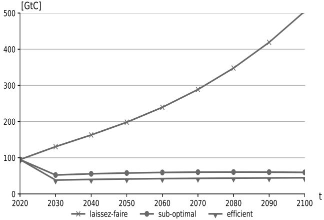
Social cost of carbon (SCC)

- Denote total costs of emitting one additional unit of CO_2 in period t by Λ_t^{MA}
- Λ_t^{MA} corresponds to discounted sum of all future marginal climate damages caused by this emission (SCC):

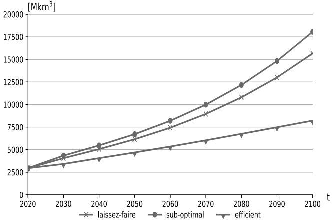
$$\Lambda_t^{MA} = \sum_{n=0}^{\infty} \frac{\beta^n}{u'(C_t)} \left(\hat{\theta}^n \underbrace{\frac{\partial v(P_{t+n}, T_{t+n})}{\partial T_{t+n}}}_{\text{direct climate impact}} + \underbrace{\frac{\psi(1-\delta)^n}{1-\hat{\theta}\beta} \frac{\partial v(P_{t+n}, T_{t+n})}{\partial P_{t+n}}}_{\text{natural cycles interaction impact}} \right) \tag{10}$$

- Key difference compared to literature: SCC contains a direct and a novel indirect climate externality component
- $\Rightarrow$ Integration of recent findings from natural sciences leads to upward adjustment of SCC

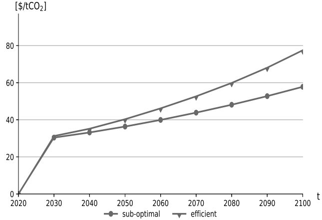
A basic quantitative example



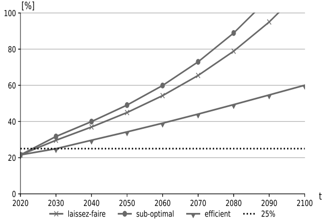
(a) Emissions



(b) Water use



(c) Social cost of carbon



(d) Water stress

Figure: Evolution under optimal and sub-optimal taxation

Summary and model extensions

- Summary
  - This work introduced a global water cycle into an otherwise standard climate-economy model
  - If global hydrological cycle is a closed system, fresh water is abundant and has no scarcity rent
  - Considering the water cycle as part of the climate problem increases the social cost of carbon
  - A climate tax reduces emissions significantly but comes at cost of temporary reduced output, increase in water consumption and potentially negative effects on water quality levels
  - Coordination of climate and environmental policies needed
- Model extensions:
  - Endogenous and directed technological change, akin to the approaches of Acemoglu et al. (2012) and Hassler et al. (2021)
  - Explicit formulation of an energy sector as in Golosov et al. (2014)
  - Multi-country model with integrated global water cycle alongside environmental constraints (Hillebrand & Hillebrand (2019))

Thank you for your attention! :-)