MADIAMS – A Multi-Actor Dynamic Integrated Assessment Model System for the analysis of climate change policies

Klaus Hasselmann

Max Planck Institute for Meteorology, Hamburg, and

European Climate Forum

GSD – ECF workshop on "System Dynamic Models of Coupled Natural-Social Systems", Bekkjarvik, 22-26 June 2009.

MADIAMS – A Multi-Actor Dynamic Integrated Assessment Model System for the analysis of climate change policies

Goal: contribution of science to climate policy by

- providing models that capture the basic processes that concern policy-makers

MADIAMS – A Multi-Actor Dynamic Integrated Assessment Model System for the analysis of climate change policies

Goal: contribution of science to climate policy by

- providing models that capture the basic processes that concern policy-makers

- communicating our understanding of these processes to the public and decision makers through easily explainable models

Overview

1. General remarks on economic modeling (from a physicist's viewpoint)

Overview

1. General remarks on economic modeling (from a physicist's viewpoint)

2. The MADIAMS project

Overview

1. General remarks on economic modeling (from a physicist's viewpoint)

2. The MADIAMS project

3. Some results

Overview

Overview

➡ 1. General remarks on economic modeling (from a physicist's viewpoint)

2. The MADIAMS project

3. Some results

4. Outlook

Current paradigm shift in macroeconomic modelling (accelerated through global financial crisis and recession) : general equilibrium theory system dynamic, agent- based models

➡

George Cooper, "…The Efficient Market Fallacy", 2008,

George Akerlof and Robert Shiller, "Animal spirits", 2009.

Current paradigm shift in macroeconomic modelling (accelerated through global financial crisis and recession) : general equilibrium theory system dynamic, agent- based models

→

George Cooper, "…The Efficient Market Fallacy", 2008,

George Akerlof and Robert Shiller, "Animal spirits", 2009.
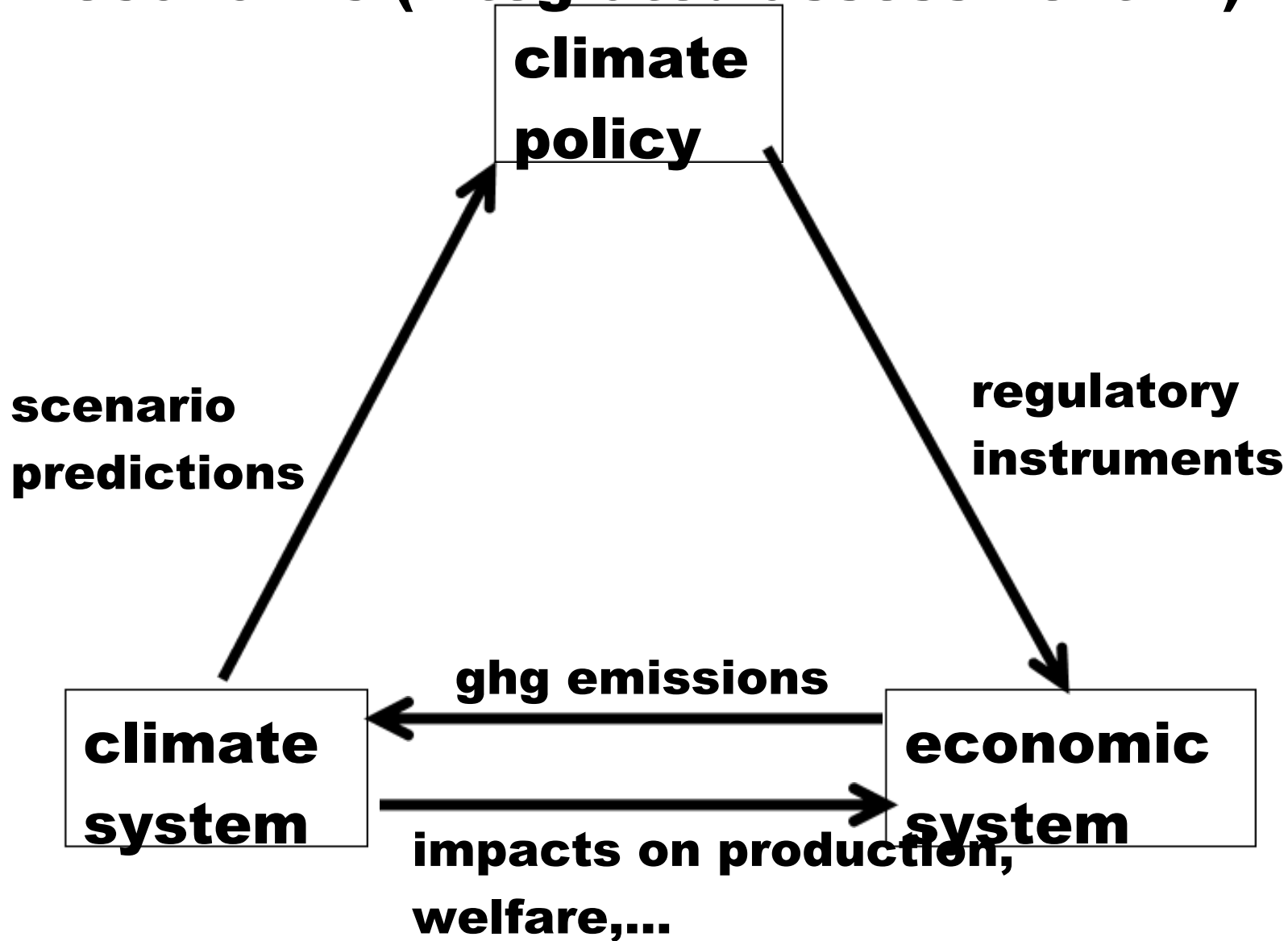
See also classical works of

John Maynard Keynes, The general theory of Employment, Interest and Money, 1936

Hyman Minsky, Stabilizing an Unstable Economy, 1986 (republished 2008)
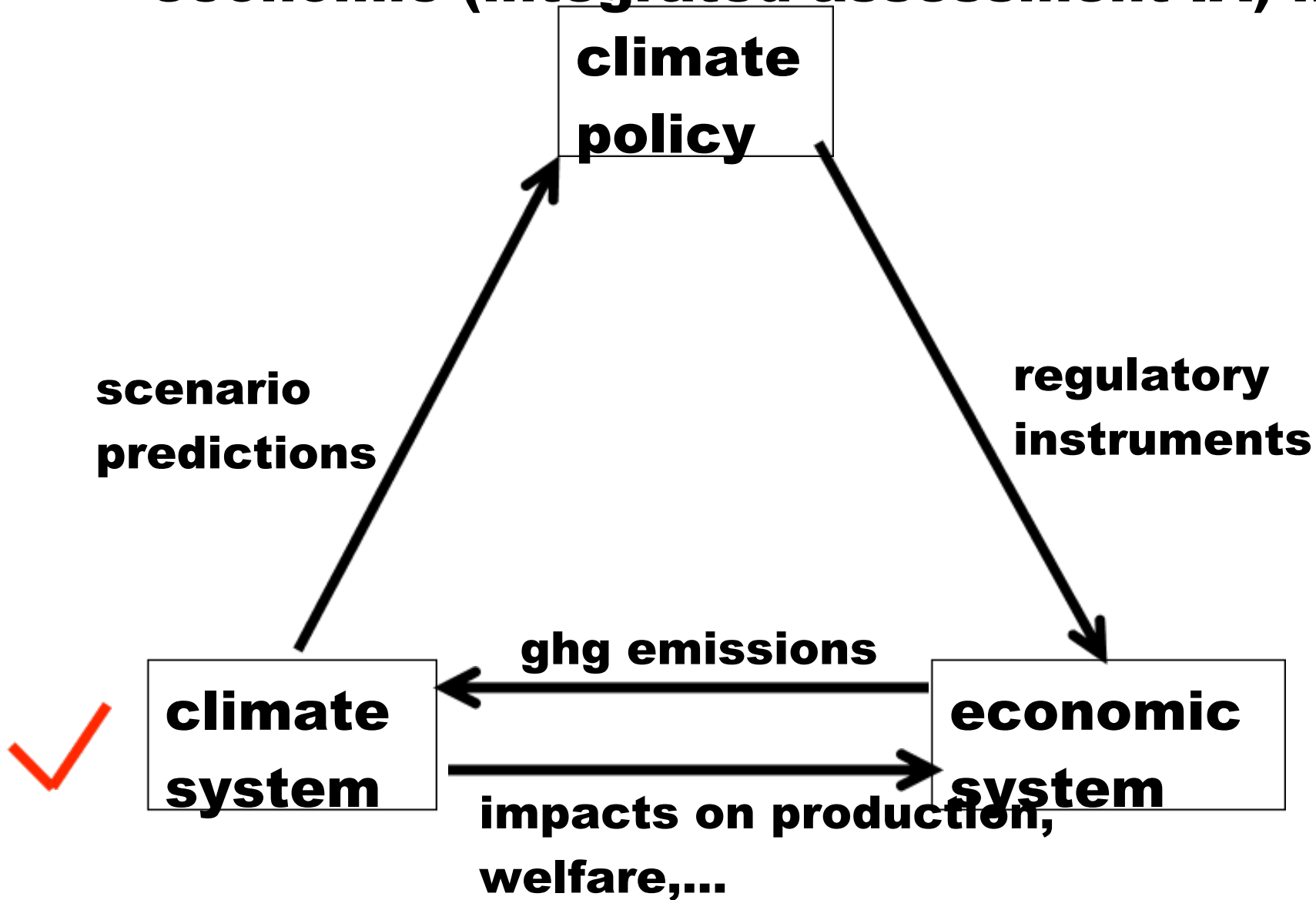
George Akerlof and Robert Shiller ("Animal spirits":, 2009):

"The real problem ...[is that] … the macroeconomics and financial profession [has] gone so far in the direction of "rational expectations" and "efficient markets" that [it] fails to consider the most important dynamics underlying economic crises. Failing to incorporate animal spirits [*i.e.actor behavior*] into the model can blind us to the real sources of trouble."
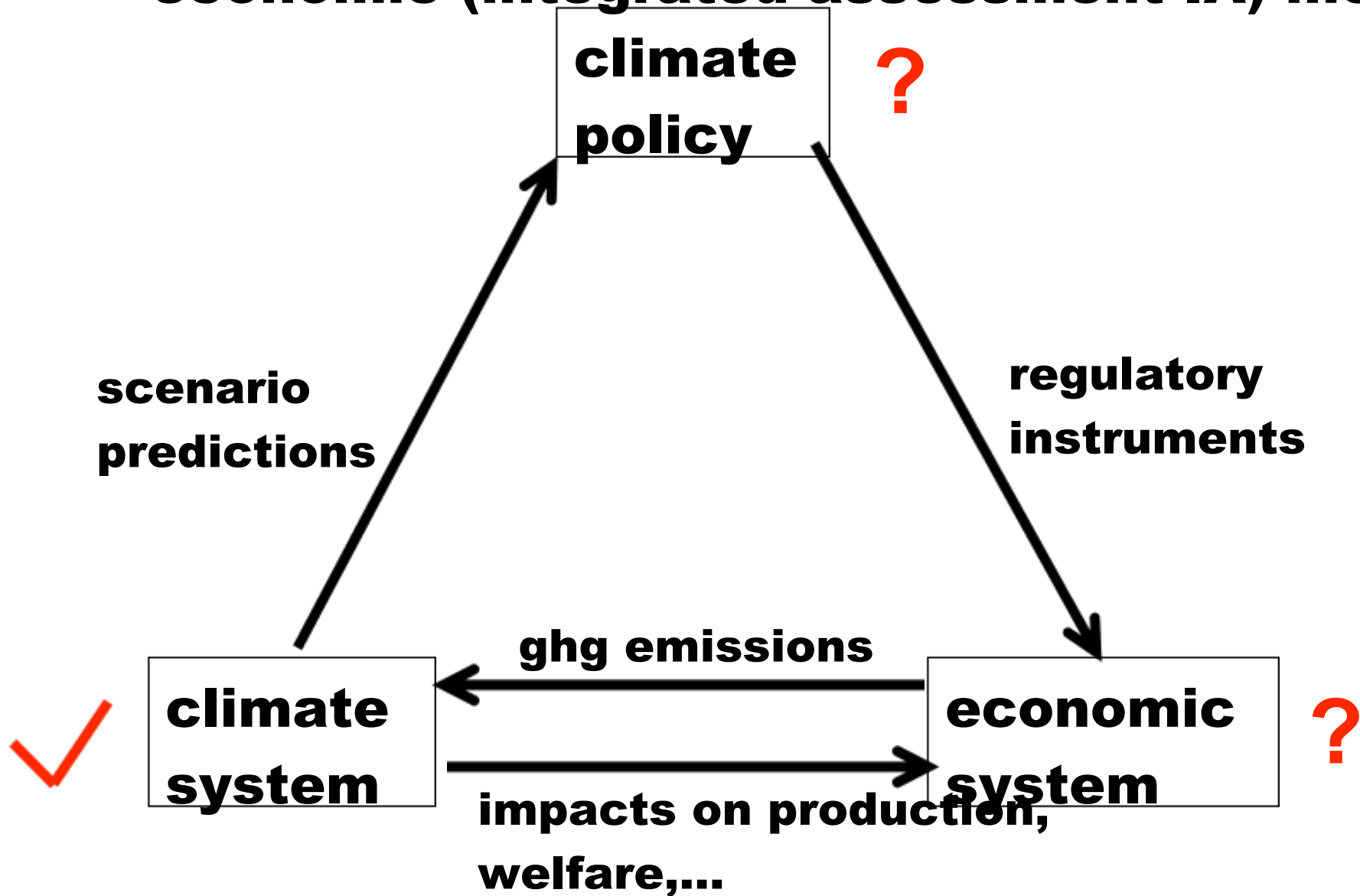
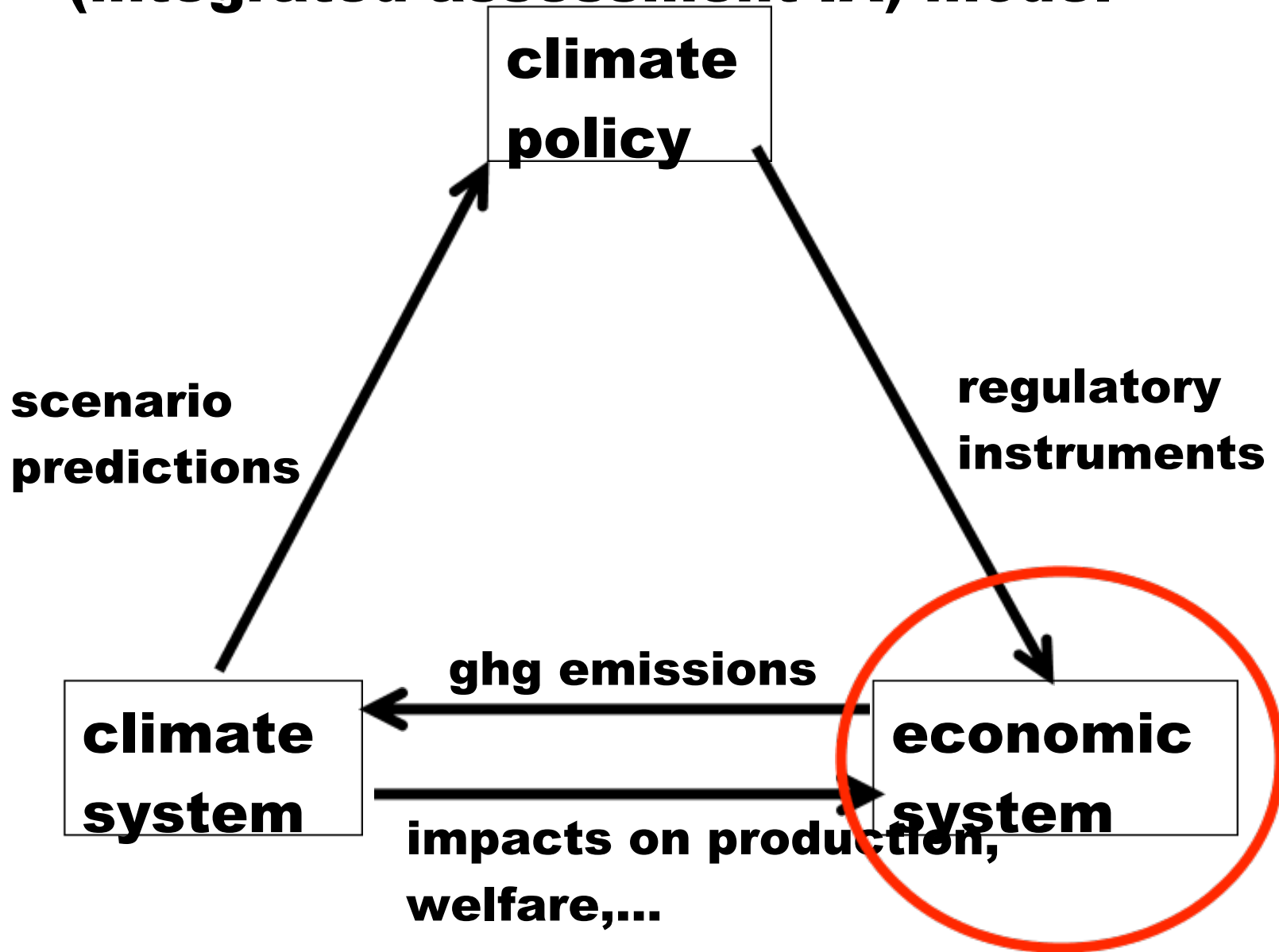# General structure of coupled climate-economic (integrated assessment-IA) model

climate policy

scenario predictions

regulatory instruments

ghg emissions

climate system

economic system

impacts on production, welfare,...

General structure of coupled climate-economic (integrated assessment-IA) model

climate policy

scenario predictions

regulatory instruments

ghg emissions

climate system

economic system

impacts on production, welfare,...

General structure of coupled climate-economic (integrated assessment-IA) model

climate policy **?**

scenario predictions

regulatory instruments

climate system

ghg emissions

economic system **?**

impacts on production, welfare,...

Traditional coupled climate-economic (integrated assessment-IA) model

climate policy

scenario predictions

regulatory instruments

ghg emissions

climate system

economic system

impacts on production, welfare,...

"invisible hand" establishes market equilibrium

Agent-based integrated assessment model

climate policy

Agents: governments, public, media, consumers, firms, workers, ...

regulatory instruments

scenario predictions

ghg emissions

climate system

economic system

impacts on production, welfare,...
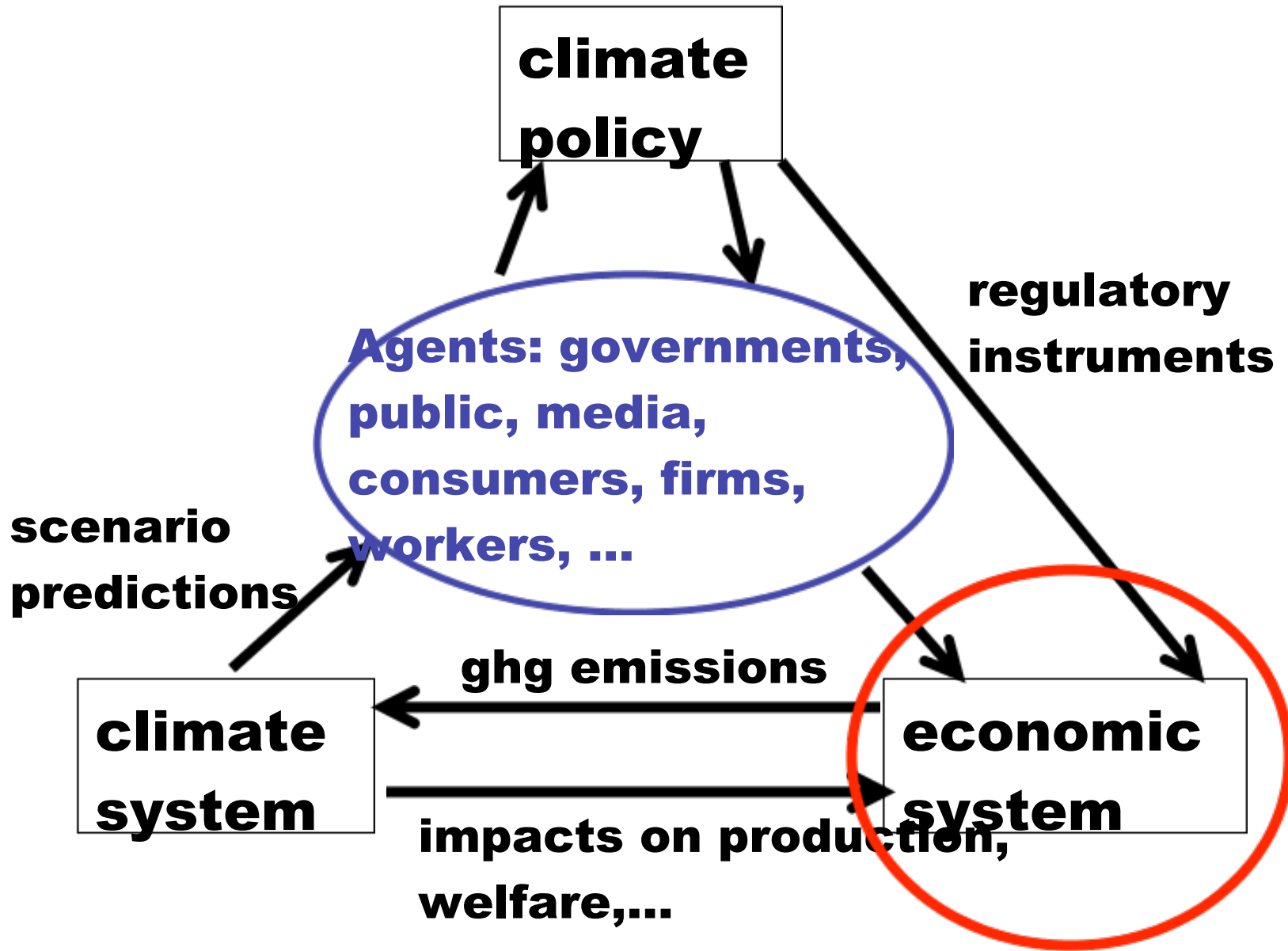
Dynamic evolution, governed by agent strategies

Divergence in views on the structure of macroeconomic systems arises already in the representation of the basic interrelations between standard economic concepts

Divergence in views on the structure of macroeconomic systems arises already in the representation of the basic interrelations between standard economic concepts

- namely the interrelation between

- products

- wealth, and

- actors

Products

Products

- goods & services
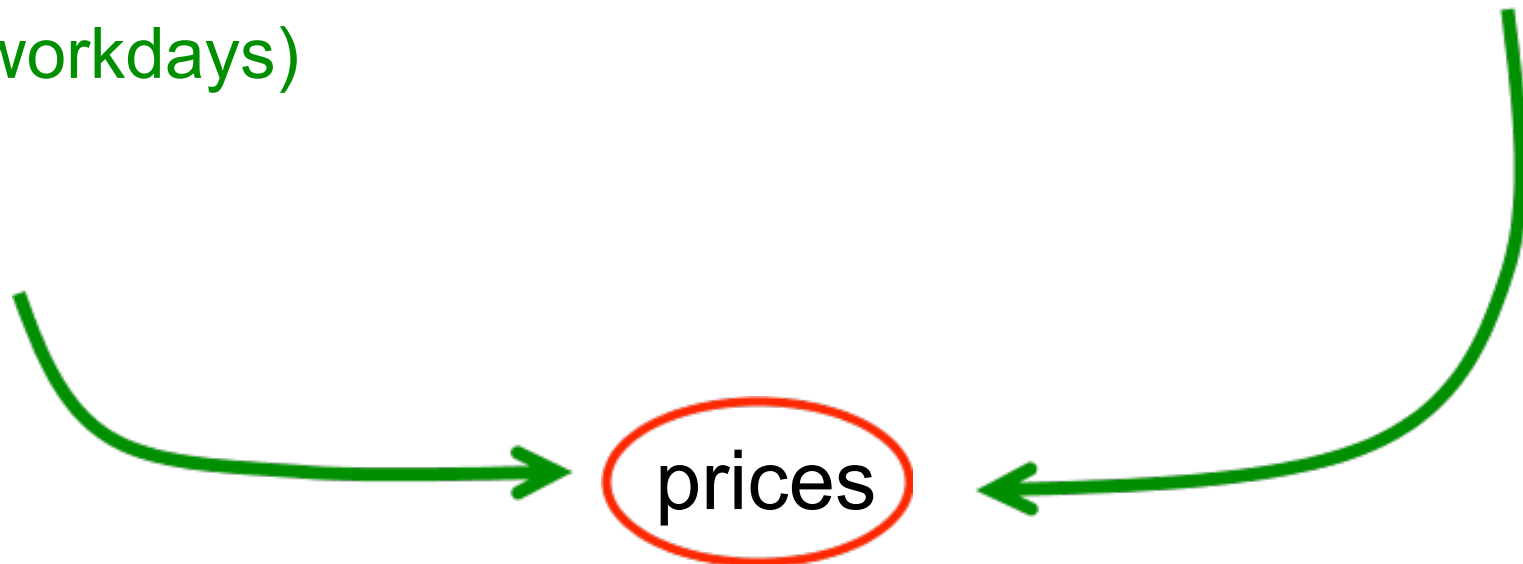
- physical capital

- human capital

- natural resources

Products

- goods & services

- physical capital

- human capital

- natural resources

(measured in different physical units – or in the common unit of human work days)

Products

- goods & services

- physical capital

- human capital

- natural resources

(measured in different
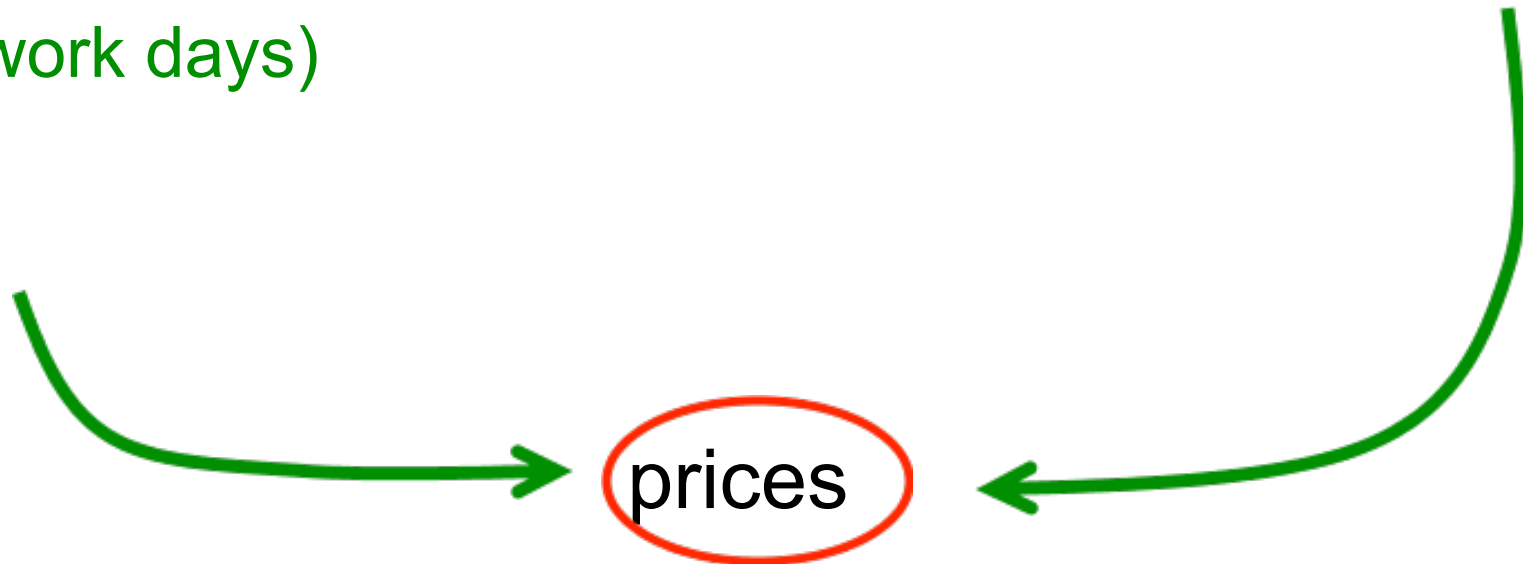physical units – or in
common unit of
human work days)

Wealth

- money
  equivalent
  of products

(measured in
currency units)

Products

- goods & services

- physical capital

- human capital

- natural resources

(measured in different physical units – or in common unit of human workdays)

Wealth

- money equivalent of products

(measured in currency units)

prices

Products

- goods & services
- physical capital
- human capital
- natural resources

(measured in different physical units – or in common unit of human work days)

Actors

- produce products
- consume products
- own products
- trade
- invest
- regulate

Wealth

- money equivalent of products

(measured in currency units)

prices

Products ⟷ Actors ⟷ Wealth

Products
- goods & services
- physical capital
- human capital
- natural resources

(measured in different physical units – or in common unit of human work days)

Actors
- produce products
- consume products
- own products
- trade
- invest
- regulate

Wealth
- money equivalent of products

(measured in currency units)

prices

Products ⟷ Actors ⟷ Wealth

Products	Actors	Wealth
• goods & services	• produce products	• money equivalent of products
• physical capital	• consume products	
• human capital	• own products	
• natural resources	• trade	
	• invest	
	• regulate	

Vensim sketch of basic stocks-and-flows dynamics

Products ⟷ Actors ⟷ Wealth
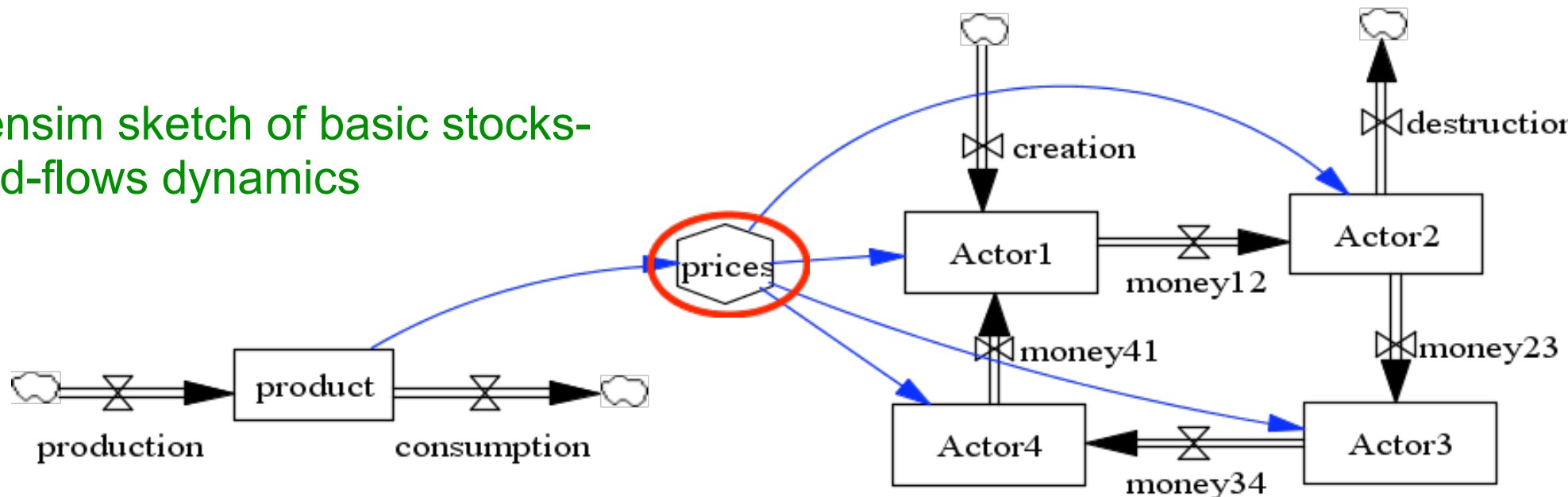
Products
- goods & services
- physical capital
- human capital
- natural resources

Actors
- produce products
- consume products
- own products
- trade
- invest
- regulate
- create money

Wealth
- money equivalent of products
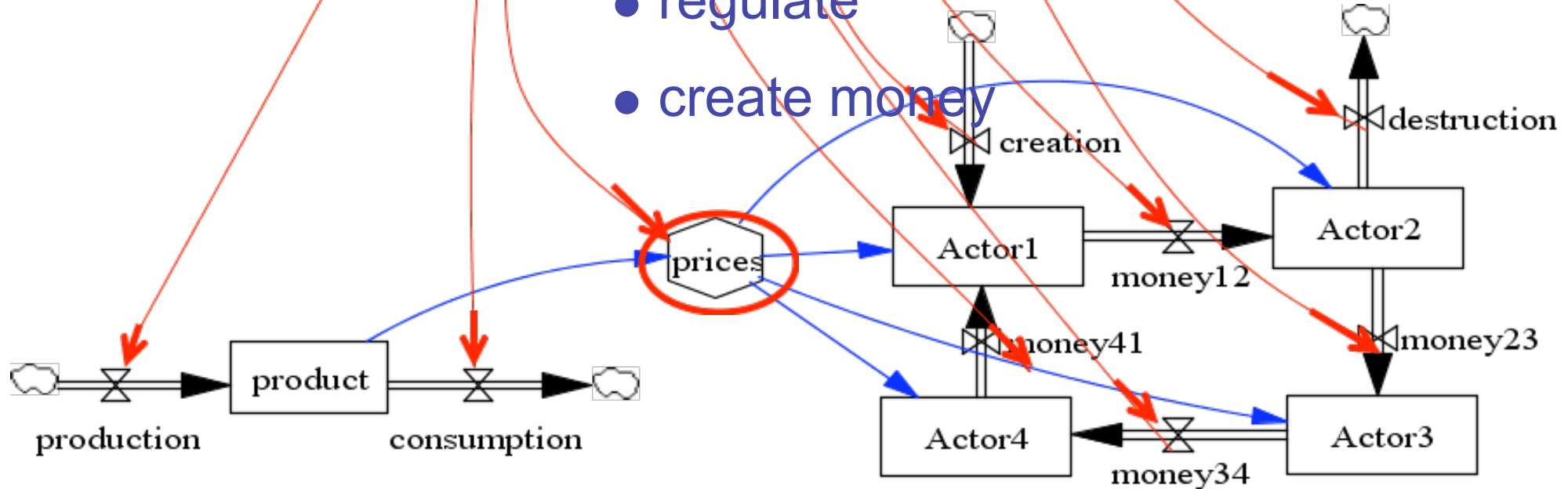
Role of actors

Invisible hand   Heterogeneous actors

Role of actors

Invisible hand   Heterogeneous actors

Both accept: different actors pursue different goals

Role of actors

Invisible hand   ## Heterogeneous actors

Both accept: different actors pursue different goals

Competition ensures optimal
actor-indep-endent outcome

Role of actors

Invisible hand   Heterogeneous actors

Both accept: different actors pursue different goals

Competition ensures optimal
actor-indep-endent outcome:

- full employment

Role of actors

Invisible hand   Heterogeneous actors

Both accept: different actors pursue different goals

Competition ensures optimal
actor-indep-endent outcome:

- full employment

- optimal allocation of
  resources

Role of actors

Invisible hand   Heterogeneous actors

Both accept: different actors pursue different goals

Competition ensures optimal
actor-indep-endent outcome:

- full employment

- optimal allocation of
  resources

- stable response to
  exogeneous shocks

Role of actors

Invisible hand

Heterogeneous actors

Both accept: different actors pursue different goals

Competition ensures optimal actor-indep-endent outcome:

"Optimal outcome" conceptually meaningless for differing actor goals

- full employment

- optimal allocation of resources

- stable response to exogeneous shocks

Role of actors

Invisible hand

Heterogeneous actors

Both accept: different actors pursue different goals

Competition ensures optimal actor-indep-endent outcome:

"Optimal outcome" conceptually meaningless for differing actor goals

- full employment

- optimal allocation of resources

- stable response to exogeneous shocks

- economic evolution strongly dependent on actor "power" and socio-economic "culture"

Role of actors

Invisible hand

Heterogeneous actors

Both accept: different actors pursue different goals

Competition ensures optimal actor-indep-endent outcome:

- full employment

- optimal allocation of resources

- stable response to exogeneous shocks

"Optimal outcome" conceptually meaningless for differing actor goals

- economic evolution strongly dependent on actor "power" and socio-economic "culture"

- system is inherently unstable and must be stabilized by governments

Role of actors

Invisible hand   ## Heterogeneous actors

Both accept: different actors pursue different goals

Competition ensures optimal actor-indep-endent outcome:

"Optimal outcome" conceptually meaningless for differing actor goals

- full employment

- optimal allocation of resources

- stable response to exogeneous shocks

- economic evolution strongly dependent on actor "power" and socio-economic "culture"

- system is inherently unstable and must be stabilized by governments

- governments must guide economic transformation to achieve sustainability

The consideration of many heterogeneous actors (wage earners, shareholders, consumers, CEOs, households, politicians, lobbyists, media, voting public, …)

The consideration of many heterogeneous actors (wage earners, shareholders, consumers, CEOs, households, politicians, lobbyists, media, voting public, …)

from many different geographical regions and cultures…

The consideration of many heterogeneous actors (wage earners, shareholders, consumers, CEOs, households, politicians, lobbyists, media, voting public, …)

from many different geographical regions and cultures…

yields a complex dynamical system that is far more multi-facetted than the general equilibrium paradigm.

The consideration of many heterogeneous actors (wage earners, shareholders, consumers, CEOs, households, politicians, lobbyists, media, voting public, …)

from many different geographical regions and cultures…

yields a complex dynamical system that is far more multi-facetted than the general equilibrium paradigm.

This implies that

1. models will need to be used first as learning and hypothesis-testing tools, only subsequently as communication and policy advisory tools

The consideration of many heterogeneous actors (wage earners, shareholders, consumers, CEOs, households, politicians, lobbyists, media, voting public, …)

from many different geographical regions and cultures…

yields a complex dynamical system that is far more multi-facetted than the general equilibrium paradigm.

This implies that

1. models will need to be used first as learning and hypothesis-testing tool, only subsequently as communication and policy advisory tools

2. models are best developed as a hierarchy

from simple models to more complex models

Tree structure of a conceivable dynamic, multi-actor, macroeconomic model hierarchy

root model | 1.0 |

Tree structure of a conceivable dynamic, multi-actor, macroeconomic model hierarchy
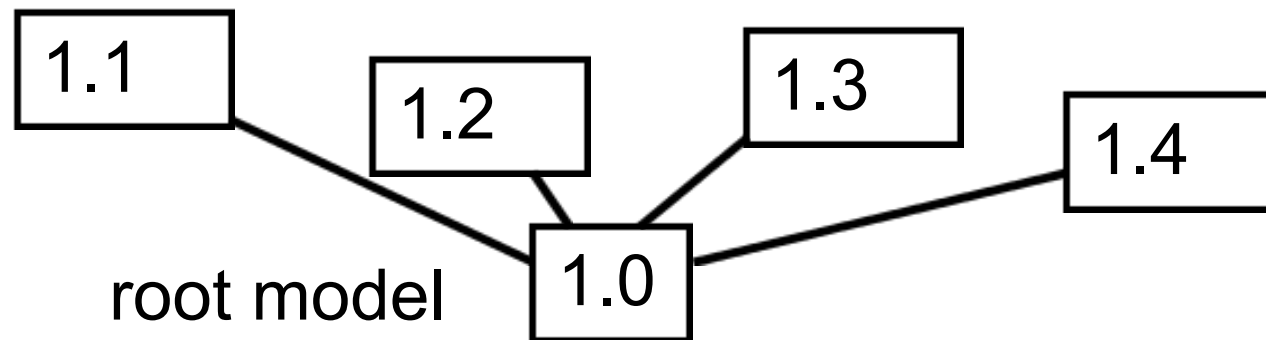
Tree structure of a conceivable dynamic, multi-actor, macroeconomic model hierarchy

Tree structure of a conceivable dynamic, multi-actor, macroeconomic model hierarchy

No longer supported by data

1.2.1

1.3.1

1.1.2

1.4.1

1.1.1

1.2.2

1.3.2

1.4.2

1.1

1.2

1.3

1.4

root model

1.0

Overview

Alternative MADIAMS path: reduce earlier higher-level MADIAM model down to simpler root model, then expand root model in new directions horizontally and vertically.

No longer supported by data

1.1.1 1.1.2 1.2.1 1.3.1 1.2.2 1.4.1 1.3.2 1.4.2

1.1 1.2 1.3 1.4

root model 1.0 2.0 2nd root model

Alternative MADIAMS path: reduce earlier higher-level MADIAM model down to simpler root model, then expand root model in new directions horizontally and vertically.

Motivation: Include business-cycles and financial instabilities

No longer supported by data

1.1.1

1.1.2

1.2.1

1.3.1

1.2.2

1.4.1

1.3.2

1.4.2

1.1

1.2

1.3

1.4

root model

1.0

2.0

2nd root model
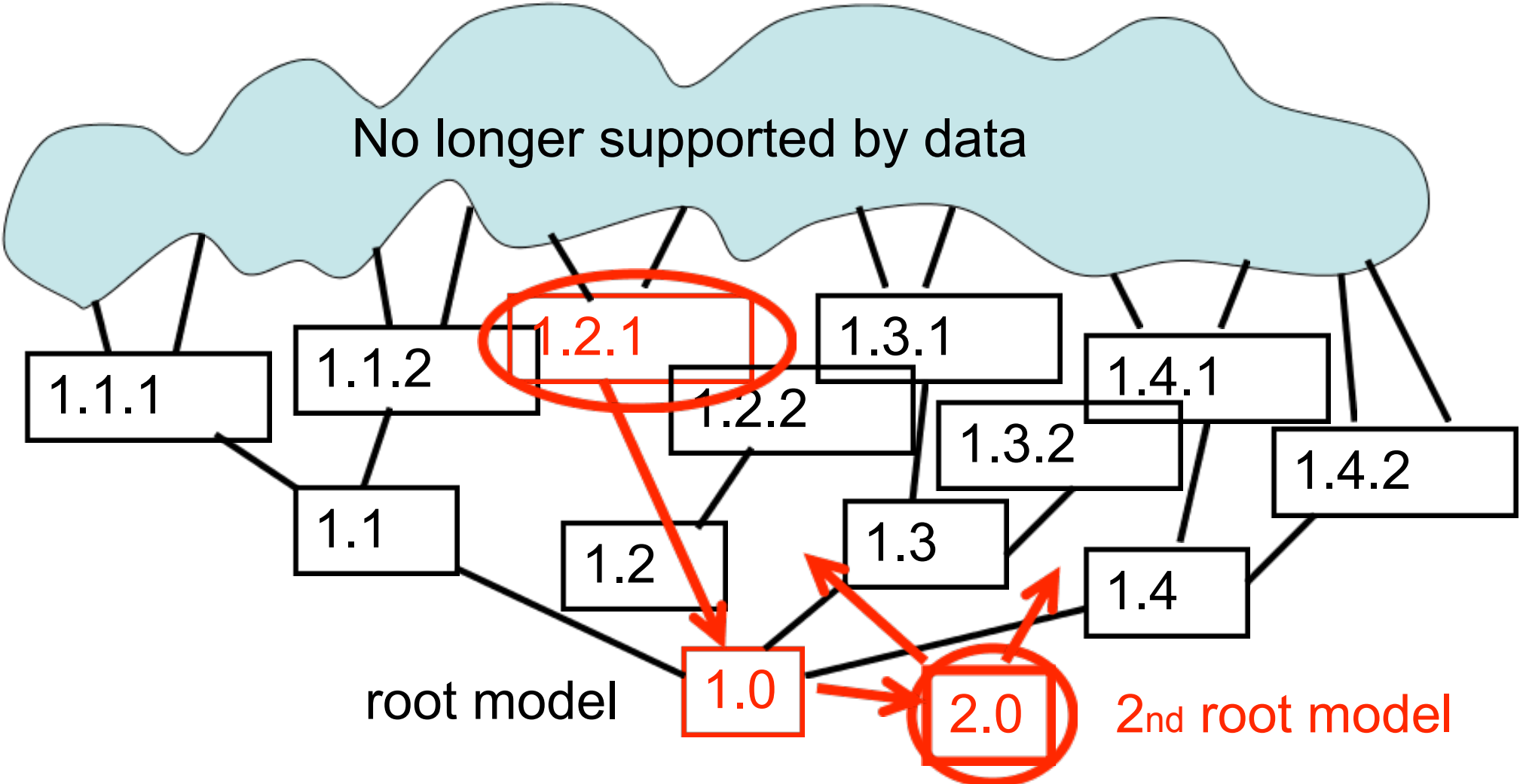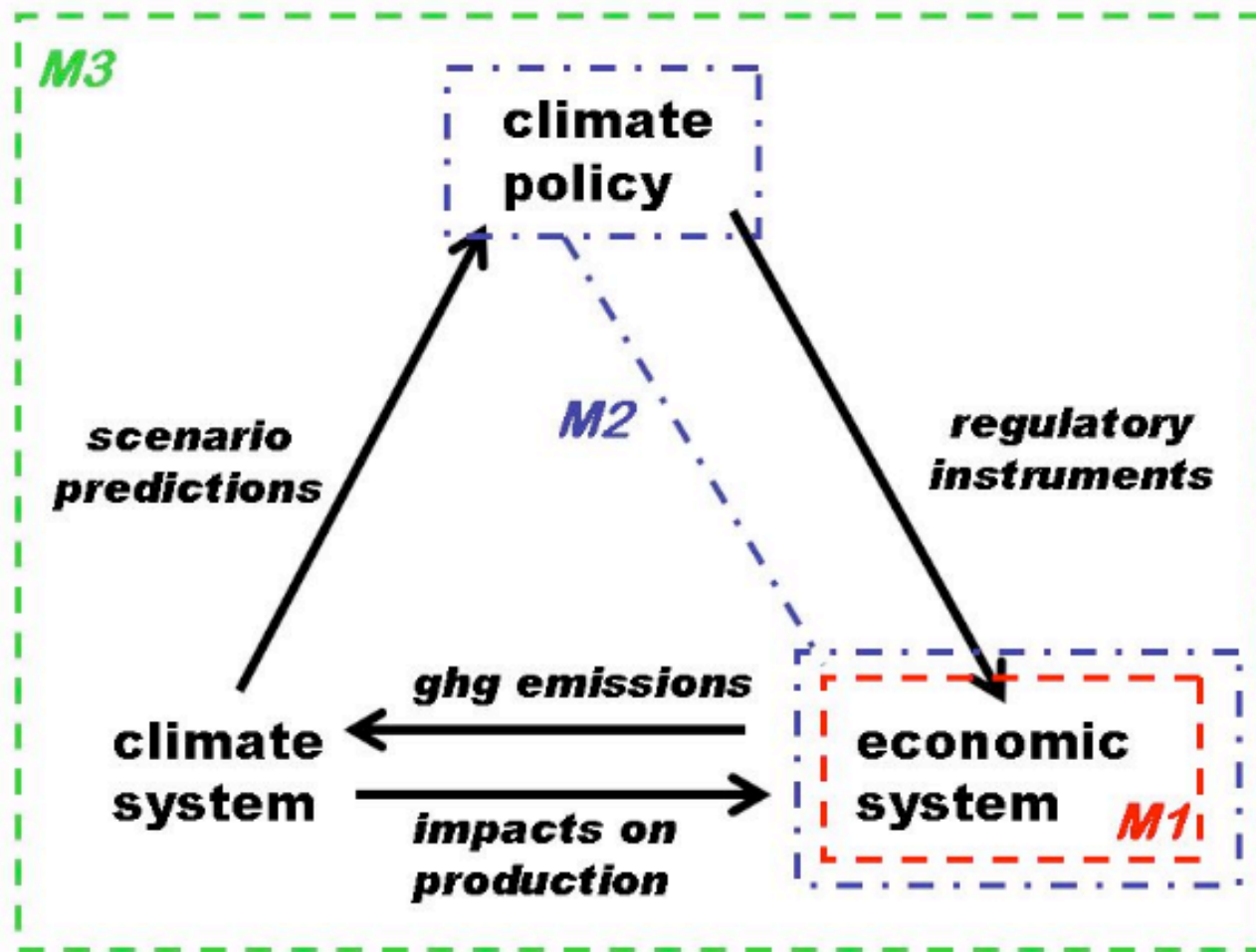
The MADIAMS model levels:

M1 : economic system without government

M2 : full economic system (i.e. with government)

M3 : full economic system plus climate system (full IA model)

Model M3.0

NICCS: Hooss et al, Climate Dynamics, 2001 MADIAM (Multi-Actor Dynamic Integrated Assessment Model): Weber et al, Ecol.Econ. 2005

Climate

NICCS: **N**on-linear **I**mpulse response coupled **C**arbon cycle-**C**limate **S**ystem

CO2 emissions

Policy + Economics

MADEM:
Multi-**A**ctor **D**ynamic **E**conomic **M**odel

Climate change : space-time fields of temperature, sea level, precipitation, etc
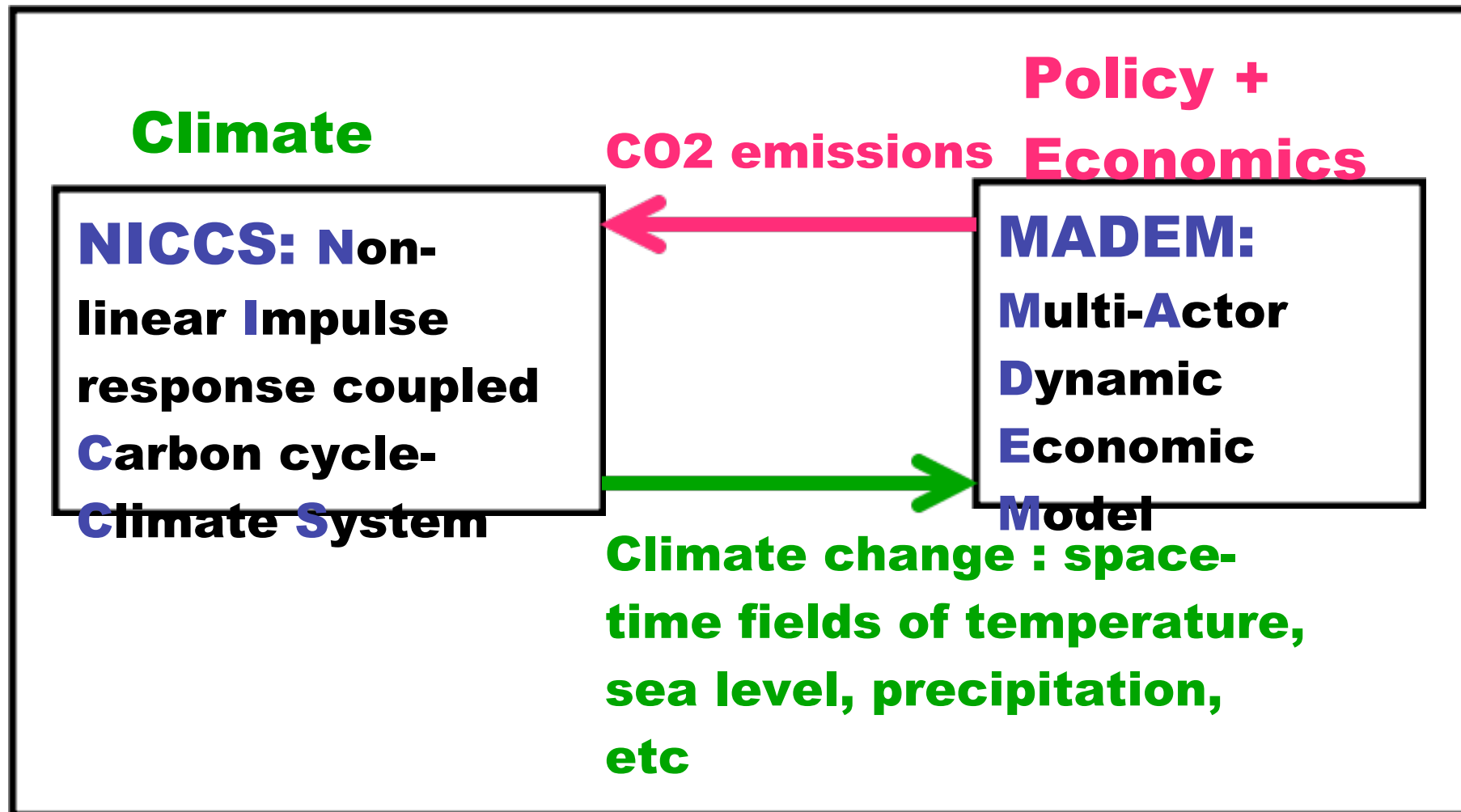
Model M3.0 (MADIAM)

NICCS: Hooss et al, Climate Dynamics, 2001 MADIAM: Weber et al, Ecological Economics, 2005

Climate

Policy + Economics

CO2 emissions

NICCS: Non-linear **I**mpulse response coupled **C**arbon cycle-**C**limate **S**ystem

MADEM: Multi-**A**ctor **D**ynamic **E**conomic **M**odel

Climate change : space-ields of temperature, vel, precipitation,
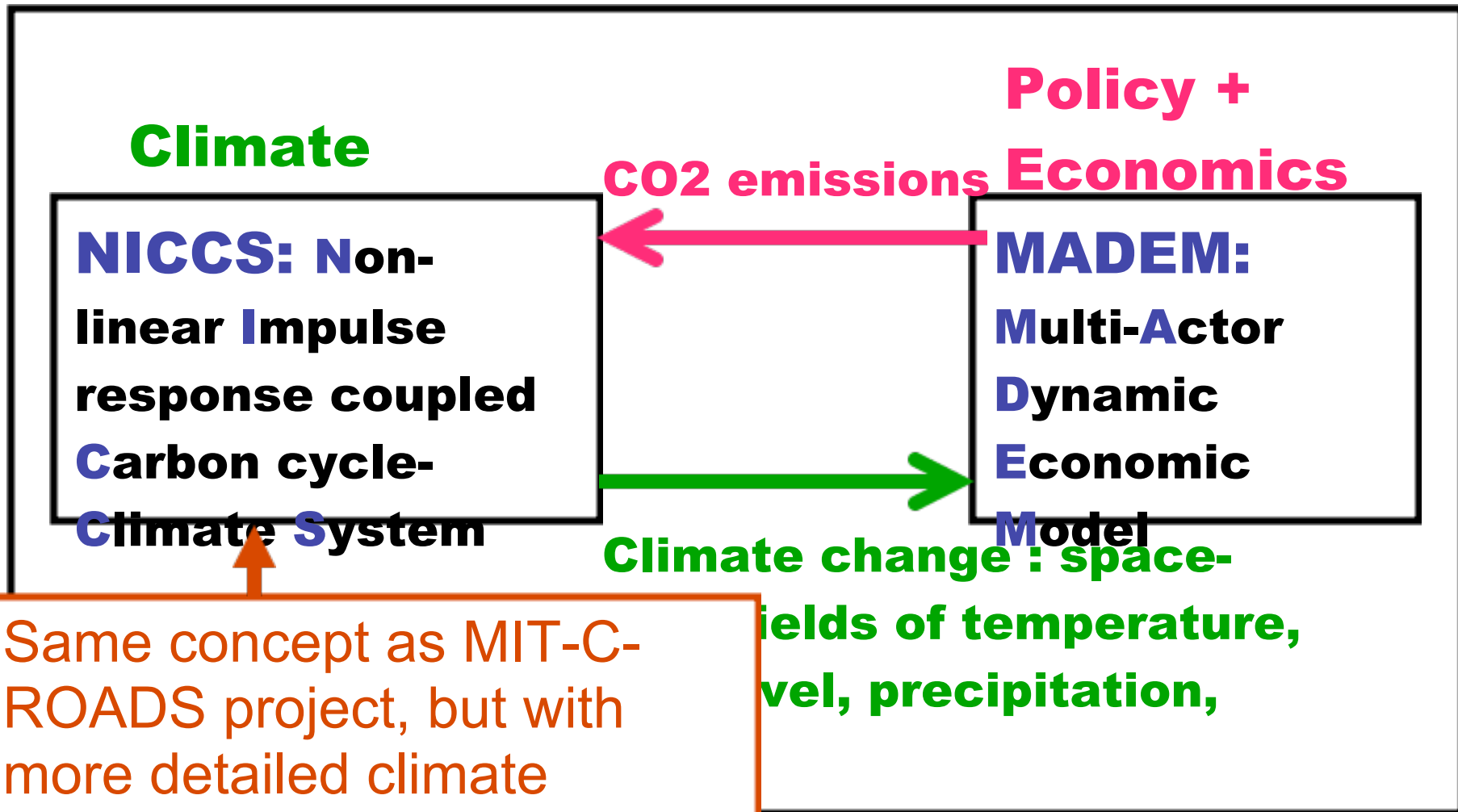
Same concept as MIT-C-ROADS project, but with more detailed climate response, less detailed input (CO2 only)

MADEM mathematical structure:

state variables $x = (x_i)$

control variables $z = (z_i) = C_i(x)$
($C_i(x)$ define the actors' control strategies)

Prognostic equations:

$$dx_i/dt = F_i(x,z) = G_i(x)$$

5 Actors: firms, workers, consumers, banks, governments

11 state variables x_i : physical capital, productivity, employed workers, wages, household and firm savings, government budget deficit, energy intensity, carbon intensity, fossil resources

Implementation:

- Fortran (Weber et al, 2005)

- As interactive 2-player computer game, Munich Climate Exhibition, German Museum

- As basis for board game "Winds of Change"

- Currently in progress: Vensim version

The "real economy": Production output in physical units
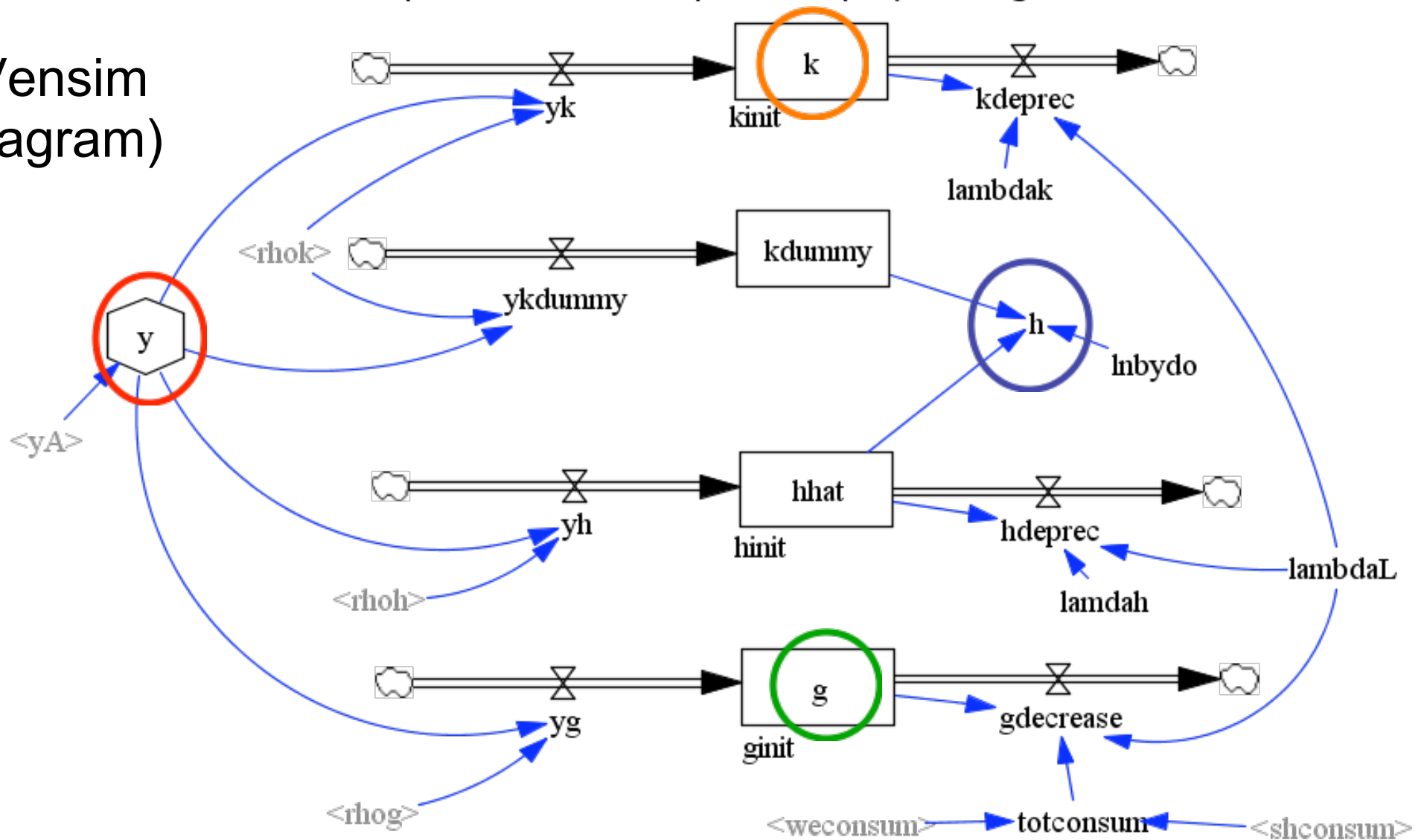
(Vensim diagram)

y: total production, invested in:

k: physical capital

h: human capital

g: consumer goods and services

The "virtual economy" (financial system): money circulation between firms, banks and households

on
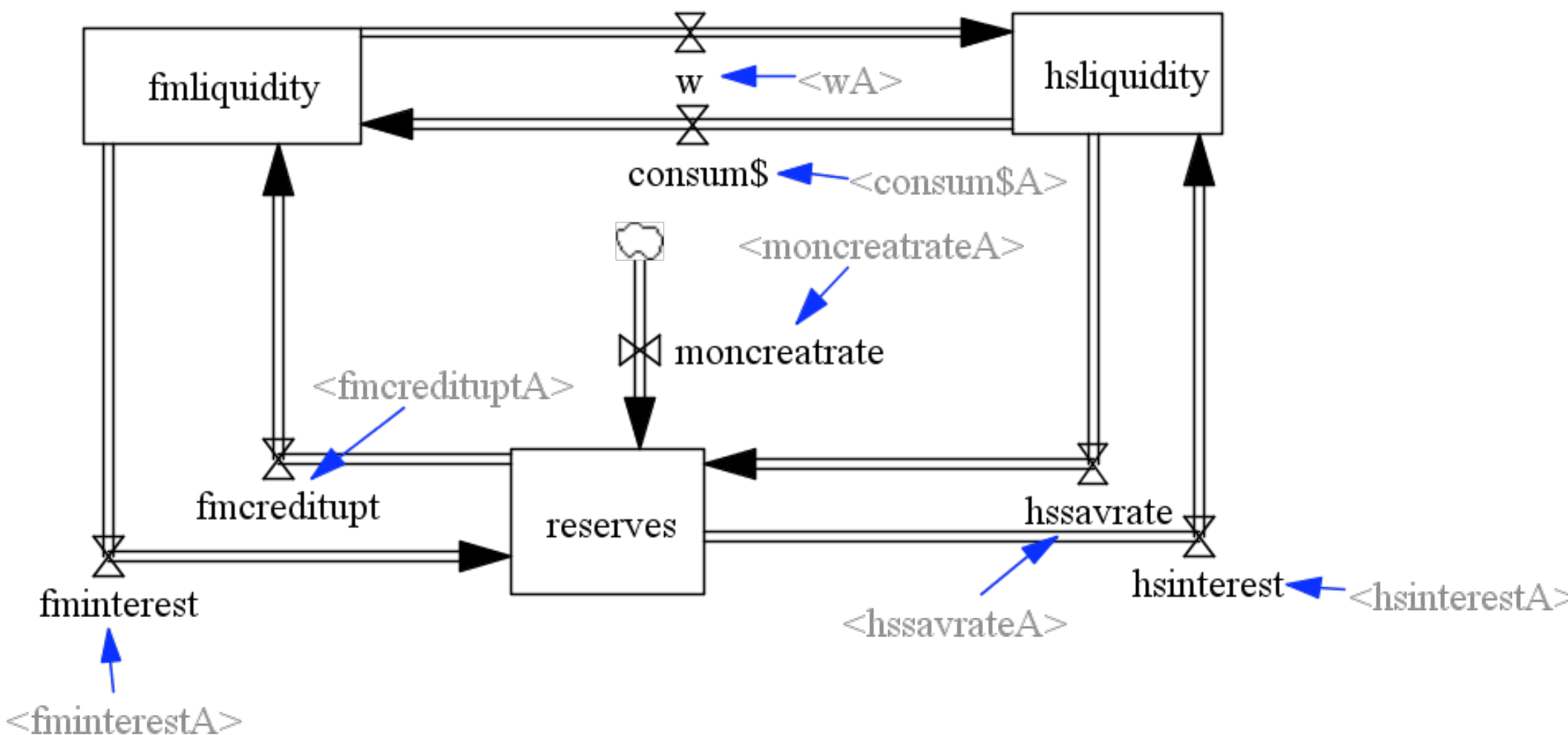
Principal differences compared with CGE model:

1. Growth of economy driven by investments in *human capital* h (technology, education, institutions,…) rather than physical capital k.

Principal differences compared with CGE model:

1. Growth of economy driven by investments in *human capital* h (technology, education, institutions,…) rather than physical capital k.

   (emphasized already by Adam Smith - as well as later classical economists - as driving force of entrepreneurs striving to escape erosion of profits through competition)

Principal differences compared with CGE model:

1. Growth of economy driven by investments in *human capital* h (technology, education, institutions,…) rather than physical capital k.

2. Labor and physical capital are *not substitutable* . Technology h determines level of employable labor and physical capital k per employed labor (Leontief, 1941).

Principal differences compared with CGE model:

1. Growth of economy driven by growth in *human capital* h (technology, education, institutions,…) rather than physical capital k.

2. Labor and physical capital are *not substitutable* . Technology h determines level of employable labor and physical capital k per employed labor (Leontief, 1941).

3. Investment decisions result from *subjectively motivated agent strategies* , including inter-agent negotiations (wages, taxes, …) and (feedback-dependent) assessments of future developments

The MADIAMS hierarchy

M3.0 (MADIAM, 2005) ⟶ M1.0 M̶1̶.̶1̶⟶

- one region

- several actors

- several physical capital sectors

- government

- consumer preferences

- climate

- no instabilities

M1.0 {
- one physical capital sector

- no government

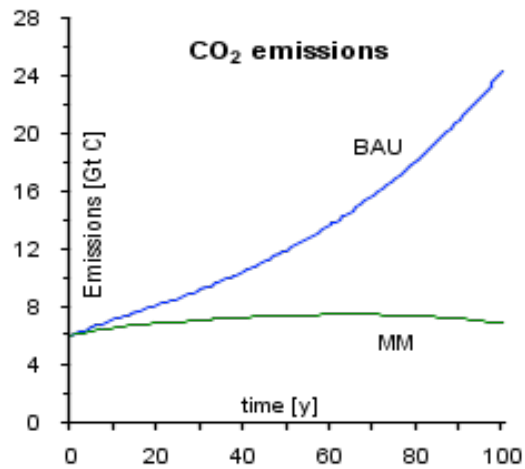- no consumer preferences

- no climate
}

- instabilities

- one region

- several actors

Market clearing assumed for consumer goods
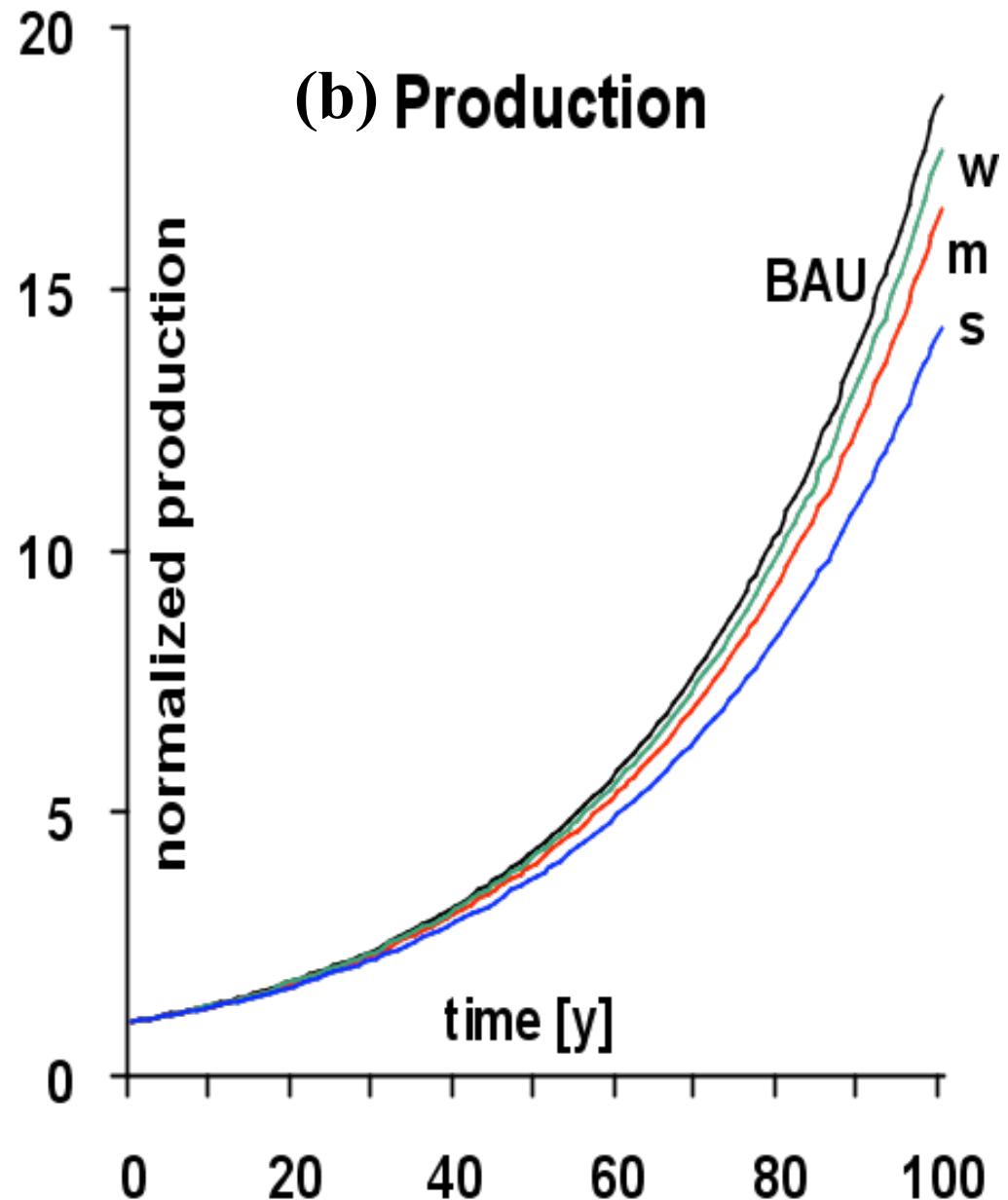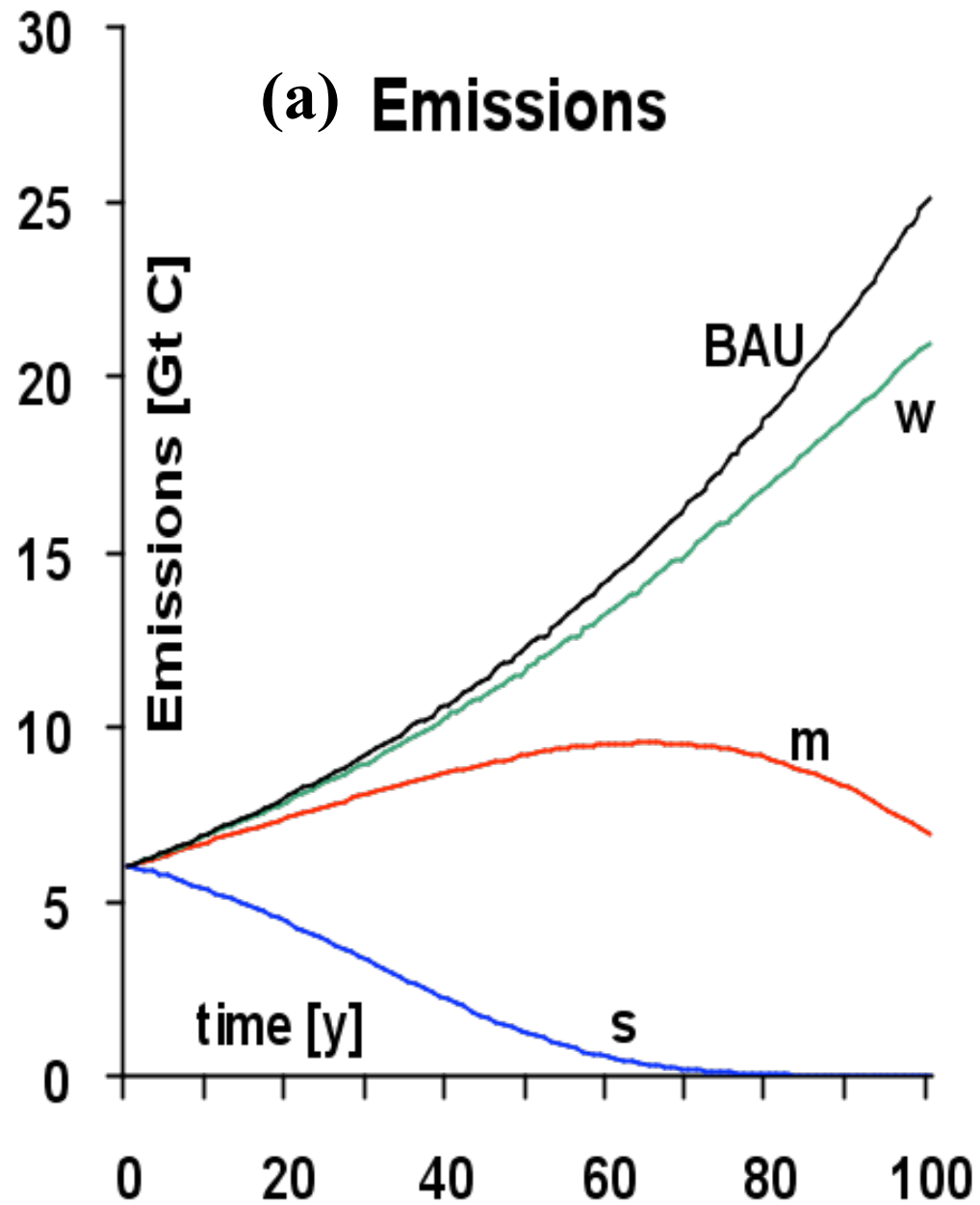
Consumer goods treated as stock variable

Overview

1. General remarks on economic modeling (from a physicist's viewpoint)

2. The MADIAMS project

➡ 3. Some results

4. Outlook

Model M3.0 (MADIAM, 2005). BAU / MM (Moder.Mitig.)
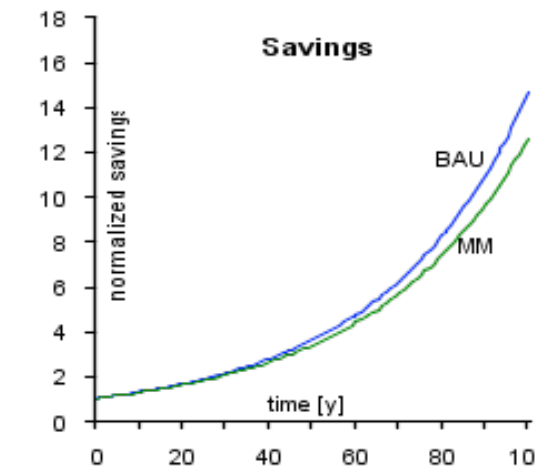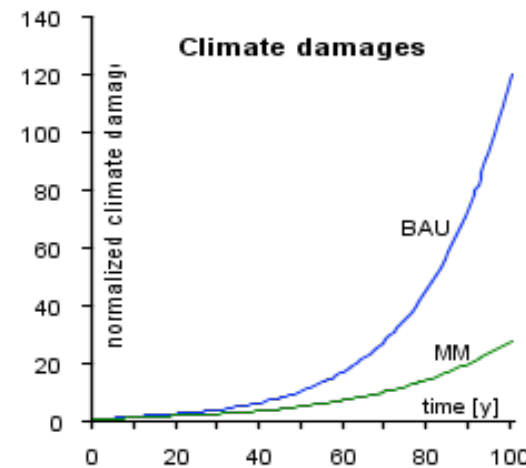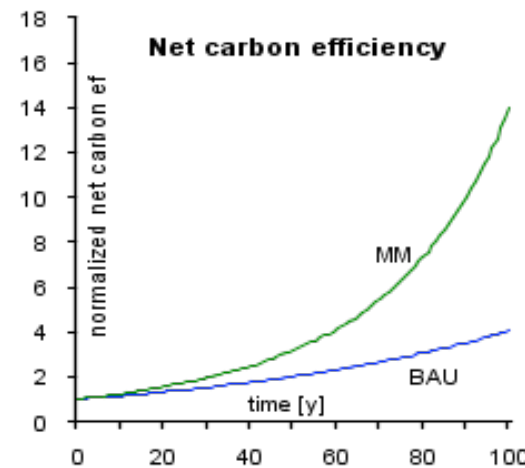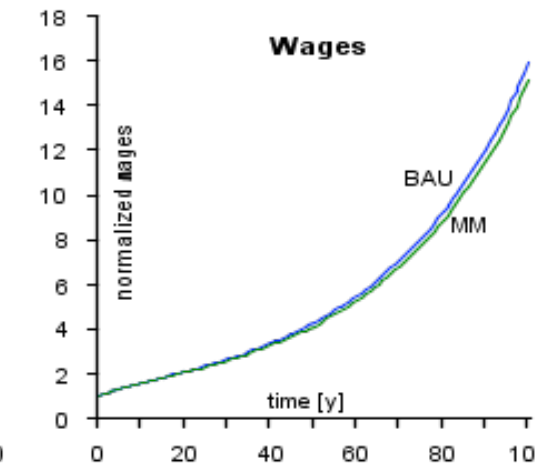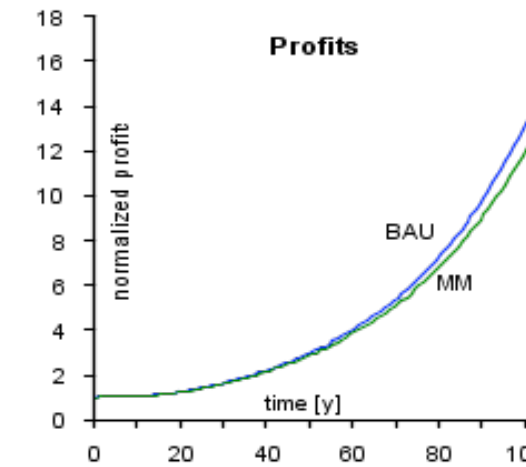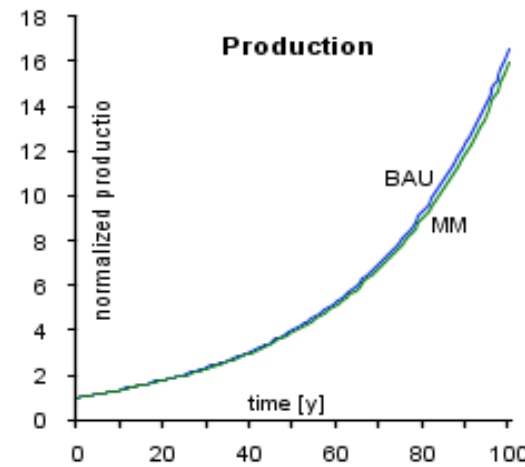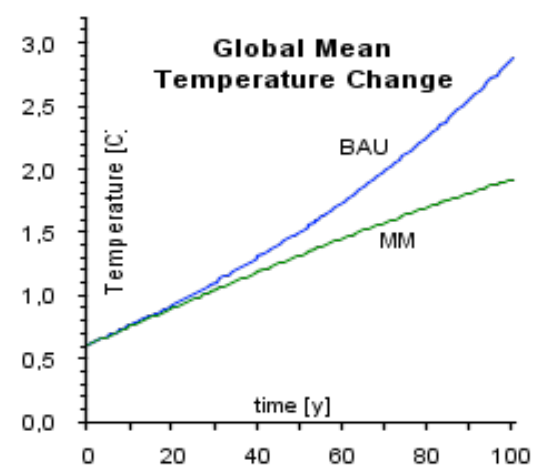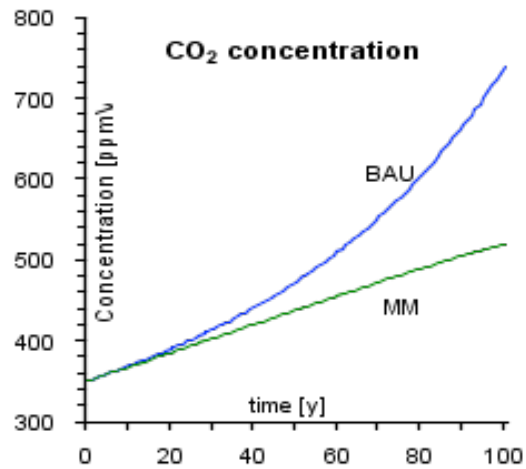
Model M3.0. mitigation measures: w: weak, m: moderate, s: strong
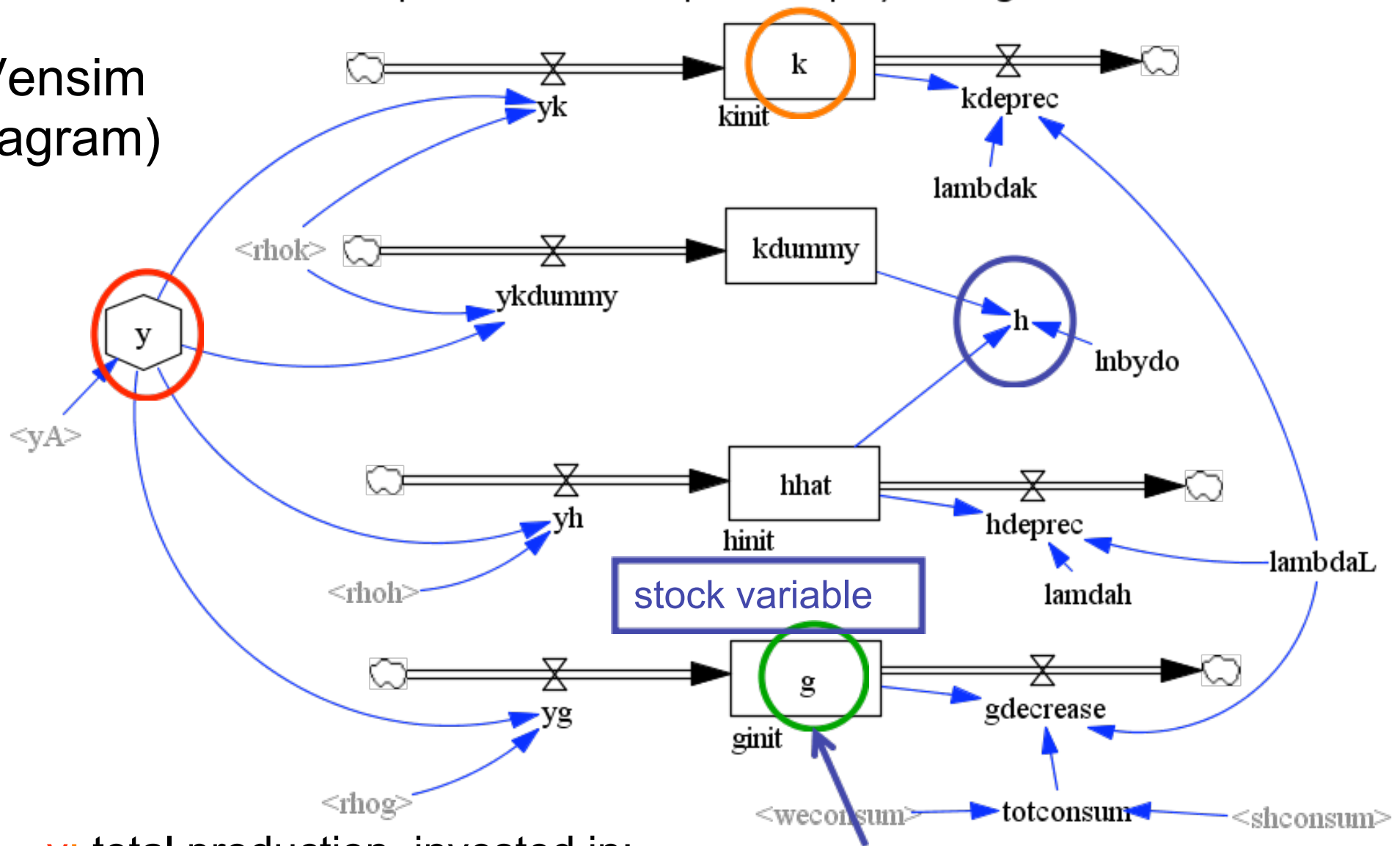
(a) Emissions

(b) Production

Shortcomings:

- Single region or global model: no interregional coupling

- No instabilities, as consumer goods cleared in the market.

The "real economy": Production output in physical units

(Vensim diagram)

stock variable

Reduce M3.0 model to M1.0 model (no government or climate), extend to M1.1 model through inclusion of instabilities

y: total production, invested in:

k: physical capital

h: human capital

g: consumer goods and services

First effect of non-instantaneous equilibrium between supply and demand of consumer goods:

Distribution of production y between investments in:

- physical capital k,

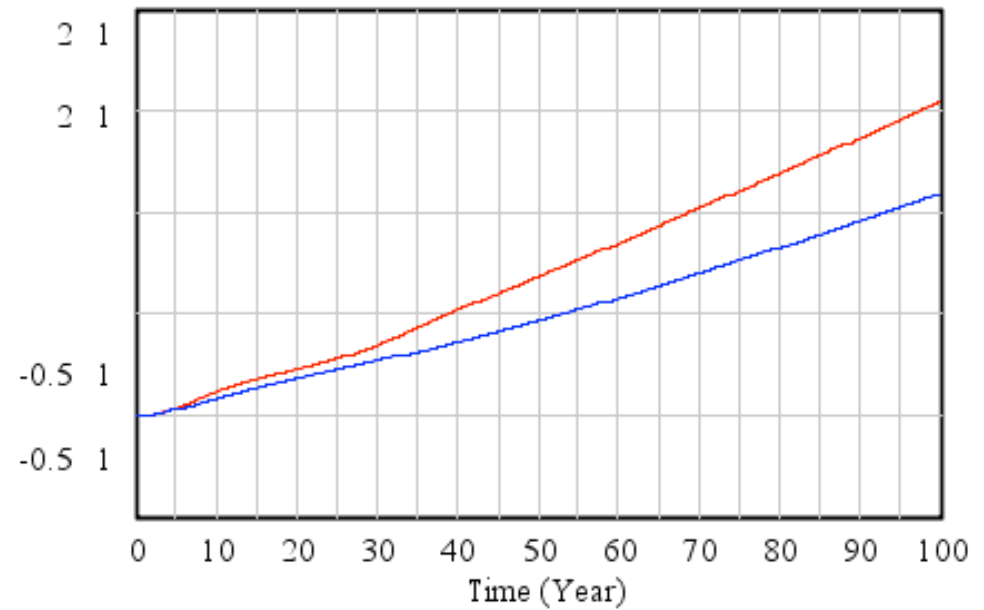- human capital (technology) h, and

- production of consumer goods g

depends on the response of firms to changes in consumer goods demand
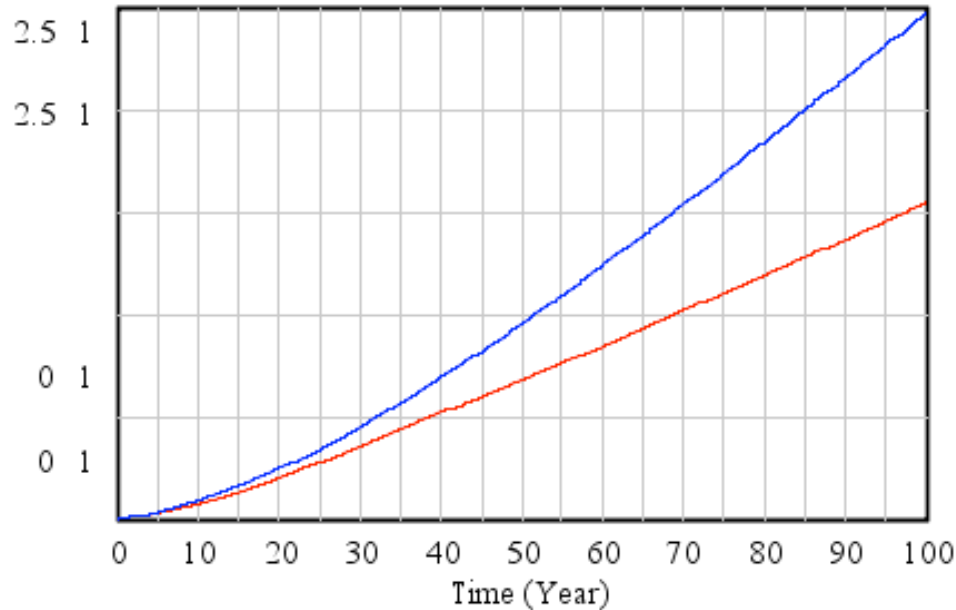
Firms response in supply of goods to variations in demand:

: maintain target for goods *stocks*

: balance *flows* of goods supply and demand

stocks balance: enhance consumption rather than growth

flows balance: enhance growth rather than consumption

Thus (in contrast to the assumptions of MADIAM = M3.0):

The long-term growth in physical and human capital depends on the short-term response strategies of firms to changes in the demand of consumer goods (for given other parameters).

Second – more important - effect of non-equilibrium between supply and demand of consumer goods:
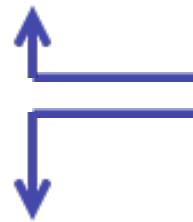The system is inherently unstable:
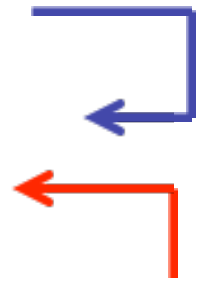A minor modification of the behaviour of consumers and suppliers leads to business cycles:

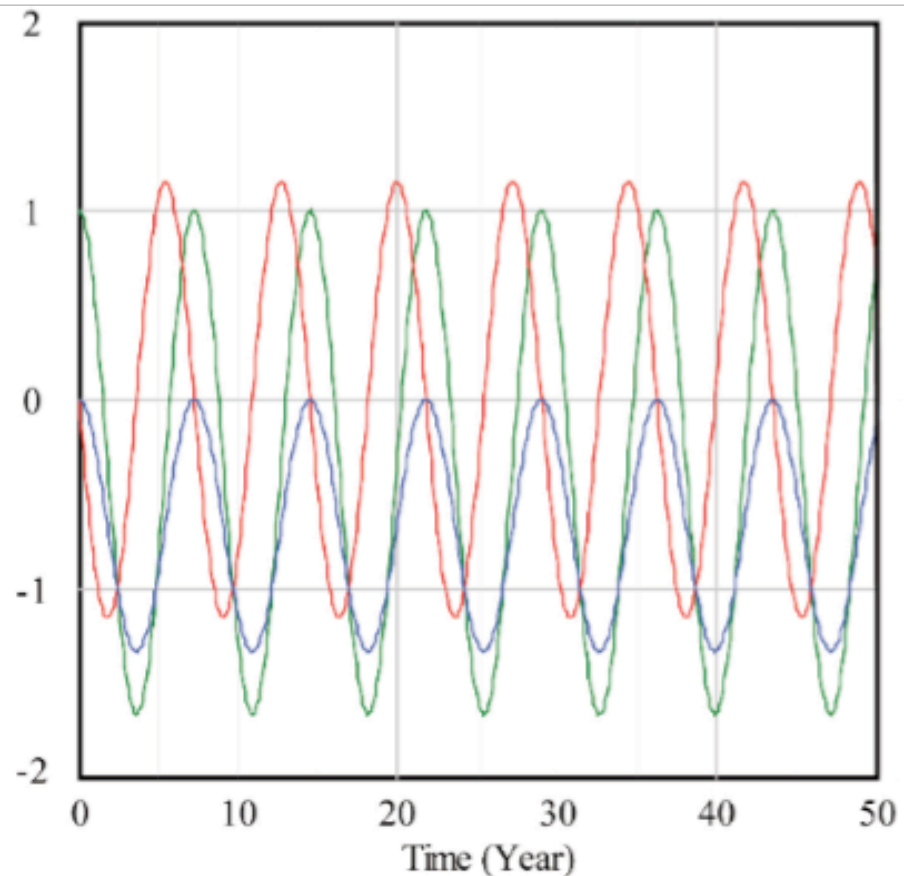# An unstable system of two-feedback loops:

consumption decrease *delcons*

positive loop
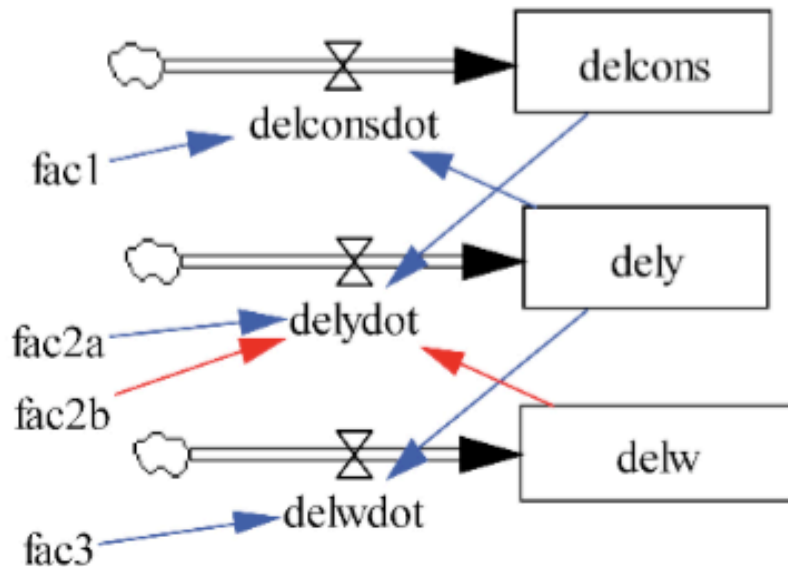
production decrease *dely*

increase

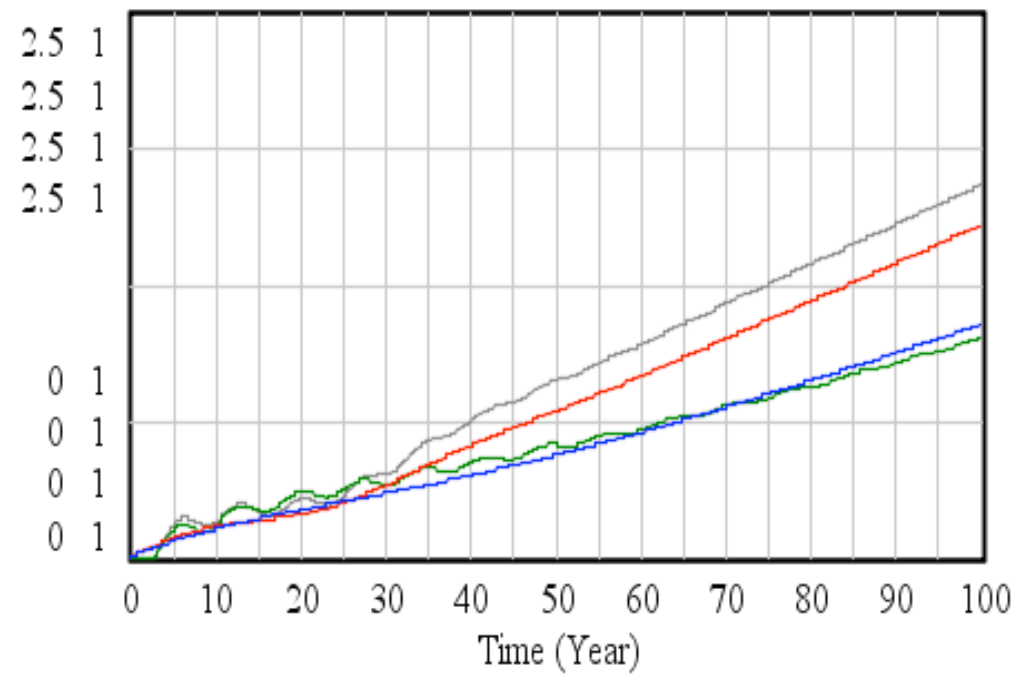negative loop   wage decrease *delw* employm. increase
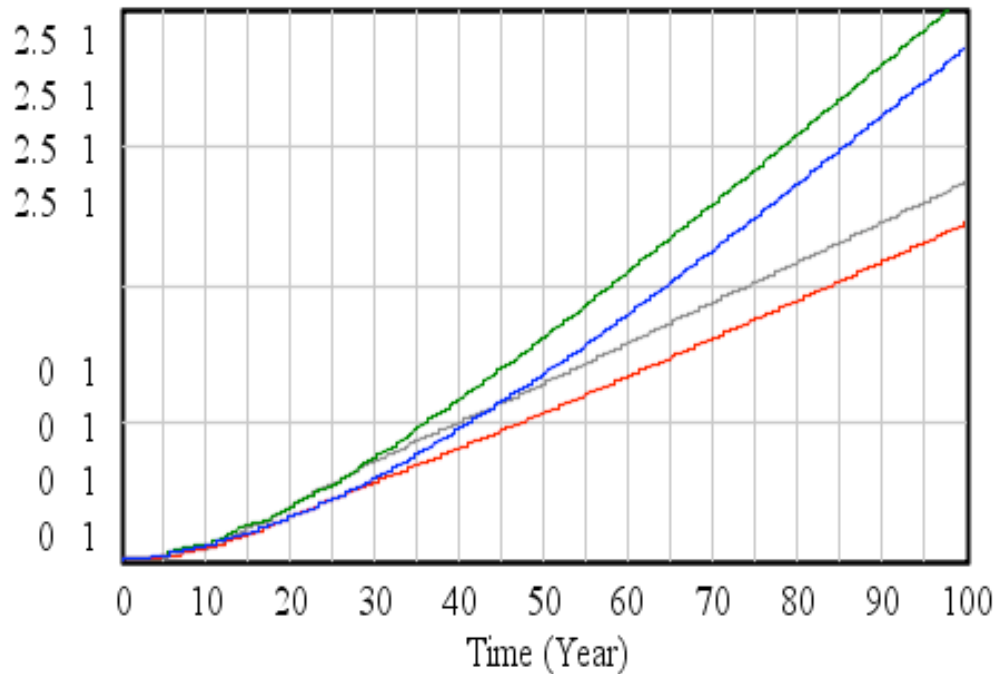
Firms response in supply of goods to variations in demand:

: maintain target goods *stocks*

: balance *flows* of goods supply and demand

Types of supply-demand feedback instabilities:

 1. Business cycles

Consumption-savings-production feedbacks

Types of supply-demand feedback instabilities:

1. Business cycles

Consumption-savings-production feedbacks

2) Financial instabilities

Feedbacks between supply, demand and price of investments in assets

Types of supply-demand feedback instabilities:

 1. Business cycles

Consumption-savings-production feedbacks

2) Financial instabilities

Feedbacks between supply, demand and price of investments in assets

In both cases instabilities arise through *anticipatory* feedbacks in an agent-based system: anticipation of future system state based on information on both present state and *past evolution*

Types of supply-demand feedback instabilities:

 1. Business cycles

Consumption-savings-production feedbacks
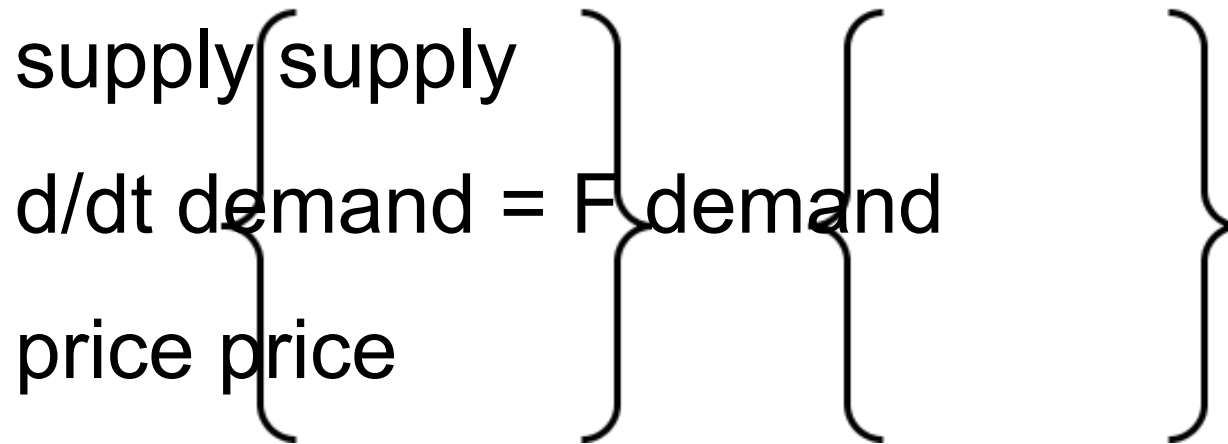
2) Financial instabilities

Feedbacks between supply, demand and price of investments in assets

In both cases instabilities arise through **anticipatory** feedbacks in an agent-based system: anticipation of future system state based on information on both present state and **past evolution** ("rational expectations", often in practice: = "self-fulfilling" expectations).

Neo-liberal paradigm:

Interactions between supply and demand via price signals in a free market leads to an optimal stable equilibrium state

$$\frac{d}{dt} \left\{ \begin{array}{l} \text{supply} \\ \text{demand} \\ \text{price} \end{array} \right\} = F \left\{ \begin{array}{l} \text{supply} \\ \text{demand} \\ \text{price} \end{array} \right\} \left\{ \phantom{\begin{array}{l} a \\ b \\ c \end{array}} \right\} \left\{ \phantom{\begin{array}{l} a \\ b \\ c \end{array}} \right\}$$

Neo-liberal paradigm:

Interactions between supply and demand via price signals in a free market leads to an optimal stable equilibrium state

$$\frac{d}{dt} \left\{ \begin{array}{c} \text{supply} \\ \text{demand} \\ \text{price} \end{array} \right\} = F \left\{ \begin{array}{c} \text{s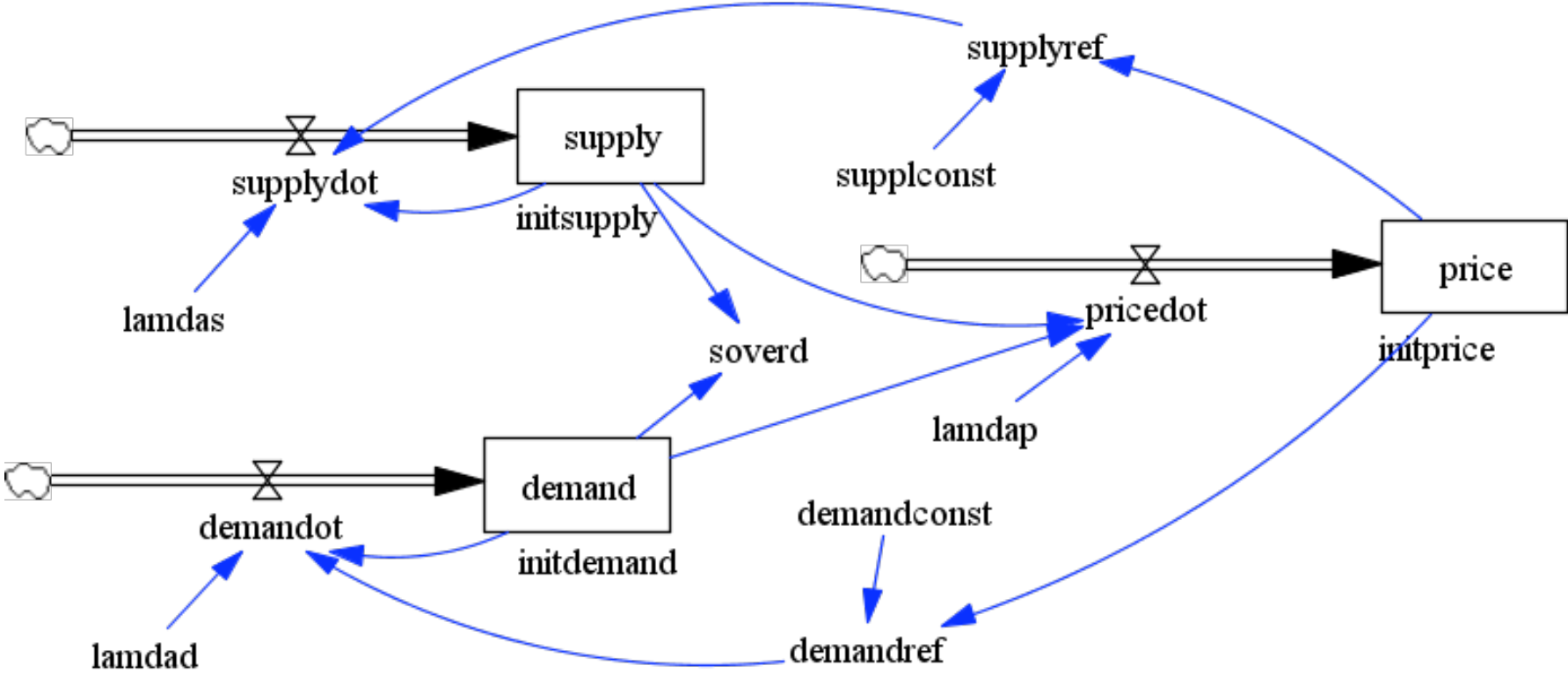upply} \\ \text{demand} \\ \text{price} \end{array} \right\} \left\{ \begin{array}{c} \\ \\ \end{array} \right\} \left\{ \begin{array}{c} \\ \\ \end{array} \right\}$$

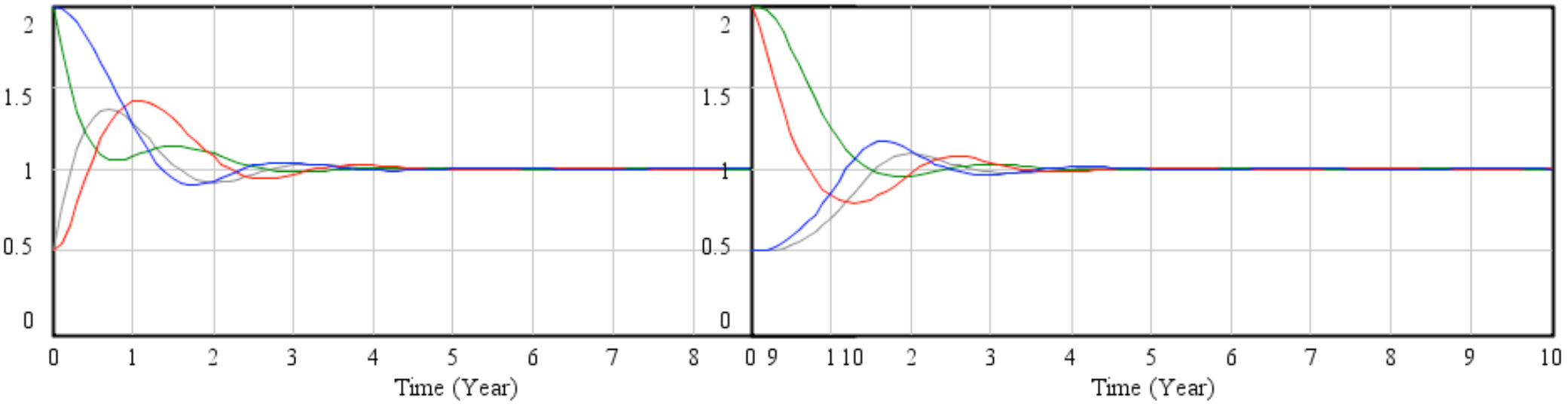$$\left\{ \begin{array}{c} \text{supply} \\ \text{demand} \\ \text{price} \end{array} \right\} > \left\{ \begin{array}{c} \\ \\ \end{array} \right\}_{\text{equilibrium}}$$

Vensim diagram of a simple "neo-liberal" stable market model without anticipatory feedbacks
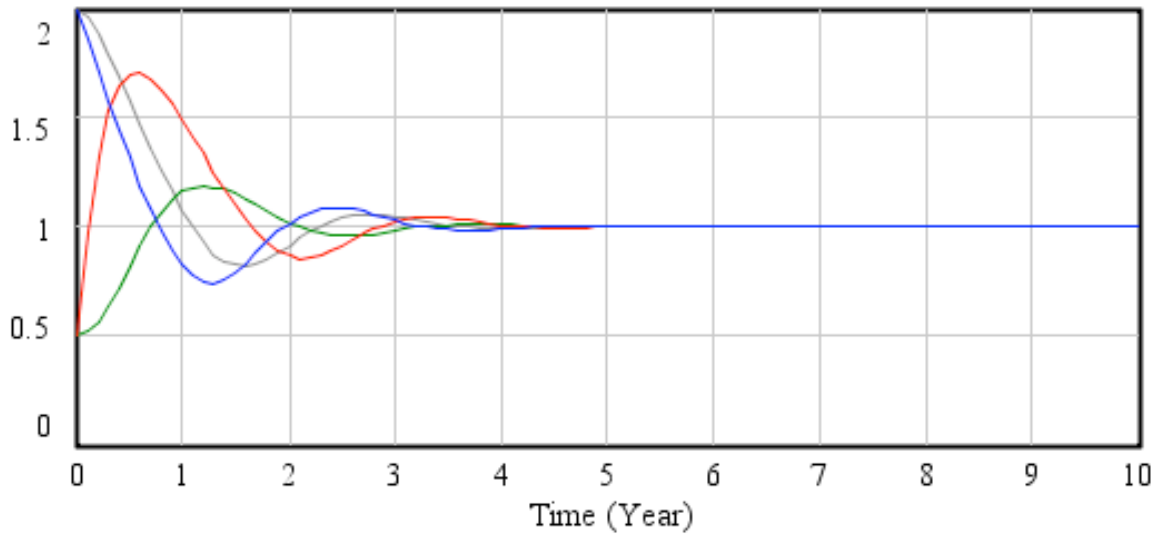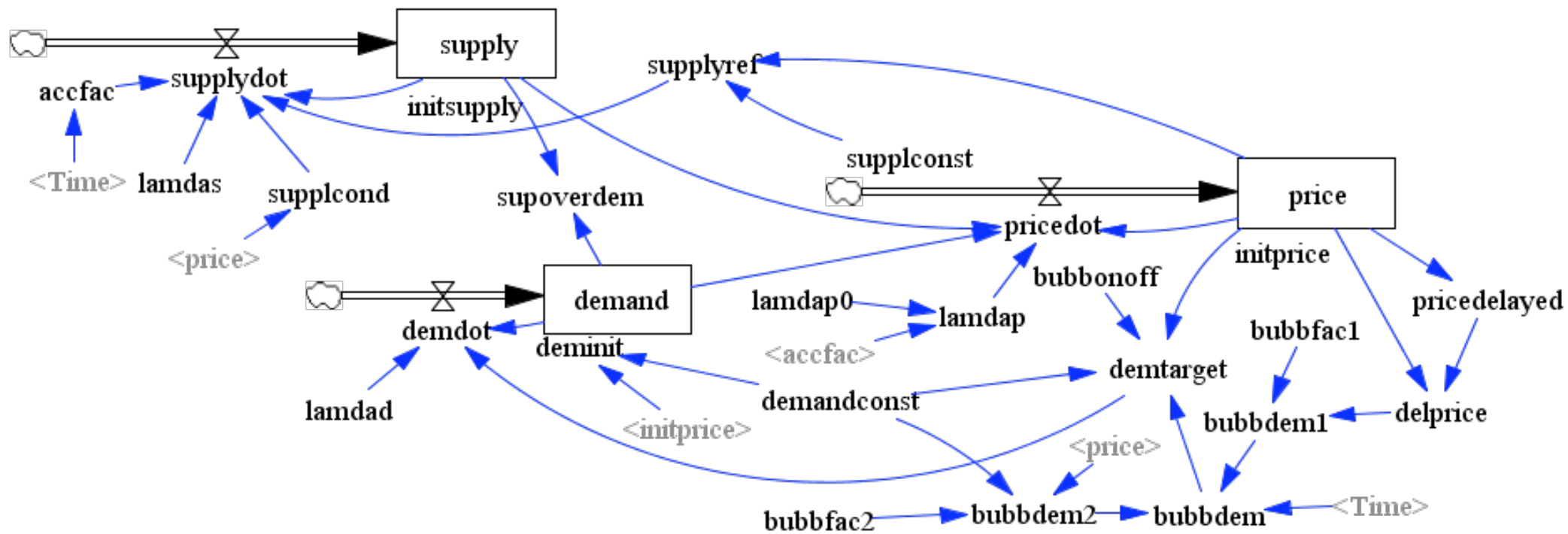
supply

demand

price

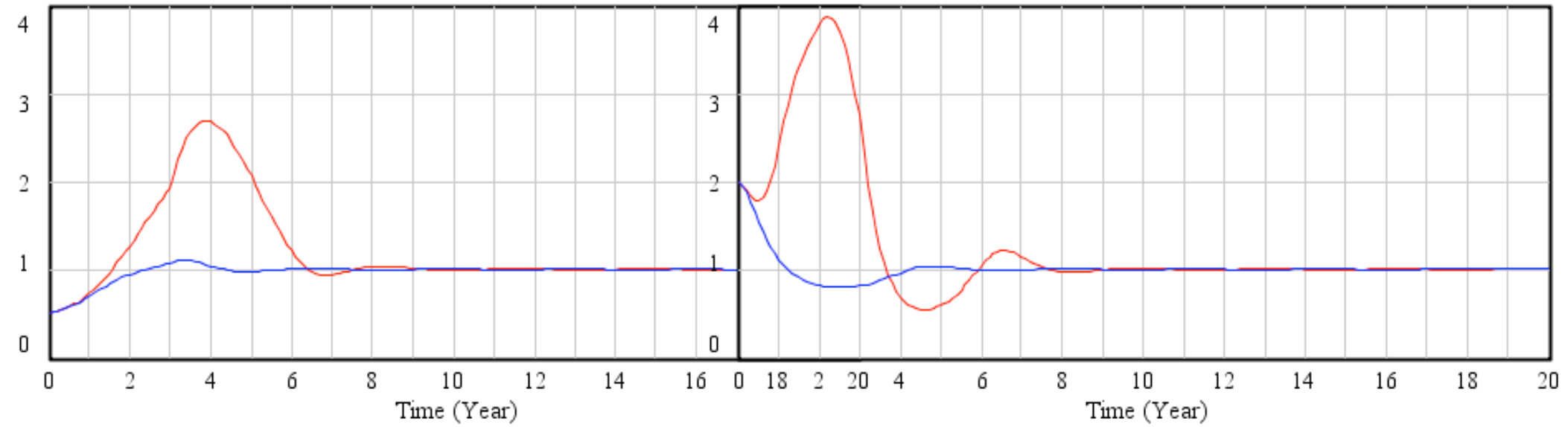Neo-liberal picture:
Evolution to joint equilibrium in supply, demand and price for four different initial conditions

Modified model with positive anticipatory feedback: increasing prices increases demand, instead of decreasing demand as in normal negative feedback model == > unstable bubble with subsequent collapse.
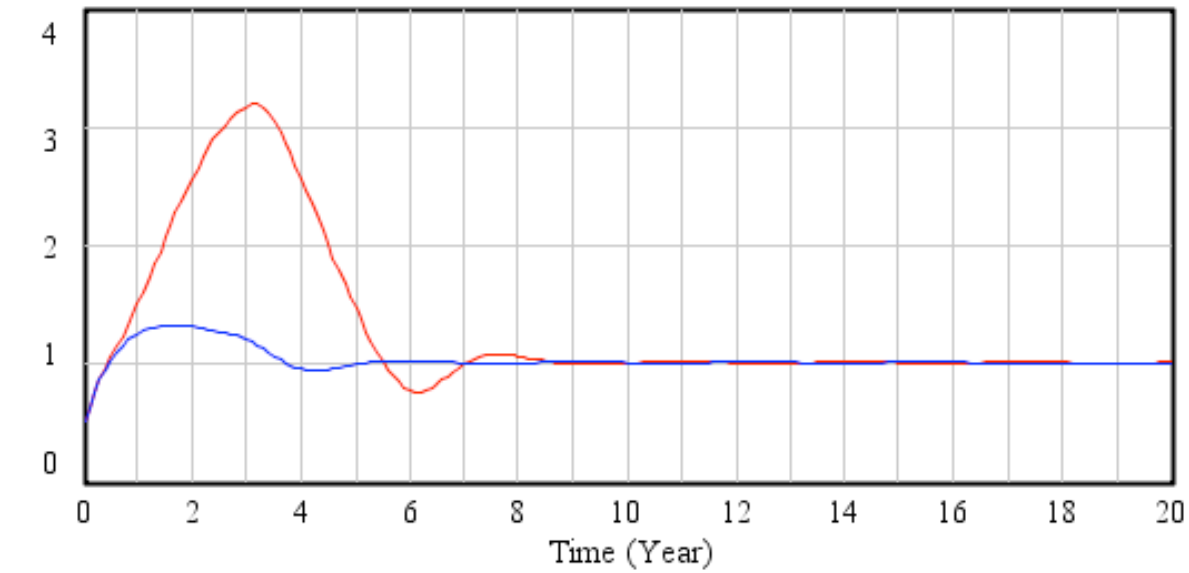
supply

demand

price

without: ————

with: ————

anticipatory (bubble) feedback

Relevance for coupled climate-socio-economic (Integrated Assessment) models:

- IA models need to include the impact of *anticipation* of market conditions on the investment decisions of firms (positive snowball effects of government carbon taxes and subsidies - together with possible unstable overshoots)

Relevance for coupled climate-socio-economic (Integrated Assessment) models:

- IA models need to include the impact of *anticipation* of market conditions on the investment decisions of firms (positive snowball effects of government carbon taxes and subsidies - together with negative unstable overshoots)

- The elementary dynamic models shown here as example need to be extended and incorporated into a more sophisticated integrated assessment model hierarchy *encompassing all three systems: financial, socio-economic and climate* .

Relevance for coupled climate-socio-economic (Integrated Assessment) models:

- IA models need to include the impact of *anticipation* of market conditions on the investment decisions of firms (positive snowball effects of government carbon taxes and subsidies - together with negative unstable overshoots)

- The elementary dynamic models shown here as example need to be extended and incorporated into a more sophisticated integrated assessment model hierarchy *encompassing all three systems: financial, socio-economic and climate* .

Comment: This not as horrendous a task at it seems using modern system dynamic software platforms!

Overview

Desirable extensions of M3 level to M3.1, M3.2, … models:

- more detailed climate impacts

Desirable extensions of M3 level to M3.1, M3.2, … models:

- more detailed climate impacts

- several regions, with trade, migration pressures, etc.

Desirable extensions of M3 level to M3.1, M3.2, … models:

- more detailed climate impacts

- several regions, with trade, migration pressures, etc.

- several sectors (transport, energy, consumer goods,…)

Desirable extensions of M3 level to M3.1, M3.2, … models:

- more detailed climate impacts

- several regions, with trade, migration pressures, etc.

- several sectors (transport, energy, consumer goods,…)

- differentiated wage income structures – problems of rich-poor inequalities

Desirable extensions of M3 level to M3.1, M3.2, … models:

- more detailed climate impacts

- several regions, with trade, migration pressures, etc.

- several sectors (transport, energy, consumer goods,…)

- differentiated wage income structures – problems of rich-poor inequalities

- detailed financial market, including network structures and feedback instabilities

Desirable extensions of M3 level to M3.1, M3.2, … models:

- more detailed climate impacts

- several regions, with trade, migration pressures, etc.

- several sectors (transport, energy, consumer goods,…)

- differentiated wage income structures – problems of rich-poor inequalities

- detailed financial market, including network structures and feedback instabilities

- detailed representation of coupled government market-stabilization and climate-mitigation policies

Desirable extensions of M3 level to M3.1, M3.2, … models:

- more detailed climate impacts

- several regions, with trade, migration pressures, etc.

- several sectors (transport, energy, consumer goods,…)

- differentiated wage income structures – problems of rich-poor inequalities

- detailed financial market, including network structures and feedback instabilities

- detailed representation of coupled government market-stabilization and climate-mitigation policies

- detailed representation of coupled international negotiations on climate change and conflict resolution

Desirable extensions of M3 level to M3.1, M3.2, … models:

- more detailed climate impacts

- several regions, with trade, migration pressures, etc.

- several sectors (transport, energy, consumer goods,…)

- differentiated wage income structures – problems of rich-poor inequalities

- detailed financial market, including network structures and feedback instabilities

- detailed representation of coupled government market-stabilization and climate-mitigation policies

- detailed representation of coupled international negotiations on climate change and conflict resolution

- stochasticity

Thank you for listening - discussions welcome!