

# Combining Adaptation and Mitigation: Insights from Ada-BaHaMa

O. Bahn<sup>1</sup>

<sup>1</sup>GERAD and MQG, HEC Montréal, Canada

2011 International Energy Workshop, Stanford University,  
July 6-8, 2011

# Adaptation vs. mitigation

In the context of policies to address global climate changes:

- **Mitigation** measures are options to **reduce GHG emission** levels (e.g., use renewable energy instead of fossil fuels).
- **Adaptation** measures provide strategies to **reduce impacts** of climate changes (e.g., crops for new climate conditions, dykes to protect against sea level rises or medical preventions against spreading tropical diseases).

Adaptation measures can be **reactive** or **preventive**.

# Integrated assessment

- **Integrated assessment (IA)** is an **interdisciplinary approach** that uses information from different fields of knowledge, in particular economy and climatology.
- **Integrated assessment models (IAMs)** are **tools** for conducting an integrated assessment, as they typically combine key elements of the economic and biophysical systems, elements that underlie the anthropogenic global climate change phenomenon.
- **Examples of IAMs** are **DICE** (Nordhaus, 1994, 2007), **MERGE** (Manne et al., 1995; Manne and Richels, 2005), **RICE** (Nordhaus and Yang, 1996), **TIAM** (Loulou and Labriet, 2008; Loulou, 2008), ..., and **BaHaMa** (Bahn et al., 2008, 2010a).

# IAMs with adaptation

- **Research** incorporating adaptation measures into IAMs **has been rare** until recently.
- Only a **few IAMs consider** explicitly **adaptation** options: **PAGE** (Hope et al., 1993; Hope, 2006), **FEEM-RICE** (Bosello, 2008), **AD-DICE** (de Bruin et al., 2009a, 2011), **AD-RICE** (de Bruin et al., 2009b) and **AD-WITCH** (Bosello et al., 2010).
- Here one uses **Ada-BaHaMa** (Bahn et al., 2010b), a deterministic version of **BaHaMa** enriched to **consider explicitly adaptation** options.

## Extending Ada-BaHaMa

- Compared to several of these IAMs, **Ada-BaHaMa considers adaptation efforts as investments** (*stock*) instead of **costs** (*flow*) and as such emphasizes its proactive aspect instead of its reactive one (Lecocq and Shalizi, 2007).
- In Bahn et al. (2010b), a **single decision maker** has been considered.
- Here, one **extends** Ada-BaHaMa to a **non-cooperative game setting** (Nash, 1950) where world regions define non-cooperatively their energy and climate policies all the while being affected by climate change related damages induced by their total GHG emissions.

# Outline

- 1 A  $n$ -player version of Ada-BaHaMa
  - Model overview
  - Model variables
  - Economic modeling
  - Damages and adaptation
- 2 Solution concepts
  - Collaborative solutions
  - Nash solutions
- 3 Numerical results
  - Scenarios
  - Calibration
  - Results
- 4 Conclusions

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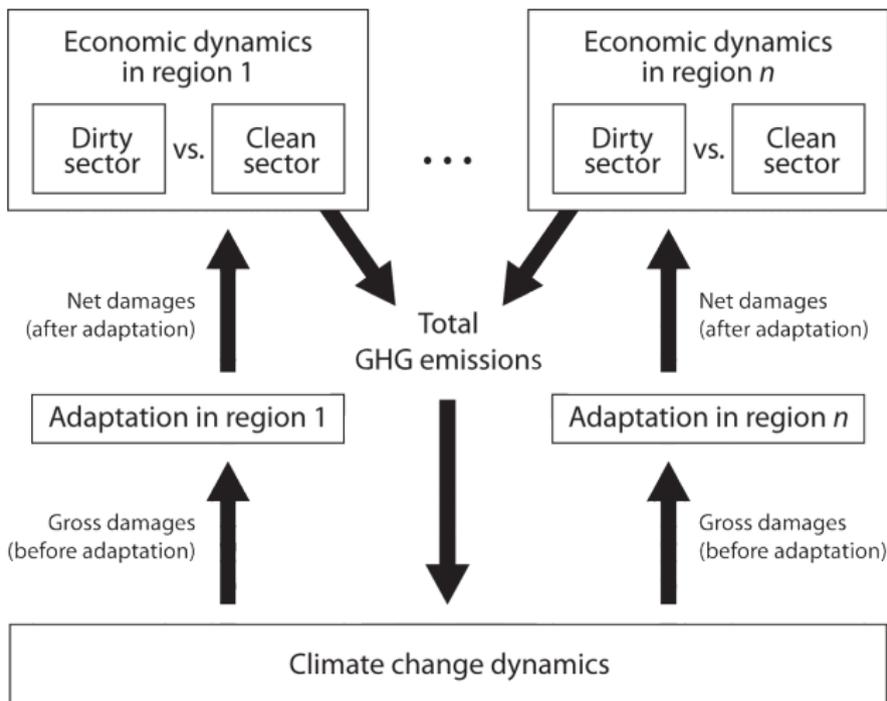
# Ada-BaHaMa vs. DICE and AD-DICE

**BaHaMa** is **similar** to **DICE**, but distinguishes between two types of economy:

- a “**carbon economy**” (our present economy), where a high level of carbon emissions is necessary to obtain output; and
- a “**carbon-free economy**” (an hydrogen economy for instance), where a much lower level of emissions is necessary to produce the economic good.

**Ada-BaHaMa** is built in the **spirit** of **AD-DICE**, but models adaptation efforts as **investments** instead of **costs**.

# Schematic overview of Ada-BaHaMa



# Variables-1

- $AD(j, t)$ : reduction of damages due to **adaptation** measures in region  $j$  at time  $t$ , in %;
- $C(j, t) \geq 0$ : total **consumption** in region  $j$  at time  $t$ , in trillions ( $10^{12}$ ) of dollars;
- $c(j, t) \geq 0$ : **per capita consumption** in region  $j$  at time  $t$ ,  $c(j, t) = \frac{C(j, t)}{L(j, t)}$ ;
- $E_1(j, t) \geq 0$ : yearly **emissions** of **GHG** (in Gt– $10^9$  tons–carbon equivalent) in the **carbon economy** of region  $j$  at time  $t$ ;
- $E_2(j, t) \geq 0$ : yearly **emissions** of **GHG** in the **clean economy** of region  $j$  at time  $t$ , in GtC;
- $ELF(j, t)$ : economic **loss factor** in region  $j$  due to climate changes at time  $t$ , in %;
- $I_i(j, t) \geq 0$ : **investment** in capital  $K_i$  ( $i = 1, 2, 3$ ) in region  $j$  at time  $t$ , in trillions of dollars;
- $K_1(j, t) \geq 0$ : physical **stock** of **productive capital** in the **carbon economy** of region  $j$  at time  $t$ , in trillions of dollars;

## Variables-2

- $K_2(j, t) \geq 0$ : physical **stock of productive capital** in the **clean economy** of region  $j$  at time  $t$ , in trillions of dollars;
- $K_3(j, t) \geq 0$ : physical **stock of adaptation capital** in region  $j$  at time  $t$ , in trillions of dollars;
- $K_{3\max}(j, t) \geq 0$ : **maximal stock of adaptation capital** in region  $j$  at time  $t$ , in trillions of dollars;
- $L_1(j, t) \geq 0$ : part of the (exogenously defined) **labor force**  $L(j, t)$  of region  $j$  allocated at time  $t$  to the **carbon economy**, in millions ( $10^6$ ) of persons;
- $L_2(j, t) \geq 0$ : part of the **labor force** of region  $j$  allocated at time  $t$  to the **clean economy**, in millions of persons;
- $M(t) \geq 0$ : atmospheric **concentration** of **GHG** at time  $t$ , in GtC equivalent;
- $WRG(j)$ : discounted **welfare** of region  $j$ ;
- $Y(j, t) \geq 0$ : **economic output** of region  $j$  at time  $t$ , in trillions of dollars.

# Regional economic dynamics

$$\text{WRG}(j) = \sum_{t=0}^{T-1} 10 e^{-\rho(j)t} L(j, t) \log[ c(j, t) ]$$

$$L(j, t) = L_1(j, t) + L_2(j, t)$$

$$C(j, t) = \text{ELF}(j, t) Y(j, t) - l_1(j, t) - l_2(j, t) - l_3(j, t) \\ - \rho_{E1}(j, t) \phi_1(j, t) E_1(j, t) - \rho_{E2}(j, t) \phi_2(j, t) E_2(j, t)$$

$$K_i(j, t+1) = 10 l_i(j, t) + (1 - \delta_{K_i})^{10} K_i(j, t) \quad i = 1, 2, 3$$

$$Y(j, t) = A_1(j, t) K_1(j, t)^{\alpha_1(j)} (\phi_1(j, t) E_1(j, t))^{\theta_1(j, t)} L_1(j, t)^{1-\alpha_1(j)-\theta_1(j, t)} \\ + A_2(j, t) K_2(j, t)^{\alpha_2(j)} (\phi_2(j, t) E_2(j, t))^{\theta_2(j, t)} L_2(j, t)^{1-\alpha_2(j)-\theta_2(j, t)}$$

# Carbon dynamics

**Accumulation**  $M$  of **GHG** in the atmosphere evolves according to:

$$M(t+1) = 10\beta \sum_{j=1}^n (E_1(j,t) + E_2(j,t)) + (1 - \delta_M) M(t) + \delta_M M_p.$$

where  $M(0) = 808.8$  GtC (385 ppm) and where parameters are defined as follows:

- $\beta$  : marginal atmospheric retention rate;
- $\delta_M$  : natural atmospheric elimination rate;
- $M_p$  : preindustrial level of atmospheric concentration;  
 $M_p = 590$  GtC (280 ppm).

## Regional damage dynamics

Increasing atmospheric GHG concentrations trigger climate changes that yield economic losses.

Net **regional damages** take into account adaptation (AD):

$$\text{ELF}(j, t) = 1 - \text{AD}(j, t) \left( \frac{M(t) - M_d(j)}{\text{cat}_M(j) - M_d(j)} \right)^2.$$

where

$M_d(j)$  : level at which damages start to occur in region  $j$ ;

$\text{cat}_M$  : “catastrophic” concentration level for region  $j$ .

## Regional adaptation dynamics

Regional **adaptation** dynamics is as follows:

$$AD(j, t) = 1 - \alpha_{AD}(j) \frac{K_3(j, t)}{K_{3\max}(j, t)},$$

with  $K_{3\max}(j, t)$  modeled as an increasing function of GHG concentration:

$$K_{3\max}(j, t) = \beta_{AD}(j) \left( \frac{M(t)}{M_d(j)} \right)^{\gamma_{AD}(j)}.$$

and where  $\alpha_{AD}$  represents the maximal adaptation effectiveness, and  $\beta_{AD}$  and  $\gamma_{AD}$  are calibration parameters.

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# Collaborative solutions

One allocates to each region  $j = 1, \dots, n$  a **weight**  $\text{rg}(j) > 0$ , such that:

$$\sum_{j=1}^n \text{rg}(j) = 1.$$

A **collaborative** (or **Pareto equilibrium**) solution associated with this weighting is obtained when one optimizes the criterion:

$$\sum_{j=1}^n \text{rg}(j) \text{WRG}(j).$$

# Nash equilibrium solutions-1

A **Nash equilibrium** is obtained when each region has chosen a strategy that corresponds to its **best reply** to the choices made by the other regions.

A **strategy**  $s_j$  for region  $j$  consists of:

- a sequence of **emissions**:  
 $\{E_1(j, t), E_2(j, t) : t = 0, 1, \dots, T - 1\}$ ;
- a sequence of **investments**:  
 $\{I_1(j, t), I_2(j, t), I_3(j, t) : t = 0, 1, \dots, T - 1\}$  in capital  $K_1$ ,  $K_2$  and  $K_3$  respectively;
- a sequence of **labor allocations**:  
 $\{L_1(j, t), L_2(j, t) : t = 0, 1, \dots, T - 1\}$  in the carbon and clean economy respectively.

## Nash equilibrium solutions-2

Let  $\psi_j(\mathbf{s}_j, \mathbf{s}^{-j})$  denotes the **payoff** to each region  $j$ , where  $\mathbf{s}^{-j}$  represents the strategies chosen by regions other than  $j$ .

Let  $\mathbf{s} = (\mathbf{s}_j : j = 1, \dots, n)$  denotes the **strategy vector** of all regions.

Let  $\mathcal{S}$  denotes the **set of all admissible strategy vectors**.

Consider the following **reply function** defined over the product set  $\mathcal{S} \times \mathcal{S}$ :

$$\theta(\mathbf{r} : \mathbf{s}', \mathbf{s}) = \sum_{j=1}^n r(j) \psi_j(\mathbf{s}'_j, \mathbf{s}^{-j}), \quad \forall \mathbf{s}' \in \mathcal{S}, \mathbf{s} \in \mathcal{S},$$

where  $r(j)$  is any positive weight allocated to player  $j$ .

A **Nash equilibrium** is a **fixed point** of the optimal reply mapping:

$$\Theta(\mathbf{r} : \mathbf{s}) = \{ \mathbf{s}^* \in \operatorname{argmax}_{\mathbf{s}' \in \mathcal{S}} \theta(\mathbf{r} : \mathbf{s}', \mathbf{s}) \}.$$

A **cobweb approach** is implemented to compute this fixed-point solution.

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## Scenarios-1

One considers for simplicity the case where the world would be divided into **two coalitions** of countries:

- **Region**  $j = 1$  that regroups all **Annex I countries** of the Kyoto Protocol (the developed countries);
- **Region**  $j = 2$  that regroups all other **non-Annex I countries** (developing countries and emerging economies).

One considers thus the simplified case of **two players** ( $n = 2$ ) and one selects  $rg(1) = rg(2) = 0.5$ .

## Scenarios-2

One considers **three** basic **scenarios**:

- a counterfactual **baseline** without any climate change related damages;
- a **mitigation-only scenario** where adaptation is not possible;
- a **combined scenario** with both mitigation and adaptation.

For each of the last two scenarios, one computes both a **collaborative (Pareto equilibrium) solution** and a **non-collaborative (Nash equilibrium) solution**.

# Calibration-1

**Calibration** of the 2-player Ada-BaHaMa model follows the **approach** detailed in **Bahn et al. (2010b)**.

It is done for the combined scenario under the collaborative approach.

**Economic** parameters are mostly from **DICE** (DICE2007).

However, compared to the dirty economy, production in the clean economy has a better energy efficiency but higher energy costs.

In addition, some **regional** parameter values have been adapted in the spirit of **RICE**:

- Regions have different population levels and energy prices;
- Region 2 has a higher elasticity of output with respect to capital and a lower initial value for energy efficiency.

As a result, the **overall production** of the 2-player Ada-BaHaMa reproduces the economic output of **DICE2007**.

## Calibration-2

**Climate** parameters are again mostly from **DICE2007**.

**Damages** and **adaptation** parameters are from **AD-DICE** and the **World Bank** (Margulis and Narain, 2009)

However, region 2 is assumed to bear higher damages for a given GHG atmospheric concentration level but also to have a higher capacity for adaptation.

*As a result*, Ada-BaHaMa reproduces the **overall magnitude** of climate change **damages** estimated by **DICE2007** and **AD-DICE**.

## GHG concentration levels (in ppm)

	BAU	P-MI	P-CO	N-MI	N-CO
2015	385	385	385	385	385
2025	402	402	402	402	402
2035	423	421	421	422	422
2045	448	443	443	445	445
2055	479	461	465	472	473
2065	517	481	486	504	506
2075	562	502	509	540	544
2085	617	526	534	581	588
2095	682	552	562	612	623
2105	758	580	593	640	658
2115	845	582	627	656	693

## GHG emission levels (in GtC)

	BAU		P-MI		P-CO		N-MI		N-CO	
	1	2	1	2	1	2	1	2	1	2
2015	3.1	5.4	2.7	5.0	2.7	5.0	3.0	5.0	3.0	5.1
2025	3.5	6.5	3.0	5.8	3.1	5.8	3.4	5.9	3.4	6.0
2035	4.2	7.9	1.2	6.9	2.4	6.9	3.9	7.0	3.9	7.1
2045	5.0	9.7	0.5	8.0	0.9	8.2	4.5	8.1	4.5	8.5
2055	6.0	11.8	0.2	9.2	0.4	9.5	5.2	9.3	5.3	10.0
2065	7.1	14.2	0.1	10.3	0.2	10.8	6.0	10.4	6.0	11.7
2075	8.3	17.0	0.1	11.4	0.1	12.1	2.0	11.5	2.1	13.1
2085	9.7	20.0	0.1	12.5	0.1	13.3	0.7	12.6	0.7	14.5
2095	11.0	23.2	0.1	4.1	0.1	14.6	0.3	9.1	0.3	15.9
2105	12.3	26.2	0.0	1.4	0.0	4.9	0.1	3.1	0.1	17.3
2115	13.0	28.2	0.0	0.5	0.0	1.7	0.1	1.1	0.1	6.7

## Clean capital $K_2$ accumulations (in trillions USD)

	BAU		P-MI		P-CO		N-MI		N-CO	
	1	2	1	2	1	2	1	2	1	2
2015	0	0	0	0	0	0	0	0	0	0
2025	0	0	0	0	0	0	0	0	0	0
2035	0	0	41	0	19	0	0	0	0	0
2045	0	0	63	0	55	0	0	0	0	0
2055	0	0	79	0	77	0	0	0	0	0
2065	0	0	96	0	95	0	0	0	0	0
2075	0	0	113	0	112	0	81	0	80	0
2085	0	0	133	0	133	0	121	0	122	0
2095	0	0	154	201	155	0	148	97	150	0
2105	0	0	175	296	178	236	171	257	175	0
2115	0	0	199	361	201	347	194	339	199	248

## Dirty capital $K_1$ accumulations (in trillions USD)

	BAU		P-MI		P-CO		N-MI		N-CO	
	1	2	1	2	1	2	1	2	1	2
2015	54	71	54	71	54	71	54	71	54	71
2025	55	81	55	80	55	80	55	80	55	81
2035	60	96	19	95	41	95	60	95	60	96
2045	70	117	7	115	14	115	69	115	69	115
2055	83	142	2	139	5	138	82	140	82	140
2065	98	172	1	167	2	168	97	168	98	170
2075	116	208	0	200	1	201	34	201	34	203
2085	136	248	0	238	0	240	12	236	12	241
2095	159	294	0	83	0	283	4	180	4	282
2105	184	344	0	29	0	99	1	63	1	328
2115	211	400	0	10	0	34	1	22	1	134

# Adaptation capital $K_3$ and $K_{3\max}$ levels (in trillions USD)

	P-CO				N-CO			
	K3		K3max		K3		K3max	
	1	2	1	2	1	2	1	2
2015	0.0	0.0	0.8	1.1	0.0	0.0	0.8	1.1
2025	0.0	0.0	0.9	1.3	0.0	0.0	0.9	1.3
2035	0.0	0.0	1.2	1.7	0.0	0.0	1.2	1.7
2045	0.0	0.0	1.5	2.1	0.0	2.2	1.6	2.2
2055	0.0	2.5	1.8	2.5	0.0	3.0	2.1	3.0
2065	0.0	3.1	2.2	3.1	0.0	4.1	2.9	4.1
2075	2.7	3.8	2.7	3.8	4.1	5.8	4.1	5.8
2085	3.4	4.8	3.4	4.8	5.4	7.5	5.4	7.5
2095	4.3	6.0	4.3	6.0	6.8	9.6	6.8	9.6
2105	5.5	7.7	5.5	7.7	8.6	12.1	8.6	12.1
2115	5.6	7.9	5.6	7.9	10.9	15.4	10.9	15.4

## Evolution of net damages (in % of production lost)

	P-MI		P-CO		N-MI		N-CO	
	1	2	1	2	1	2	1	2
2015	0.3	0.5	0.3	0.5	0.3	0.5	0.3	0.5
2025	0.5	0.8	0.5	0.8	0.5	0.8	0.5	0.8
2035	0.8	1.1	0.8	1.1	0.8	1.1	0.8	1.1
2045	1.0	1.4	1.1	1.4	1.2	1.6	1.2	0.9
2055	1.3	1.7	1.4	1.0	1.8	2.2	1.8	1.3
2065	1.7	2.1	1.9	1.3	2.5	3.0	2.6	1.8
2075	2.2	2.7	1.6	1.6	3.6	4.2	2.6	2.5
2085	2.8	3.3	2.1	2.1	4.5	5.1	3.3	3.2
2095	3.6	4.2	2.7	2.6	5.5	6.1	4.1	3.9
2105	3.6	4.2	3.4	3.2	6.0	6.7	5.0	4.7
2115	3.5	4.0	3.4	3.3	5.9	6.6	6.1	5.7

## GDP losses (% from baseline) and overall welfare (WRG)

	P-MI		P-CO		N-MI		N-CO	
	1	2	1	2	1	2	1	2
2015	-0.5	-0.7	-0.5	-0.7	-0.4	-0.7	-0.4	-0.6
2025	-0.7	-1.1	-0.7	-1.0	-0.6	-1.0	-0.6	-1.0
2035	-1.4	-1.6	-1.2	-1.5	-0.9	-1.5	-0.9	-1.3
2045	-2.1	-2.1	-2.0	-2.0	-1.4	-2.2	-1.4	-1.5
2055	-2.6	-2.8	-2.6	-2.2	-2.1	-3.1	-2.1	-1.9
2065	-3.2	-3.5	-3.2	-2.6	-3.1	-4.3	-2.9	-2.6
2075	-3.9	-4.5	-3.4	-3.1	-4.8	-5.9	-3.9	-3.6
2085	-4.7	-5.4	-3.9	-3.8	-6.4	-7.5	-4.9	-4.7
2095	-5.7	-7.5	-4.5	-4.5	-7.9	-9.6	-6.1	-5.8
2105	-6.2	-8.7	-5.5	-6.3	-9.1	-11.6	-7.3	-7.0
2115	-6.2	-9.2	-5.8	-7.3	-9.5	-12.5	-8.9	-9.3
WRG	9,961,585		9,961,592		9,961,576		9,961,585	

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# Conclusions

**Ada-BaHaMa** has been **extended** to a **game setting** where several regions define non-cooperatively their energy and climate policies.

Numerical results deliver several **insights**:

- 1 The non-collaborative setting is **detrimental** to the environment: compared to the collaborative setting, players delay their transition to the clean economy, so concentrations reach higher values.
- 2 In region 1: **adaptation** is only a **complement** to mitigation.
- 3 In region 2 (assumed to be more sensitive to climate changes and where adaptation is assumed to be more efficient): **adaptation substitutes** for mitigation during some initial periods.
- 4 But in all cases, adaptation does not prevent an (almost complete) **phase-out** of the dirty economy by the end of the model horizon.

## A work in progress...

We plan to consider in Ada-BaHaMa, as future research:

- both **proactive** and **reactive** adaptation (following eg Agrawala et al., 2010);
- **more regions** (at least the following 3 regions: OECD, BRICs, ROW);
- **uncertainty** related to climate change and technological progress, following a **stochastic control approach** as in the (original) BaHaMa model.  
(Caveat: model solving becomes here an issue!)