INTEGRATED ASSESSMENT, WATER RESOURCES, AND SCIENCE-POLICY COMMUNICATION

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Abstract

Traditional climate change modeling neglects the role of feedbacks between different components of society-biosphere-climate system. Yet, such interconnections are critical. This paper describes an alternative, Integrated Assessment (IA) model that focuses on feedbacks not only within individual elements of the society-biosphere-climate system, but also on their interconnections. The model replicates the relevant dynamics of nine components of the society-biosphere-climate system at the sectoral, or single-component, level: climate, carbon cycle, hydrological cycle, water demand, water quality, population, land use, energy and economy. The paper discusses the role of the model in science-policy dialogue.

1. Introduction

Climate change is occurring and is almost certain to have anthropogenic origins, according to a recent Intergovernmental Panel on Climate Change (IPCC) report [1]. In attempting to mitigate and adapt to the effects of climate change, it is therefore necessary for society to understand the potential effects of climate change on all elements of the Earth-system.

A common approach to understanding the Earth-system involves the use of mathematical modelling. Climate models come in various forms [2]. Complex, high-resolution models, like GCMs, provide the majority of climatic predictions and policy-relevant information to the policy-development community. GCM use has many limitations, including spatial and temporal resolution, simulation durations and data analysis. Furthermore, since GCMs require socio-economic driving scenarios to force model behaviour, they neglect social-economic-climatic feedbacks that play a crucial role in the Earth-system’s evolution [3].

This paper presents the use of less complex, but more comprehensive, feedback-based models as an important alternative to complex climate models.

2. Modelling feedback

The model described in this paper produces the main characteristics of several important sectors in the society-biosphere-climate system. Covering the period from 1960-2100, the model operates at an annual scale, so that it provides a long-term view of the feedback effects of global change, but disregards variations at seasonal or shorter timescales. In terms of
methodology, the research offers a system dynamics approach for explicit modelling of the feedbacks within and between components of the society-biosphere-climate system. System dynamics focuses on systems that are characterized by dynamic complexity, which means that they have a relatively small number of components tightly coupled through numerous feedback loops, and their behaviour arises from the resulting feedback-rich system structure. The overall goal of the system dynamics approach is an improved understanding of the basic connections and relationships within a system that determine its behaviour, rather than the prediction of future events.

Figure 1 Model components and their feedbacks

An application of system dynamics, the model replicates the relevant dynamics of nine components of the society-biosphere-climate system at the sectoral, or single-component, level: climate, carbon cycle, hydrological cycle, water demand, water quality, population, land use, energy and economy (see Figure 1). At the inter-sectoral level, the individual model sectors are linked through feedbacks, identified in Figure 1 as arrows with associated italic script. This linking of individual components produces a closed-loop structure, whereby each sector affects the others in a causal fashion, and the positive or negative polarity associated with each arrow indicates the direction of change one model component imposes on the next. All the major elements of the system are endogenous, or included explicitly, so that the dynamic behaviour of the model arises from the system structure, rather than from driving scenarios.

2.1 Model Sectors

A description of each model sector follows. Most of the sectors build on the knowledge of respective disciplines.
2.1.1 Climate, carbon, land use, population, economic, and energy sectors

The climate sector is an upwelling-diffusion energy-balance model (UD/EBM) based on the Box Advection-Diffusion (BAD) model of Harvey and Schneider [4]. Our reproduction of BAD has a climate sensitivity of roughly 1.8°C for an atmospheric doubling of CO₂, or 2xCO₂ concentrations, and therefore lies near the low-to-middle end of the 1.0°C-4.1°C temperature-change spectrum.

The carbon cycle comes from Goudriaan and Ketner [5], with a modified oceanic sector developed by Fiddaman [6], and represents carbon flows between the atmosphere, the terrestrial biosphere, and the oceans, focusing on atmosphere-mixed ocean layer interactions, and on carbon storage in soil, the terrestrial biosphere, and the deep oceans. An associated land use sector includes the effects of land conversion for agriculture, burning, and forest harvest [5].

Population growth is modelled on the approach taken by both Nordhaus and Boyer [7], but is modified to use water scarcity as its driver. During the historical period of the simulation, from 1960-2005, the population growth simulated by our model matches UN figures [8].

The economic sector is an adaptation of a well-known climate-economy model called DICE [9], which models the global aggregate economic output (GDP, or gross domestic product) using a Cobb-Douglas production function that includes total factor productivity, capital, and labour as inputs. DICE also calculates industrial emissions as a product of economic activity and climate change policy.

2.1.2 Water use, quality, and the natural hydrological cycle

The three water sectors simulate the natural hydrological cycle, water use, and the effects of that use on water quality. The first water sector component includes the reservoirs of gaseous, liquid, and solid forms of water, as well as water transfers between these states. Water reservoirs therefore include the oceans, the land surface, groundwater, ice sheets, and the atmosphere [10], while transfers include evaporation and evapotranspiration, advection, precipitation (both solid and liquid), melting, groundwater percolation into, and base-flow from, aquifers, and surface runoff to the oceans [10, 11, 12].

The second component, which includes both water use and water quality, represents anthropogenic water use for domestic, industrial, and agricultural purposes, beginning with water withdrawals and consumption, and the effects of that use on water quality. Water quality components of the water sector include the generation of water pollution and its impact on surface water availability, and wastewater treatment and reuse as approaches to reducing water scarcity. The water sector also includes groundwater withdrawals and desalination, while the economic sector and an embedded power-generation sector, affect the degree to which these possible solutions to surface water scarcity are adopted. Anthropogenic water withdrawals and consumption depend on overall surface water availability. In this model, the available surface water is set to 37% of the total runoff, giving a base value of roughly 16000 km³ yr⁻¹. This available surface water can then be allocated to two forms of human water use: water withdrawals and water consumption, each of which have three
components – domestic, industrial, and agricultural – and different drivers, related to the quantitative elements of anthropogenic water demand. In the case of the domestic sector, drivers of change are technological change, and changes in the standard of living and in the municipal water system efficiency, all of which are related to the economic sector. For the industrial sector, the drivers include ongoing structural changes in the approach to cooling power generation plants, and changes in water-use efficiency per unit energy via technological change. For the agricultural sector, the main drivers are total irrigated area and technological change, and climate change also plays an important role in determining irrigation water requirements, since the rate of evapotranspiration from irrigated areas will rise as the surface temperature increases. Expansion of irrigated lands in the future is likely limited [13], and technological change affects the base irrigation water requirement per hectare of irrigated land.

Domestic use, industrial processes, and irrigation projects generate wastewater, which causes pollution of receiving waters, and can make that water unsuitable for further use, especially for drinking-water supply [12]. In the domestic sector, all returnable waters require treatment [11], while in the industrial sector, thermal power plants do not generate chemical pollution, so only the wastewater from manufacturing processes requires treatment. In the agricultural sector, returnable waters come from broadly distributed fields and cannot be treated, despite the presence of fertilizers and toxic chemicals [13]. Since untreated wastewater greatly increases the amount of surface water appropriated for human use, the model converts the actual surface water withdrawal into an effective withdrawal by applying a dilution factor, of between 8 and 10 in value, to the untreated wastewater volume.

Water scarcity is often measured by water stress, which “is a measure of the degree of pressure put on water resources by users of the resources, including municipalities, industries, power plants and agricultural users” [14]. The most commonly used water stress indicator is the “annual withdrawals-to-availability (wta)” ratio, where wta values of 0.2 indicate “mid-stress” and values of 0.4 and higher indicate “severe stress”. According to the usual ratio approach, then, water stress equals the total withdrawal over the surface water availability, or,

\[ wta = \frac{W}{R} \quad (1) \]

Where, W is the actual surface water withdrawal and R is the total surface runoff available for human use; however, due to overestimation in this research, water stress is altered in two ways to take water pollution into account by using the effective, rather than actual, withdrawal, and a reduced fraction of the total runoff, called A_s. These modifications give water stress the following form,

\[ wta = \frac{W_{sw}}{A_s} \quad (2) \]

Where, wta is now the effective surface water withdrawal, W_{sw}, divided by the available runoff volume, A_s.
Water reuse offers a means to reduce water stress [11, 15, 16]. As clean surface water becomes scarcer, there is greater incentive to treat larger volumes of wastewater and then to reuse a portion of that treated wastewater.

Water scarcity also drives a search for alternative water sources, with additional water supply coming in the form of desalination and groundwater pumping. In this model, groundwater pumping refers to the extraction of non-renewable groundwater resources, where growth in groundwater use depends on the degree of water scarcity, and its simulation follows the approach in Simonovic [16]. In terms of desalination, Gleick [15] provides information on worldwide capacity growth, and suggests that the domestic sector is the primary user of desalinated water. Once the individual supply and demand components described above have been coupled together to create the water sector, its overall behaviour must be investigated.

2.1.3 Energy demand, resources, economics, production, and emission

The Energy Demand component of the model calculates the net energy demand, which changes over time as a result of economic activity and of price-inspired efficiency measures and technological change. In this component, the net demand is divided into the heat-energy and electric-energy demands. Heat-energy demand is further divided into specific demands for deliveries of quantities of coal, oil, and natural gas resources.

Energy Resources contains the non-renewable energy reserves used as primary energy sources and as important inputs to secondary energy production. Remaining amounts of the three fossil fuels represented in the model are tracked model component, and can increase through prescribed energy resource discoveries, and decrease through production, or depletion.

The Energy Economics component includes determination of the total investment in the maximum electricity production capacity, which is based both on historical trends and on replacing capacity lost to obsolescence, as well as the division of that total among competing electricity production technologies, which can be based on market forces, in the case of coal, oil, and natural gas-fired plants and alternative energy sources, or on the prescriptions of decision makers, in the case of nuclear and hydroelectric power.

Energy Production represents the supply portion of the energy sector by producing primary and secondary energy to meet energy demands. Energy is produced from fossil fuel resources both as heat- and electric-energy, and from other electricity production technologies, with electricity production allocated among the competing options according to production costs.

Finally, the Energy Emissions component calculates the carbon emissions resulting from the combustion of fossil fuels used to meet energy demands, and from non-energy processes such as cement production and natural gas flaring.

2.2 Intersectrol feedbacks

The carbon cycle-climate sector feedback depends on the atmospheric CO₂ concentration as determined by the carbon sector, and uses a forcing equation to translate the atmospheric
concentration into a radiative forcing, which then leads to an increase in surface temperature. A doubling of CO₂ causes an equilibrium surface temperature increase of 1.8°C, and the forcing equation is linear with this form:

\[ F = S \left( \frac{C_A}{C_{A0}} \right) - S \]  

(3)

F is the climate forcing (W m⁻²), S is a ‘climate sensitivity’ constant (W m⁻²), C_A and C_{A0} represent the current and initial atmospheric carbon dioxide concentrations, respectively.

The climate and surface flow sectors are connected via the surface temperature change. Since increased surface temperature will likely increase the intensity of the hydrological cycle as well as amplify precipitation volumes, the model includes a temperature multiplier equation that increases evaporation, evapotranspiration, snowfall, and melting rates within the natural hydrological sector by a fixed percentage for every degree of warming. The equation for the temperature multiplier is based on two equations,

\[ T_{\text{feedback}} = 1 + \left( \frac{P_{\text{mult}}}{100} \right) \]  

(4)

\[ P_{\text{mult}} = P_{\text{mult,base}} \Delta T_s \]  

(5)

Where, T_{feedback} is the temperature multiplier described above, which takes its value from P_{mult}, the precipitation multiplier calculated by equation (5). P_{mult} and P_{mult,base} are the current percentage increase in precipitation and the base level multiplier, 3.4% K⁻¹. Again, P_{mult} depends on the change in surface temperature, ΔT_s, measured in Kelvin.

The climate influences the economy through two equations: i) a temperature damage function, D, and ii) a climate damage multiplier, Ω, which is derived from D.

\[ D = \theta_1 \Delta T_s + \theta_2 \Delta T_s^2 \]  

(6)

Where, D is the percentage damage to the economy as a function of changing surface temperature, θ₁ and θ₂ are parameters, and ΔT_s is the surface temperature change from pre-industrial levels.

The climate damage multiplier affects the Cobb-Douglas production function used by DICE, and takes this form [7], where, again, Ω is a unit less multiplier with an initial value of one.

\[ \Omega = 1/(1 + D/100) \]  

(7)

The surface flow, water demand and population sectors are connected through global water stress levels. The reasoning behind this connection runs as follows: water availability determines agricultural output, economic growth, and power generation; water scarcity limits all three, and severe water scarcity results in lower fertility rates, or even famine and
increased mortality rates. Therefore, water stress essentially serves as a proxy for many other aspects of population growth.

\[ g = b \cdot wta \]  \hspace{1cm} (8)

Where, \( g \) represents the decline in the population growth rate – a second-order, deceleration-like term – and \( wta \) is the water stress level, taking pollution effects into consideration. The parameter \( b \) is an arbitrary, dimensionless constant that matches simulated values with historical population figures from UNESA [8], and has a value of 0.025 for most model simulations. To obtain the growth rate for the global population, the form of the equation is,

\[ \frac{dr}{dt} = r \cdot g \]  \hspace{1cm} (9)

Where, \( r \) is the population growth rate, and \( g \) is the decline in the population growth rate, change over time. Finally, the change in population per year follows the same format as equation (9), such that, \( \frac{dp}{dt} = P \cdot r \). These equations are solved by numerical integration, since none of the relevant variables (\( wta \), \( g \), and \( r \)) are constant – recall that \( wta \) depends on water availability, demand, and pollution, all of which are variable and are subject to model feedbacks.

The economy, water demand, and population sectors use a set of equations developed by Alcamo et al. [17] that relate economic performance, as modelled in the economy sector, to water use levels in the domestic and industrial sectors of the water use sector. These equations calculate values for domestic and industrial structural water intensities, or DSWI and ISWI, which depend on absolute and relative measures of gross domestic product, respectively. The DSWI curve also depends on global population, since domestic water demand is modelled on a per capita basis, while ISWI also depends on electrical power generation.

\[ DSWI = DSWI_{\text{min}} + DSWI_{\text{max}} \left( 1 - e^{-\gamma_i \left( \frac{Q}{Q_0} \right)^2} \right) \]  \hspace{1cm} (10)

\[ ISWI = ISWI_{\text{min}} + \frac{1}{\gamma_i \left( \frac{Q}{Q_0} \right) \frac{Q}{Q_0}} \]  \hspace{1cm} (11)

Where, DSWI is the domestic structural water intensity in \( m^3 \) person\(^{-1} \) yr\(^{-1} \), \( DSWI_{\text{min}} \) is the base amount, \( DSWI_{\text{max}} \) is the maximum amount, \( \gamma_i \) is a curve parameter, \( Q \) is the total annual economic output from the economic sector of the model, and \( P \) is the current global population from the model’s population sector. In equation (11), \( \gamma_i \) is a curve parameter, \( Q_0 \) is the initial global output, and \( P_0 \) is the initial global population.

In a similar fashion, the population and economy sectors are connected through an important element of the DICE model’s Cobb-Douglas production function, like the following form,
\[ Q = zK^\gamma L^{1-\gamma} \]

(12)

Where, \( z \) is the total factor productivity, \( K \) is the capital stock, \( \gamma \) is an elasticity parameter, and \( L \) is labour, or the global aggregate population.

The calculation of industrial emission levels is a component of the DICE model, and depends on the economic output calculated by equation (12) as well as a ratio of emissions to output or emissions intensity, \( \sigma \), and emissions control measures, \( \mu \), such as carbon tax policies. In equation form, industrial emissions, \( E \), are therefore calculated as,

\[ E = (1 - \mu)\sigma Q \]

(13)

The population and carbon sectors are linked through the land-use sector, following the approach of Goudriaan and Ketner [5], who model CO\(_2\) emissions from clearing and burning within a terrestrial biome, and from land-use conversions that establish new landcover in the place of the previous vegetation.

The energy, economy, water use, and carbon sectors use a set of equations that relate energy production, as modeled in the energy sector. The mathematical equations altered by the incorporation of the energy sector in the society-biosphere-climate models are given below,

\[ E_{\text{Ind}}(t) = E_{\text{coal}} + E_{\text{oil}} + E_{\text{nat gas}} + E_{\text{cement}} + E_{\text{flaring}} \]

(14)

Where \( E_{\text{Ind}}(t) \) represents the carbon cycle sector's received emissions from industrial and energy-based processes, and the right-hand side variables are the energy-sector variables. In this equation mass of carbon emission by coal, oil, natural gas, cement and flaring of natural are represented by \( E_{\text{coal}}, E_{\text{oil}}, E_{\text{nat gas}}, E_{\text{cement}} \) and \( E_{\text{flaring}} \) respectively.

Next, the endogenous energy demand equation connects the endogenous energy demand to the economic output, \( Q(t) \), measured in \( 10^{12} \) US$yr\(^{-1}\) at market exchange rates,

\[ ED(t) = r_{E_{\text{D}}/GDP_{1990}}Q(t)\text{SMOOTH}\left[\frac{\text{AEP}}{\text{AEP}_{1990}}\right]_{10}^{p_e} \]

(15)

Where, \( ED \) is the net energy demand and \( r_{E_{\text{D}}/GDP_{1990}} \) is the ratio of energy use to GDP in 1990. AEP, \( \text{AEP}_{1990} \), \( p_e \) stands for the average energy price, normal energy price of 1990 and price elasticity respectively. The SMOOTH function averages the values within the parenthesis (in this case for 10 years) of mentioned time.

Finally, water withdrawal and consumption for industrial purposes depend on electricity production. The equations involved are showing the new connection in bold type,
\[ W_{\text{desired}} = EIP_{TWh} \alpha_{MWh} - Q_{\text{ww reuse}}, \]  
\[ C_{\text{desired}} = EIP_{TWh} k_{MWh} \]  

(16)  

(17)

Where, \( W_{\text{desired}} \) and \( C_{\text{desired}} \) are, respectively, the desired withdrawal and consumption of surface waters for industrial purposes (in km\(^{3}\) yr\(^{-1}\)), \( EIP_{TWh} \) is the electricity production, \( \alpha_{MWh} \) and \( k_{MWh} \) are variables that represent the required surface water withdrawals and consumption per MWh of electricity produced (in m\(^{3}\) MWh\(^{-1}\)), and \( Q_{\text{ww reuse}} \) is the amount of treated wastewater reused for industrial purposes (in km\(^{3}\) yr\(^{-1}\)).

2.3 Model Simulations

Experiments with the model provide examples of its function, and of the feedback on model behavior. To provide a basis for comparison with the results of the model experiments, a model “baseline” is required, which is generated using the initial model configuration. Changes in other major variables in the feedback loop of Figure 1 are given in Table 1, below. Given these “business-as-usual” values, the question is how feedback within, and particularly between, model sectors affects the overall behavior of the model. Because of the focus in the paper on water use and the hydrological cycle, the experiment described below deals with the feedback effects, on the behavior of the model as a whole, of water stress calculation.

2.3.1 Experiment: Water stress

The following experiments investigate the effects of two different water stress calculations: i) the traditional definition, referred to as “traditional wta” in the experimental results, and ii) the novel definition, or “novel wta”. The difference between the two measurements is the neglect or inclusion of water pollution.

<table>
<thead>
<tr>
<th>Year</th>
<th>1960</th>
<th>2000</th>
<th>2050</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Population (people)</td>
<td>3.02 x 10(^{9})</td>
<td>6.05 x 10(^{9})</td>
<td>9.16 x 10(^{9})</td>
<td>11.3 x 10(^{9})</td>
</tr>
<tr>
<td>Temperature Change</td>
<td>0 °C</td>
<td>0.17 °C</td>
<td>0.70 °C</td>
<td>1.54 °C</td>
</tr>
<tr>
<td>Atmospheric CO(_2) Level</td>
<td>310 ppm</td>
<td>351 ppm</td>
<td>458 ppm</td>
<td>612 ppm</td>
</tr>
<tr>
<td>GDP (1990 US$)</td>
<td>5.45 x 10(^{12})</td>
<td>26.2 x 10(^{12})</td>
<td>57.1 x 10(^{12})</td>
<td>93.6 x 10(^{12})</td>
</tr>
<tr>
<td>Global Tropical Forest Cover</td>
<td>3814 Mha</td>
<td>3312 Mha</td>
<td>2243 Mha</td>
<td>815 Mha</td>
</tr>
<tr>
<td>Surface Water Flow Change</td>
<td>0 km(^{3}) yr(^{-1})</td>
<td>-280 km(^{3}) yr(^{-1})</td>
<td>-57 km(^{3}) yr(^{-1})</td>
<td>555 km(^{3}) yr(^{-1})</td>
</tr>
<tr>
<td>Surface Water Withdrawals</td>
<td>1961 km(^{3}) yr(^{-1})</td>
<td>3870 km(^{3}) yr(^{-1})</td>
<td>4242 km(^{3}) yr(^{-1})</td>
<td>4311 km(^{3}) yr(^{-1})</td>
</tr>
<tr>
<td>Surface Water Consumption</td>
<td>1120 km(^{3}) yr(^{-1})</td>
<td>2144 km(^{3}) yr(^{-1})</td>
<td>2546 km(^{3}) yr(^{-1})</td>
<td>2817 km(^{3}) yr(^{-1})</td>
</tr>
<tr>
<td>Global Water Stress</td>
<td>0.38</td>
<td>0.69</td>
<td>0.50</td>
<td>0.39</td>
</tr>
</tbody>
</table>

The second part of the investigation compares two separate simulation runs: the baseline simulation, which shows the impact on model behavior of using the “novel wta” definition for water stress calculations, and an alternative simulation, which uses the “traditional wta” definition as the water stress value. In this second part, we will show that the choice of water stress definition affects model behavior significantly.
**Water stress values in the baseline simulation**

Table 2, 3 & 4 compares the water stress values calculated with the usual withdrawal-to-availability ratio to those calculated with equation 2, which includes the effect of pollution on the global water stress level.

Table 2: Comparison of two water stress calculation methods: Historical values (dimensionless)

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional wta</td>
<td>0.13</td>
<td>0.16</td>
<td>0.19</td>
<td>0.23</td>
<td>0.23</td>
<td>0.24</td>
</tr>
<tr>
<td>Novel wta</td>
<td>0.38</td>
<td>0.49</td>
<td>0.59</td>
<td>0.64</td>
<td>0.64</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Table 3: Comparison of two water stress calculation methods: Future values (dimensionless)

<table>
<thead>
<tr>
<th>Year</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
<th>2060</th>
<th>2070</th>
<th>2080</th>
<th>2090</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional wta</td>
<td>0.25</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.26</td>
</tr>
<tr>
<td>Novel wta</td>
<td>0.65</td>
<td>0.63</td>
<td>0.58</td>
<td>0.54</td>
<td>0.50</td>
<td>0.44</td>
<td>0.40</td>
<td>0.39</td>
<td>0.39</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Clearly, the choice of the water stress calculation approach affects the wta value significantly.

**Impact of water stress calculation approach on model behaviour**

Water stress values influence the model quite strongly, since they directly affect variables such as population growth, power generation, water use, desalination capacity, groundwater withdrawals, wastewater treatment, and wastewater reuse, and indirectly affect many more.

Most notably, the difference in global population figures between the two simulations is considerable. Although the population figures are very similar in the “traditional wta” and “novel wta” experiments from 1960-2005, they diverge rapidly during the remaining years of the simulation period – see Table 4.

Table 4: Population (in billions) and water stress in traditional and novel wta experiments

<table>
<thead>
<tr>
<th>Year</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
<th>2060</th>
<th>2070</th>
<th>2080</th>
<th>2090</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Stress (wta)</td>
<td>0.26</td>
<td>0.27</td>
<td>0.28</td>
<td>0.28</td>
<td>0.29</td>
<td>0.29</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>Water Stress incl. Pollution</td>
<td>0.81</td>
<td>0.84</td>
<td>0.86</td>
<td>0.87</td>
<td>0.86</td>
<td>0.85</td>
<td>0.83</td>
<td>0.80</td>
<td>0.77</td>
<td>0.72</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
<th>2060</th>
<th>2070</th>
<th>2080</th>
<th>2090</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>2) Novel wta expt. Population</td>
<td>6.84</td>
<td>7.54</td>
<td>8.19</td>
<td>8.80</td>
<td>9.36</td>
<td>9.89</td>
<td>10.4</td>
<td>10.9</td>
<td>11.3</td>
<td>11.7</td>
</tr>
<tr>
<td>Water Stress (wta)</td>
<td>0.25</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Water Stress incl. Pollution</td>
<td>0.70</td>
<td>0.66</td>
<td>0.58</td>
<td>0.54</td>
<td>0.50</td>
<td>0.44</td>
<td>0.40</td>
<td>0.39</td>
<td>0.39</td>
<td>0.39</td>
</tr>
</tbody>
</table>

3. **Policy analysis**

The interaction between policy and an integrated assessment model of the society-biosphere-climate system is being investigated as (a) the best mean of improving our understanding of the vital feedbacks that connect human activities to the global climate system and the carbon cycle and (b) the tool for support of policy making. The model is used to answer two interrelated questions: (i) *What are the specific requirements that policy imposes on science?* and (ii) *What is the most effective way of communicating science to policy?*
First question explores the particular types of information that policy-makers demand of science in specific decision-making processes. In particular, partners in the Meteorological Service of Canada, Finance Canada, Environment Canada, Natural Resources Canada, and Fisheries Oceans Canada are consulted as to their policy objectives. Ultimately, each department/actor will aim to protect a different set of interests and will thus utilize science in different ways. In the context of this research, science is represented by the integrated assessment model of the society-biosphere-climate system.

System dynamics simulation allows an investigation of “what if” questions, helps to identify useful policies and practices, and improves understanding of modelled interconnections and their impacts on simulated and real-world behaviour. An initial, "base case" simulation serves as a basis for comparison with other simulations that differ from the base case. These alternative simulations represent alternative policies, and may cause minor alterations in model behaviour in some cases, and substantial changes in others. The causes of changes can then be traced by identifying reasons for differences in the behaviour of model variables between simulation runs. Such causes include sensitivities built into model equations, structural elements of the model (particularly in terms of integration effects), and combinational effects.

4. Global vs regional model

This integrated modeling is a replica that combines simplified representations of the socioeconomic determinants of greenhouse gas emissions, the atmosphere and oceans, and impacts on human activities and ecosystems in a global scale. The model, developed through a system dynamics methodology, currently has nine major sectors, all of which interact with one another through feedback relationships. It shares important characteristics with climate-economy models, integrated assessment models, and hydrological models at a global scale.

Despite the work to date, the model requires major improvements in one particular area. Its individual sectors represent socio-economic and natural processes at a global scale, and therefore omit important regional processes. On the regional scale one important goal of the work is to develop climate-change adaptation and mitigation strategies for different regions of the world where the representation of regional effects is critical. A focus on regionalization will allow in investigating the differential effects of global climate change on regional water resources, economic performance, energy supply and demand, land use, energy, and will be based on geographic and economic factors. At present, 12 regional blocs are under consideration. However, sectors like carbon, climate and part of water sector will remain on global scale.

5. Conclusions

This paper describes an option for global change modelling, based on an integrated assessment approach. Our approach can be seen as an inversion of the “depth-first, breadth-second” approach – we focus on intersectoral feedbacks, rather than intrasectoral relationships. As compared with the more complex modelling approaches, which involve
general circulation models, coupled carbon cycle-climate models, or the use of climate models with driving scenarios, this feedback-based approach offers a straightforward approach to the analysis of complex, nonlinear systems.

A shift is underway from a global-aggregate to a regional representation of global change, which is expected to improve the model significantly both, from a policy and natural science perspective.

6. References

