# 1 Integrated Assessment Models

Most modeling in climate change is done with *integrated assessment models*. These models are actually a combination of multiple models, with feedbacks between the various systems. For example, we may start with a model of the Earth's climate and a model of the world's economy, integrated assessment models would take each of these and provide links between the two. This acknowledges that human activity (economic activity) has an effect on the climate and climate has an effect on human activities (e.g., production and welfare). And of course, policies can be designed to affect human behavior, which in turn affects the environment. In a perfect modeling world, the state of the climate would also influence policy, but this would be much tougher to model.

The climate and economic sectors are obviously complex systems, so complex that we cannot possibly model all aspects of either, much less both at the same time. So we must pick and choose our battles. You should always keep in mind what your goals are in modeling (do you want to model regional impacts, global impacts, impacts on ecosystems, etc), what the assumptions (and thus the limitations) are of the models you are using, and what you can and cannot hope to learn from these models. Models are an abstraction from reality, and good models are much like good fiction. They are parallels of reality that highlight something interesting, and can often tell us more than nonfiction could ever do.

The main integrated assessment model we will be looking at is the DICE model by William Nordhaus.

1. verbal description
2. mathematical description (equations)
3. programming (GAMS)

# 2 Background and description of the DICE model

This section outlines the DICE-2007 model as presented in "A Question of Balance" by William Nordhaus. It is assumed that students will have already read Chapter 1, Summary for the Concerned Citizen. DICE stands for "Dynamic Integrated model of Climate and the Economy". It is a fairly simple model with a lot of instructional power. It is written in GAMS.

## 2.1 Economic Model

1. Neoclassical growth model - agents invest in capital, education, and technologies by consuming less in the current period, in return for increased consumption in future periods.

   Single commodity that can be either consumed or saved (investment). Endowed with initial stocks of capital and labor and an initial level of technology.

   Population growth and technological change are exogenous (not determined within the model) - note that this is also a MAJOR ASSUMPTION

2. natural capital - GHG emissions are reductions in the capital stock and reductions emissions are investments into natural capital. AN IMPORTANT IMPLICATION of this modeling procedure is that society reduces current consumption in order to reduce emissions, reduce harmful effects from climate change, and possibly increase consumption in the future.

3. One country model - all countries are aggregated into one country. His RICE model separates out different regional effects.

   Regional outputs and capital stocks are aggregated using purchasing power parity exchange rates.

4. There is a well-defined *Social Welfare Function* over different paths of consumption, increasing in per capital consumption of each generation, with diminishing marginal utility of consumption. ASSUMPTION IMPLIED - we know what we want and we can measure it - no political bickering about what we are trying to achieve. And we value consumption of all equally. Consumption is consumption.

5. What matters is not total consumption, but per capita consumption. Thus, total population in a generation also determines its value.

6. Future consumption is discounted. The pure rate of time preference and the marginal utility of consumption will determine the discount rate on goods, which is critical for intertemporal choices.

   What is the economic justification for discounting?

7. Consumption depends on economic (production) and geophysical (environmental influences on production) factors.

8. Two major decision variables in the model: the overall savings rate for physical capital and the emissions-control rate for greenhouse gases.

9. Output is produced by a Cobb-Douglas production function using capital, labor, and energy.

10. Energy is either from carbon-based fuels (such as coal) or non-carbon-based technologies (such as solar, geothermal, nuclear).

11. Technology change takes two forms: economy-wide technological change and carbon-saving technological change. Carbon-saving technological change is modeled as reducing the ratio of CO2 emissions to output. Both forms of technological change are exogenous (ASSUMPTION) in the model.

12. Carbon fuels are limited in supply. Substitution of non-carbon fuels for carbon fuels takes place over time as carbon-based fuels become more expensive, either because of resource exhaustion or because policies are taken to limit carbon emissions.

13. There is a backstop technology, which allows for complete replacement of all carbon fuels at a price that is relatively high but declines over time.

    Talk about backstops. Solar? Talk about solar.

### 2.2 Geophysical Sectors

The DICE model has several relationships that link the economy with the different factors affecting climate change, including:

- carbon cycle
- radiative forcing
- climate-change equations
- climate-damage relationship

1. The only GHG subject to controls (explicitly modeled) is CO2. Other GHGs are included as exogenous trends in radiative forcing; these include primarily CO2 emissions from land-use changes, other well-mixed GHGs, and aerosols.

2. CO2 emissions are determined by:
   - a time-varying emissions-output ratio - global average
   - an emissions-control rate determined by the policy being considered

3. Carbon cycle based on three-reservoir model calibrated to existing carbon-cycle models and historical data

   (a) atmosphere
   (b) quickly mixing reservoir in the upper oceans and biosphere
   (c) deep oceans

   Carbon flows in both directions between adjacent reservoirs. The mixing between the deep oceans and the other two is extremely slow.

4. climate equations
   (a) radiative forcing – calculates the impact of accumulation of GHGs on radiative balance of globe
   (b) mean surface temperature of the globe
   (c) average temperature of the deep oceans

   calibrated by larger general circulation models.
5. Economic impact from climate change. Generally assumed that small changes, no big deal, but rise nonlinearly with extent of climate change.

### 2.3 diversion - Hoteling rents as the 'market solution'

Consider a nonrenewable resource with fixed supply Q that must be allocated between two periods. Let there be fixed marginal costs of extraction MEC, and inverse demand $P(Q)$.

- Graphical example -

- Numerical example to be worked in the ubung.

Definition: scarcity (or Hoteling) rents - rents that arise because a resource is in fixed supply.

Hoteling's Rule: Rents must rise at the rate of interest.

### 2.4 DICE equations

#### Social Welfare Function

The objective is to maximize population-weighted discounted per capita consumption over the course of history.

$$W = \sum_{t=1}^{Tmax} u[c(t), L(t)]R(t) \tag{1}$$

Assumes economic forces are as they exist today. Any large-scale social change is not modeled.

$R(t)$ is the discount factor in time period $t$. $\rho$ is the "pure rate of social time preference", or how society discounts future time periods. There are a bunch of different ways to calculate this. Basically it is the return on a risk-free capital asset minus inflation. Then the question is what the risk-free capital asset should be. To foreshadow, the value you choose for this parameter is critical to your results.

$\alpha$ is the marginal utility of consumption and is given in various econometric studies. $L(t)$ is the population, $c(t)$ is per capital consumption and $C(t)$ is total consumption. It is assumed that consumption includes both market and non-market goods. For example, existence value from endangered species would be included.

$$R(t) = (1+\rho)^{-t} \tag{2}$$

$$U[c(t), L(t)] = L(t)[c(t)^{1-\alpha}/(1-\alpha)] \tag{3}$$

Population growth is based on an initial level, with a growth rate that declines over time until a global population of 8.5 billion people is reached.

**Production**

Total output $Q(t)$ in period $t$ is produced using a Cobb-Douglas production function, with adjustments from technological improvements, environmental damages, and abatement costs.

$A(t)$ is called a Hicks-neutral technology adjustment. As technology improves over time we get more output for a given amount of inputs.

$$Q(t) = \Omega(t)[1-\Lambda(t)]A(t)K(t)^{\gamma}L(t)^{1-\gamma} \tag{4}$$

$\Omega$ is the damage function. Climate change is expected to cause a drain on society, making production less efficient. For example, strain on our water resources may lead to more irrigation, which imposes an additional cost on society. Loss of ecosystem services implies that society will have to engineer something that the environment used to do for free (e.g., storm buffers). Other damages would be the cost of sea level rise, adverse effects on health, and catastrophic damages. Notice the shape of damages. Once we start parameterizing our model you may want to graph this.

$$\Omega(t) = 1/[1+\pi_1 T_{AT}(t) + \pi_2 T_{AT}(t)^2] \tag{5}$$

$$\pi(t) = \psi(t)^{1-\theta_2} \tag{6}$$

Enacting a policy will also use some resources. Production with renewable energy, for example, is more costly than production with coal, otherwise, firms would not use it. Thus, making the kinds of changes requires will lead to less efficient production processes (at least in the short run). $\Lambda$ is the abatement cost function, and expresses these costs as a fraction of total output.

$$\Lambda(t) = \pi(t)\theta_1(t)\mu(t)^{\theta_2} \tag{7}$$

$\pi(t)$ is participation cost markup - abatement cost with incomplete participation as fraction of abatement costs with complete participation. $\theta_1(t)$, $\theta_1(t)$, $\pi_1$, $\pi_2$, are parameters $\mu$ is the emissions control rate as fraction of uncontrolled emissions

Why?

¡¡Talk about global efficiency in reductions for a global pollutant¿¿

*Perfect mixing assumption*

*Porter hypothesis* - that stricter regulations will lead to more efficient technologies and increased long run growth.

Built into the DICE model is a textitbackstop technology, which allows for production without emissions. It could take any form, from a technology that removes carbon from the air post-production, to something like solar power, which allows for emission-free production. It is assumed that the price of the backstop is initially too high to be viable, but declines over time with carbon saving technological change. It is modeled by setting the time path of the parameters in the model so the marginal cost of abating 100 percent is equal to the price of the backstop.

**Budget equations**

$$Q(t) = C(t) + I(t) \tag{8}$$

$$c(t) = C(t)/L(t) \tag{9}$$

$$K(t) = I(t) + (1 - \delta_K)K(t-1) \tag{10}$$

$$E_{Ind}(t) = \sigma(t)[1 - \mu(t)]A(t)K(t)^{\gamma}L(t)^{1-\gamma} \tag{11}$$

$$CCum \leq \sum_{t=0}^{Tmax} E_{Ind}(t) \tag{12}$$

$\sigma(t)$ is the carbon intensity of output. $CCum$ is the total amount of the fossil fuel available.

**Emissions and climate equations**

Emissions are from industrial production (endogenous) and land use (exogenous).

$$E(t) = E_{Ind}(t) + E_{land}(t) \tag{13}$$

There are three atmospheric reservoirs for carbon: the atmosphere, a quickly mixing reservoir in the upper oceans and biosphere, and the deep oceans. The deep oceans provide a finite vast sink in the long run. Each reservoir is assumed to be well mixed in the short run, while mixing between reservoirs is slow. The climate equations are calibrated to match the carbon cycle in the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC).

$$M_{AT}(t) = E(t) + \phi_{11}M_{AT}(t-1) + \phi_{21}M_{UP}(t-1) \tag{14}$$

$$M_{UP}(t) = \phi_{12}M_{AT}(t-1) + \phi_{22}M_{UP}(t-1) + \phi_{32}M_{LO}(t-1) \tag{15}$$

The effects of greenhouse gases on the climate are modeled through three very simple relationships. First, accumulations of greenhouse gases lead to warming of the surface through increases in radiative forcing. Radiative forcing in the DICE model is from accumulation of CO2. Effects from other greenhouse gases are included in the exogenous parameters and calibrations, partly because its simpler and partly because they account for a relatively small percentage of emissions.

$$F(t) = \eta log_2[M_{AT}(t)/M_{AT}(1750)] + F_{EX}(t) \tag{16}$$

Higher radiative forcing warms the atmospheric level, which then transfers heat to the other reservoirs. Inertia is maintained in the system by using lagged variables. The model is calibrated so an equilibrium doubling of CO2 will lead to a three degree Celsius rise in global temperature.

$$T_{AT}(t) = T_{AT}(t-1) + \xi_1 F(t) - \xi_2 T_{AT}(t-1) - \xi_3[T_{AT}(t-1) - T_{LO}(t-1)] \tag{17}$$

$$T_{LO}(t) = T_{LO}(t-1) + \xi 4 T_{AT}(t-1) - T_{LO}(t-1)] \tag{18}$$