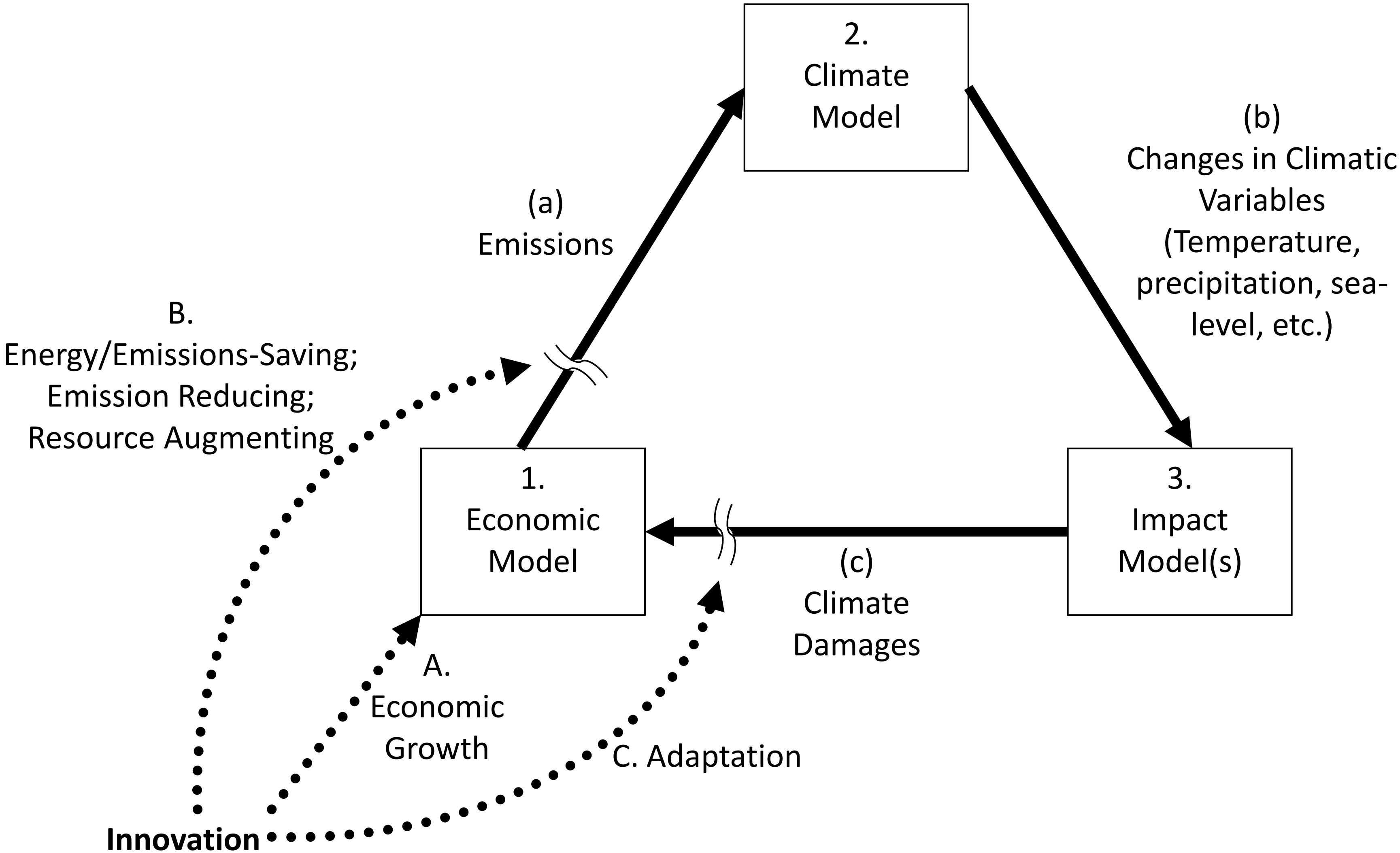
Sectoral and Regional Disaggregation and Interactions

Ian Sue Wing
Boston University

Improving the Assessment and Valuation of Climate Change Impacts for Policy and Regulatory Analysis
Nov. 18-19, 2010

What Is an Integrated Assessment Model?



Desiderata in Model Development:

If neither empirical estimates nor computational resources were an issue, what kind of IAM would we construct?

A Canonical Intertemporal IAM

Welfare: max $\sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

Sectoral Output: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q_{j,r,t} = C_{j,r,t} + I_{j,r,t} + \mathcal{P}[X_t] \cdot E_{j,r,t}$

Energy Extraction: $X_{t+1} = \sum_j \sum_r E_{j,r,s} + X_t$

Capital Accum.: $K_{j,r,t+1} = \psi_{j,r} \cdot \sum_{j'} I_{j',r,t} + (1 - \delta) K_{j,r,t}$

Carbon Cycle: $G_{\rho,t+1} = \mathcal{H}_\rho[\sum_j \sum_r E_{j,r,t}, G_{\rho,t}]$

Regional Climate: $M_{\mu,r,t} = \mathcal{M}_{\mu,r}[G_{1,t}, G_{2,t}, \ldots]$

Regional Impacts: $Z_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M_{2,r,t}, \ldots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

A Canonical Intertemporal IAM

1. Economy

Welfare: $\max \sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

Sectoral Output: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q_{j,r,t} = C_{j,r,t} + I_{j,r,t} + \mathcal{T}[X_t] \cdot E_{j,r,t}$

Energy Extraction: $X_{t+1} = \sum_j \sum_r E_{j,r,s} + X_t$

Capital Accum.: $K_{j,r,t+1} = \psi_{j,r} \cdot \sum_{j'} I_{j',r,t} + (1 - \delta) K_{j,r,t}$

Carbon Cycle: $G_{\rho,t+1} = \mathcal{H}_\rho[\sum_j \sum_r E_{j,r,t}, G_{\rho,t}]$

Regional Climate: $M_{\mu,r,t} = \mathcal{M}_{\mu,r}[G_{1,t}, G_{2,t}, \ldots]$

Regional Impacts: $Z_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M_{2,r,t}, \ldots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

A Canonical Intertemporal IAM

Welfare: $\max \sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

Sectoral Output: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q_{j,r,t} = C_{j,r,t} + I_{j,r,t} + \mathcal{T}[X_t] \cdot E_{j,r,t}$

Energy Extraction: $X_{t+1} = \sum_j \sum_r E_{j,r,s} + X_t$

Capital Accum.: $K_{j,r,t+1} = \psi_{j,r} \cdot \sum_{j'} I_{j',r,t} + (1 - \delta) K_{j,r,t}$

Carbon Cycle: $G_{\rho,t+1} = \mathcal{H}_\rho[\sum_j \sum_r E_{j,r,t}, G_{\rho,t}]$

Regional Climate: $M_{\mu,r,t} = \mathcal{M}_{\mu,r}[G_{1,t}, G_{2,t}, \ldots]$

2. Climate

Regional Impacts: $Z_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M_{2,r,t}, \ldots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

A Canonical Intertemporal IAM

Welfare: $\max \sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

Sectoral Output: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q_{j,r,t} = C_{j,r,t} + I_{j,r,t} + \mathcal{T}\!\!\mathcal{T}[X_t] \cdot E_{j,r,t}$

Energy Extraction: $X_{t+1} = \sum_j \sum_r E_{j,r,s} + X_t$

Capital Accum.: $K_{j,r,t+1} = \psi_{j,r} \cdot \sum_{j'} I_{j',r,t} + (1 - \delta)\, K_{j,r,t}$

Carbon Cycle: $G_{\rho,t+1} = \mathcal{H}_\rho[\sum_j \sum_r E_{j,r,t}, G_{\rho,t}]$

Regional Climate: $M_{\mu,r,t} = \mathcal{M}_{\mu,r}[G_{1,t}, G_{2,t}, \ldots]$

Regional Impacts: $Z_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M_{2,r,t}, \ldots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

3. Impacts

A Canonical Intertemporal IAM

Welfare: max $\sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

Sectoral Output: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q_{j,r,t} = C_{j,r,t} + I_{j,r,t} + \mathcal{T\!\!T}[X_t] \cdot E_{j,r,t}$

Energy Extraction: $X_{t+1} = \sum_j \sum_r E_{j,r,s} + X_t$

Capital Accum.: $K_{j,r,t+1} = \psi_{j,r} \cdot \sum_{j'} I_{j',r,t} + (1 - \delta) K_{j,r,t}$

Carbon Cycle: $G_{\rho,t+1} = \mathcal{H}_\rho[\sum_j \sum_r E_{j,r,t}, G_{\rho,t}]$

Regional Climate: $M_{\mu,r,t} = \mathcal{M}_{\mu,r}[G_{1,t}, G_{2,t}, \ldots]$

Regional Impacts: $Z_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M_{2,r,t}, \ldots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

Maximand: Global Intertemporal Welfare Over a Policy Horizon

Welfare: $\max \sum_r \sum_{t=\{0,\dots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \dots]$

Sectoral Output: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q_{j,r,t} = C_{j,r,t} + I_{j,r,t} + \Pi[X_t] \cdot \dots_{,t}$

Energy Extr... $X_{t+1} = \sum_j \sum \dots E_{j,r,s} + X_t$

Capital Acc... $K_{j,\dots} = \dots_{j,r} \cdot \sum \dots$

Carbon Cycle: $G \dots$

Regional Climate: $M_{\mu,r,t} \dots M_{\mu,\dots}$

Regional Impacts: $Z_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M_{2,r,t}, \dots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \dots]$

Regional welfare weights

Discount factor

Regional instantaneous utility denominated over consumption of *j* individual commodities in *r* regions

Production is Where We Model Climate Damages Exerting Their Effects

Welfare: $\max \sum_r \sum_{t=\{0,\dots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \dots]$

Sectoral Output: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q_{j,r,t} = C_{j,r,t} + I_{j,r} \dots + \Pi[X_t] \cdot E_{j,r,t}$

Energ… n: $X_{t+1} = \dots \sum_r E_{j,r,s} + \dots$

Capit… $K_{j,r,t} \dots \psi_{j,r} \cdot \sum \dots (1-\delta) K \dots$

Carbon Cyc… $\mathcal{H}_\rho[\dots$

Regional Cl… $\mathcal{M}_{\mu,r} \dots$

Regional In… $\dots_{j,r}[\dots$

Regional D… $\dots [Z_{1,j,r,t}, Z_{2,j,r,t}, \dots]$

Region-by-sector instantaneous economic output

Productivity shock associated with contemporaneous region- and sector-specific climate damage. This is <u>the</u> key unknown.

Region-by-sector production function denominated over inputs of capital and carbon-energy

Disposition of Product Determines the Capacity Constraint of the Economy

Welfare: $\ldots_{,\ldots,T\}}\ \phi_{r,t} \cdot \beta^{t} \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

S…put: $Q_{j,r,t}$ … $A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q_{j,r,t} = C_{j,r,t} + I_{j,r,t} + \Pi[X_t] \cdot E_{j,r,t}$

Energy Extract… X … $\Sigma_r E_{j,r,s} + X_t$

Capital Accum.. $K_{j,r,t+1} = \psi_{j,r} \cdot \sum_{j'} I$ … $(1 -$

Carbon Cycle: $G_{\rho,t+1}$ …

Regional Climate: $M_{\mu,r,t}$ … …]

Regional Impacts: $Z_{i,j,r,t}$ … $_{,t}, \ldots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

Output of each sector

Consumption

Investment

Global carbon-energy supply curve, i.e., average/marginal cost of energy as function of global energy use

Region-by-sector carbon-energy use

Cumulative Carbon-Energy Extraction Drives Increase in Global Marginal Cost

Welfare: $\sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

Sectoral ... $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q_{j,r,t} = C_{j,r,t} + I_{j,r,t} + \Pi[X_t] \cdot E_{j,r,t}$

Energy Extraction: $X_{t+1} = \sum_j \sum_r E_{j,r,t} + X_t$

Capital Accum.: $K_{j,r,t+1} = \ldots_{j,r} \cdot \sum_{j'} I_{j',\ldots} + (1-\delta) K_{j,r,t}$

Carbon Cycle: $\ldots_\rho[\sum_j \ldots$

Regional Climate: $\ldots_{\mu,r}[\ldots$

Regional Impacts: $Z_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M_{2,r,t}, \ldots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

Cumulative extraction of carbon-energy

Current energy use

Past history of extraction

(Endogenous) Accumulation of Capital is the Key Engine of Economic Growth

Welfare: $\max \sum_r \sum_{t=\{0,\dots,T\}} \phi_{r,t}\cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \dots]$

Sectoral …: $Q_{j,r,t} = A_{j,r,t}\cdot \mathcal{F}_{j,r}[K \dots, E \dots]$

Absorpt…: $Q_{j,r,t} = C_{j,r,t} + I_{j,r,t}$ … ${}_{j,r,t}$

Energy Extractio…: $X_{t+1} = \sum_j \sum_r E_{j,r,s} + X_t$

Capital Accum.: $K_{j,r,t+1} = \psi_{j,r}\cdot \sum_{j'} I_{j',r,t} + (1-\delta)\, K_{j,r,t}$

Carbon Cycle: $G_{\rho,t+1} = \mathcal{H}[\sum_j \sum_r E_{j,r,t}, G_{\rho,\dots}]$

Regional Climate: … ${}_{1,t}, G_{2,t}, \dots$

Regional Impacts: … ${}_{r,t}, M_{2,r,t}, \dots$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \dots]$

New region- and sector-specific capital

Depreciation factor

Sectoral investment (sectors enjoy fixed shares of aggregate investment)

Extant region- and sector-specific capital

Carbon Cycle Model ($\mathcal{H}$) Translates GHG Emissions into Reservoir Concentrations

Welfare: $\max \sum_r \sum_{t=\{0,\ldots,T\}}$ … $_{,r,t}, C_{2,r,t}, \ldots]$

S… $Q_{j,r,t} = A_{j,r,t} \cdot$ …]

A… $Q_{j,r,t} = C_{j,r,t} + I_{j}$ … $+ \mathcal{T}[X_t] \cdot E_{j,r,t}$

E…: $X_{t+1} = \sum_j \sum_r E_{j,r,s}$ … X_t

Capital Accum.: $K_{j,r,t+1} = \psi_{j,r} \cdot \sum_{j'}$ … $_{j',r,t} + (1 - \delta)\, K_{j,r,t}$

Carbon Cycle: $G_{\rho,t+1} = \mathcal{H}_\rho[\sum_j \sum_r E_{j,r,t}, G_{\rho,t}]$

Regional Climate: $M_{\mu,r,t} = \mathcal{M}_{\mu,r}[G_{1,t}, G_{2}$ …]

Regional Impacts: $Z_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M$ …

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,}$ …

New GHG concentrations by reservoir ρ (e.g., atmosphere, mixed-layer ocean, deep ocean) at global scale

Global emissions from use of carbon-energy

Extant GHG concentrations by reservoir

Climate Model ($\mathcal{M}$) Translates GHG Concentrations into Meteorology

Welfare: $\max \sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t}\cdot \beta^t\cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

Sectoral Output: $Q_{j,r,t} = A_{j,r,t}\cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

$Q_{j,r,t} = C_{j,r,t} + I_{j,r,t} + \mathcal{T}[X_t]\cdot E_{j,r,t}$

: $X_{t+1} = \sum_j \sum_r E_{j,r,s} + X_t$

$K_{j,r,t+1} = \psi_{j,r}\cdot \sum_{j'} I_{j',r,t}$ … $_t$

Carbon Cycle: $G_{\rho,t+1} = \mathcal{H}_\rho[\sum_j \sum_r E_{j,r,t}$ … $_{\rho,t}]$

Regional Climate: $M_{\mu,r,t} = \mathcal{M}_{\mu,r}[G_{1,t}, G_{2,t}, \ldots]$

Regional Impacts: $Z_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M_{2,r,t}, \ldots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

Meteorological variables (e.g., temperature, precipitation, sea levels) at regional scales

Extant GHG concentrations by reservoir

Impacts Model (Ω) Translates Regional Meteorology into Physical Endpoints

Welfare: $\max \sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

Sectoral Output: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q \ldots = C_{j,r,t} + I_{j,r,t} + \Pi[X_t] \cdot E_{j,r,t}$

Energy … $\sum_j \sum_r E_{j,r,\ldots}$

Capital … $= \psi_{j,r} \cdot \sum \ldots K_{j,r,t}$

Carbon … $_{t+1} = \mathcal{H}_\rho[\sum_j \sum_r \ldots, G_{\rho,t}]$

Regional Climate: $T_{\mu,r,t} = \mathcal{M}_{\mu,r}[G_{1,t}, \ldots_{2,t}, \ldots]$

Regional Impacts: $Z_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M_{2,r,t}, \ldots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

Contemporaneous values of *i* physical impact endpoints by sector, region and time period

Regional values of meteorological variables

Damage Model (Δ) Translates Physical Impact Endpoints into Productivity Shocks

Welfare: $\max \sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \cdot \beta^t \cdot \mathcal{U}_r[C_{1,r,t}, C_{2,r,t}, \ldots]$

Sectoral Output: $Q_{j,r,t} = A_{j,r,t} \cdot \mathcal{F}_{j,r}[K_{j,r,t}, E_{j,r,t}]$

Absorption: $Q_{j,r,t} = C_{j,r,t} + I_{j,r,t} + \Pi[X_t] \cdot E_{j,r,t}$

Energy E… $= \sum_j \sum_r E_{j,r,s} + X_t$

Capital … $= \psi_{j,r}$ … $) K_{j,r,t}$

Carbon … $= \mathcal{H}_{\rho}$ …

Regional … $_{,r,t} = \mathcal{M}_{\mu,r}[$ … $G_{2,t}, \ldots]$

Regional Impacts: … $_{i,j,r,t} = \Omega_{i,j,r}[M_{1,r,t}, M_{2,r,t}, \ldots]$

Regional Damage: $A_{j,r,t} = \Delta_{j,r}[Z_{1,j,r,t}, Z_{2,j,r,t}, \ldots]$

Contemporaneous effect of climate damages on the productivity of individual sectors in each region

Distinct physical effects of climate change on a given sector

Key Points

- IAMs would be constructed so as to have sectoral as well as regional detail in production, consumption and climate damages
- Based on simulated climatic changes at the regional scale, we would first want to elaborate impacts by category of physical endpoint, sector, region and future time period
- Only then would we aggregate across endpoints to generate sector-by-region trajectories of shocks
- No aggregate damage function per se, so transparent causal chain from both ex ante shocks (A) and ex-post adjustments in regional/sectoral output and consumption (i.e., reactive adaptation) to ultimate welfare effects

Implications:
The Marginal External Cost of Carbon

- Climate impacts of an additional unit of carbon energy use at $t = 0$, cumulated over future periods:

Marginal utility of consumption of output of affected sector

potential output by region/sector

Marginal effects of impact endpoints on productivity of sectors in each region

$$\sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \beta^t \sum_j \langle \partial \mathcal{U}_r / \partial C_{j,r,t} \times \mathcal{F}_{j,r,t} \times \sum_i \{ \partial \Delta_{j,r} / \partial Z_{i,j,r,t} \times \sum_\mu [\partial \Omega_{i,j,r} / \partial M_{\mu,r,t} \times \sum_\rho (\partial \mathcal{M}_{\mu,t} / \partial G_{\rho,t} \times \partial \mathcal{H}_\rho / \partial E_0)] \} \rangle$$

Marginal effects of meteorological variables on physical impact endpoints, disaggregated by region/sector

Marginal effects of reservoir GHG concentrations on meteorology at regional scales

Marginal effect of emissions on the global carbon cycle

A Critical Review of the State of Current Practice

The Damage Function Approach (Nordhaus)

- Based on exogenous global-scale climate change projections, elaborate impacts (some denominated by category of physical endpoint, some by sector) by region for a benchmark global mean temperature change (2.5°C)
- Monetize, aggregate and express the resulting estimates as a proportion of future potential GDP
- Use assumptions about how proportion will scale with (a) income and (b) a simplified index of the magnitude of climate change (global mean temperature change, $\mathcal{T}$) to specify aggregate damage function ($\mathcal{D}$)
- Some baby steps toward the sector/impact category disaggregation of the canonical model: sea-level rise in RICE-2010

The Marginal External Cost of Carbon as Calculated in RICE

Marginal utility of aggregate regional consumption

Potential regional GDP

Marginal effect of temperature on aggregate output in each region

$$\sum_r \sum_{t=\{0,\ldots,T\}} \phi_{r,t} \beta^t \partial \mathcal{U}_r / \partial C_{r,t} \times \mathcal{F}_{r,t} \times \partial \mathcal{D}_r / \partial \mathcal{T}_t$$

$$\times \sum_\rho \left(\partial \mathcal{T}_t / \partial G_{\rho,t} \times \partial \mathcal{H}_\rho / \partial E_0 \right)$$

Marginal effects of reservoir GHG concentrations on global mean temperature change

Marginal effect of emissions on the global carbon cycle

Difficult Problems, with Elusive Remedies

- Aggregation is inevitable, but on the modeling side, the key research need is to explicitly incorporate sectoral detail (*j*), impact categories (*i*) in IAMs
- Major obstacle: lack of empirical or detailed modeling studies; most of existing ones don't go past 2050 (cf. World Bank, 2010; Eboli et al., 2009)
- Targeting later decades for quasi-empirical assessment is critical, as 2050 likely to underestimate the onset of warming and climate damages late in the century
- But the further one goes out in time the less confidence one has in detailed estimates, leading to tradeoff between overall response magnitude and sectoral/regional specificity
- No easy way to cut this Gordian knot

CGE Models for Climate Impact Analysis

- Promising new direction, particularly given increasing climate model skill at regional scales
- An explicitly multi-regional/multi-sectoral approach: compute shocks based on exogenous information on physical endpoints by sector, impose consequent shocks on affected sectors within the various regions
- Key problems are CGE models' recursive-dynamic character (which precludes anticipation of impacts), limited time horizon (2050 in ICES)