Climate change, economic growth and sustainability: issues, Australian dynamic integrated general equilibrium model and policy options

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Abstract: The present study is an example of the potential for developing a climate change and economic growth model and policy analysis for a particular country. It develops a dynamic general equilibrium model of climate and the economy for Australia, as a non-cooperative differential game, to address the global warming and growth concerns and issues faced in Australia. It presents the current and future forecasts and implications for climate, economic growth and policy in the Australian economy. The results show that the benefit of emission abatement is higher than its cost. As there is no such long-horizon growth model and forecasts for the Australian economy, the results of the present model are useful in understanding the long-term dynamics of the ecosystem and the economy.

Keywords: climate change; dynamic modelling; Australia.

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1 Introduction

Global warming is caused by higher levels of greenhouse gas (GHG) emissions into the atmosphere, which result in higher GHG concentrations. Recent scientific reports have confirmed that increased GHG concentrations in the atmosphere will substantially increase mean global temperatures [1,2]. Climate change has separate implications for the global economy as well as individual national economies. Modelling global climate change is well developed [1,2], however, modelling country level climate change and economic growth is not well developed.

Climate plays a pivotal role in the Australian economy; Australia's severe climate variability exacerbates the greenhouse effect in Australia. Some of the effects of climate change on the Australian economy are already evident. A large set of controversial issues have emerged in climate-change economics and policy in Australia in recent years, a short list of the points to which these issues relate to is provided below:

- possible evidence of climate change and global warming
- the physical, economic and social impacts of climate change
- the costs and benefits of climate-change abatement and adaptation policies in determining the optimal policy responses
- the urgency for taking immediate climate-change policies in view of the uncertainty in the science of climate change
- combination of different forms (economic, legal and engineering) of optimal policies to be implemented
- international dimensions of Australian climate change including the unequal impacts of climate change among different regions of the world, the need and mechanism for intertemporal cooperation and legal and institutional developments
- intertemporal and intergenerational equity and valuation.

The mathematical modelling of a climate–economic system for the examination of the above issues surrounding global warming and the greenhouse effect has been an important area in contemporary growth and environmental economics. For a survey of the global theoretical models, see [3,4] and for a survey of large-scale integrated numerical models in this area, see [5,6]. Some of these models are developed within the optimal growth-modelling framework: DICE and RICE [7], MERGE [8] and CETA [9]. As these models are global models, they cannot be used separately for modelling climate change and economic growth of a national economy like the Australian economy. *Such modelling of a national economy is important, but not well known.* The objective of this paper is to develop a climate change and economic growth model for an individual country within the framework of optimal growth modelling.

This paper *makes a contribution to the literature* as it develops a dynamic climate change and economic growth model of a national (the Australian) economy in an applied general equilibrium framework and studies the national policy implications of the results of the model. The paper also generates very long-term growth scenarios of the ecosystem and the economy, which do not exist in other Australian studies. The scenarios will have important information inputs to policy making.

2 Climate change: economic modelling and ADICE

A survey of the main greenhouse economic issues and models developed to address these global and Australian issues can be found in [10]. The Dynamic Integrated Model of Climate and the Economy (DICE) [7], which is a general equilibrium climate-change economic growth model, is an important model in global warming literature. DICE has the capability of forecasting economic and environmental variables and parameters for the possible longest term. As global warming involves long-term changes and adjustments in the ecosystem, DICE is an excellent model for studying the interrelated issues of global warming and economic growth. It also provides a useful framework for formulating optimum global warming policies evaluated on the considerations of benefits and costs of such policies. For all these reasons, DICE was adapted in this project – extended and renamed as the Australian DICE (ADICE) model [11].

3 Outline of the ADICE model [12]

ADICE, which is a dynamic applied general economic model, is of the standard Ramsey-type optimal economic growth model incorporating a linkage between climate change and the economy. The model optimises social utility over a given time horizon subject to the usual economic constraints with additional climate change. The social utility is defined as the sum of individual utilities and is dependent on the level of consumption.

There are two sectors in the model: an economic sector and a climate sector. The economic sector produces one good competitively which is perfectly substitutable with other composite goods. This composite good is optimally allocated by the social planner between consumption and investment to maximise intertemporal social welfare. Population growth, improvement in energy efficiency and technological change are assumed exogenous to the model. Economic activities generate GHGs that increase the mean temperature in the economy. Total global GHG emission is separated as Australian (endogenous in ADICE) and emissions from the rest of the world (exogenous in ADICE). The rest of the world GHG emissions projection is obtained from the DICE model. The base case model result of DICE without policy control is split between Australian and the rest of the world emissions. The social planner in the Australian economy withdraws resources from the economic sector and allocates them to the climate sector in order to reduce GHG emissions and to lower the detrimental effects of climatic changes to the economy, given the rest of the world emissions. Therefore, ADICE is a non-cooperative game where Australia is undertaking climate-change abatement policies independently of the rest of the world.

The ADICE model is specified by embedding the elements of an optimal growth programme of the following form [13–17] as a framework for rational social choice [18]:

1. an optimality criterion or a social welfare function contained in an objective function, consists of the discounted sum of the utilities provided by consumption at every period
2. the finite planning horizon
3. intertemporal social choice framework by social time preference in the form of a positive or zero discount rate
4. the boundary conditions given by the initial values of the variables and parameters and by the terminal conditions
5. a growth model of the Australian economy

6 an optimal control theory structure with the following property:
   a a feedback/adaptive rule
   b policy variables classified as the state variables and the control variables, as is developed in the theory of economic policy [15].

An abstract representation of ADICE [7,11] model is given below and the full model presented in Appendix A. The present version of the ADICE model is based on [7], while a recent version of the model may be seen in [19].

Maximise: $\sum t\rho^{-t} u[c(t), \rho(t)]L(t)$ (1)

Subject to:

$$Y(t) = f[K(t), L(t), E(t), t] \quad (2)$$

$$c(t) = C(t)/L(t) \quad (3a)$$

$$Y(t) = C(t) + I(t) \quad (3b)$$

$$E_{\mathrm{AUSt}}(t) = E(\mu(t), Q(t)) \quad (3c)$$

$$D(t) = g[T(t), Y(t)] \quad (3d)$$

$$TC(t) = n[T(t), Y(t)] \quad (3e)$$

$$C_{tax}(t) = X(ee(t), kk(t)) \quad (3f)$$

$$K(t+1) = (1 - \delta_K)K(t) + I(t) \quad (3g)$$

$$M(t+1) = (1 - \delta_M)M(t) + \beta[E_W(t) + E_{\mathrm{AUSt}}(t)] \quad (4)$$

$$T(t+1) = s[T(t), M(t), O(t)] \quad (4a)$$

$$O(t+1) = r[T(t), O(t)] \quad (4b)$$

$$I(t), E(t) \geq 0 \quad (5)$$

where:
I = investment (control variable)
E_W = emissions of GHGs (world) (exogenous)
E_{AUS} = Australian GHGs
K = capital stock
M = atmospheric carbon concentration
T = mean atmospheric temperature
O = mean deep ocean temperature
c = per-capita consumption
D = climate damage
Y = GDP
C_{tax} = carbon tax
$ee(t)$ = shadow price of emissions
$kk(t)$ = shadow price of capital
ρ = discount factor
δ_K = capital depreciation rate
δ_M = GHG decay rate
L = Population/labour supply
t = time/technology

β = GHG emission factor
$\mu(t)$ = emission control rate (control variable)
TC = total cost of abatement

Equations (1–3) constitute the basic economic model and other equations describe the links between the economy and climate change.

4 Methodology and mathematical properties of ADICE

ADICE is specified within the structure of optimum control theory and is numerically implemented as a differential non-cooperative game problem based on a nested two-level algorithm. An inner simplex method and non-linear-programming algorithms combining a reduced gradient and quasi-Newton method with a projected Lagrangian algorithm is as coded in GAMS [20]. The methodology of dynamic optimisation covers the theory of, and algorithm for, optimal control with a list of possible computer programs to solve optimum control problems as discussed in [21]. ADICE was solved using a modified Australian version of the GAMS [22] program developed in [7]. A report on experiments of solving the ADICE model by other computer programs is also in [21].

Data for the model which are broadly economic and climate related were obtained from published sources, Australian and international, or calibrated from similar studies. The Australian economic data on GDP, population, technological progress, capital and GHG emissions were adopted from [23,24]. Data on the global warming variables and parameters were adopted from DICE compiled by Nordhaus [25], which was considered to be appropriate for ADICE [26].

Mathematical properties of the model and its results including existence, uniqueness and global optimality need to be investigated. The Weierstrass Theorem can be applied to determine the properties of the ADICE solutions. First, as the opportunity set of the constraints of the ADICE model is non-empty and compact (closed and bounded) it was expected that there would exist a solution to the model. The remaining criterion of consistency of the constraints is required to be satisfied, and the ADICE results show that the constraints were consistent as the ADICE model solution provided a set of feasible optimal results. The objective function and the constraints of ADICE are not convex, and therefore, we cannot determine whether the ADICE solution is a global optimum or not. The issue of global optimality in applied policy modelling work like the present study is generally resolved by arguing that the results may characterise an improved policy outcome.

5 ADICE results

ADICE determines the global warming and other economic effects of Australian GHG emissions and optimum global warming for Australia, given the global emissions and global optimum policy.

ADICE was solved for five sets of parameters (Table 1), which are reported in the following sections. ADICE spans 40 periods, one period being equivalent to 10-year duration.

Table 1 Details of model runs

Model runs	*Emission control rate*	*Discount rate (%)*	*Growth rate of ratio of uncontrolled emissions*
Run 1	No GHG emissions in the model (economic model)		
Run 2	No control	3.0	–0.1168
Run 3	Control	3.0	–0.1168
Run 4	Control	3.0	–0.2168
Run 5	Control	0.0	–0.1168

Source: Islam [11].

The numerical results are reported in Table 2 (climate and environmental variables), Table 3 (economic variables), Table 4 (policy variables) and Table 5 (cost–benefit analysis).

5.1 Climate and environmental variables and parameters

The path of Australian GHG emissions for model runs varies substantially. In Model run 1, there is no greenhouse effect (the climate and environmental variables are not included in the ADICE model). Model runs 2, 3 and 5 all show increases in GHG emissions, while model run 4 shows a declining level of GHG emission.

The emissions for model runs 2 and 3 are very similar and increasing. Model run 2 has no emission control abatement policy variable, suggesting that GHG emission policy formation is non-existent. The effect of the emission control strategy shows in the results of model 3 as a decrease in emissions, compared to model run 2 emissions, of the order of 1% per annum.

The highest level and increase in GHG emissions are in model run 5. This model adopts a 0% social discount rate (SDR) and shifts present consumption into the future in the model. Model run 5 indicates that higher levels of emissions will be produced due to higher level of investment at the present and as consumption increases. The initial optimal emission control rate is 3.2%, while for the other model runs (3 and 4) it is only 1.0%, necessitating a policy choice of greater abatement and higher carbon tax.

Model run 4 shows a steady decline in the Australian GHG emissions (0.587 B/t in period 1 to 0.108 B/t in period 40), which is due to the decreasing rate of the ratio of uncontrolled GHG emissions to GDP ($\sigma(t)$). The model run suggests that a decrease in the value of $\sigma(t)$ in the range of –0.1168 to –0.2168 (the rate of decarbonisation) will produce a sustainable growth path.

The CO_2 concentration, radiative forcing, atmospheric temperature and lower-ocean temperature values shown in Table 2 are world values. They are only slightly affected by the Australian GHG emissions. All the model runs predict very similar results: an atmospheric temperature rise of about 2.5°C, a 0.298°C rise in lower-ocean temperature, an increase in radiative forcing of about 4.0 W/m^2 and an increase of the world CO_2 concentration by 500 B/t over the next century. The effect of an Australian policy of no abatement is evident from the CO_2 concentrations of GHG abatement policy and no abatement policy cases making a difference of 0.005%.

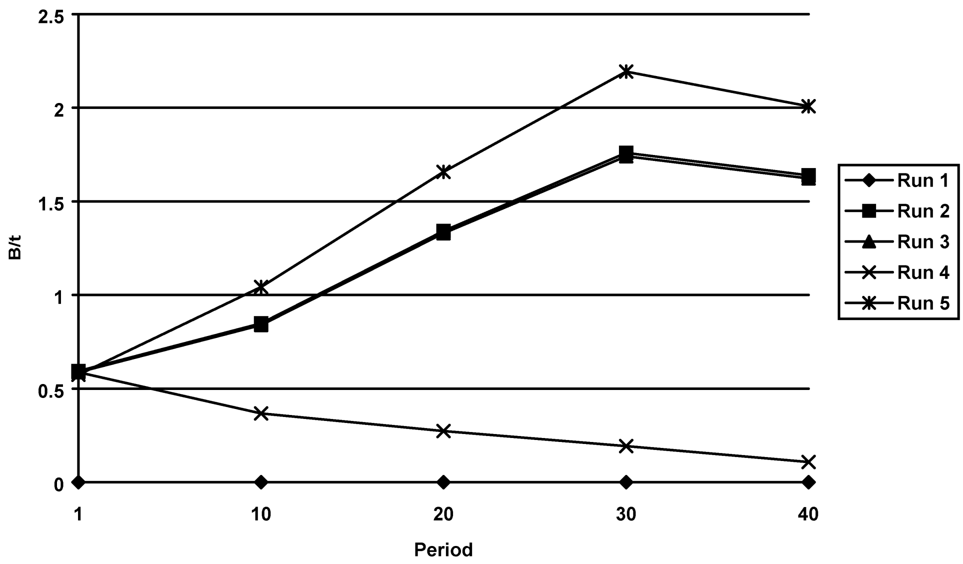
Table 2 Results for Australian climate-emissions under different runs

	Run	Period 1	10	20	30	40
CO_2 emissions (B/t)	1	–	–	–	–	–
	2	0.593	0.848	1.342	1.759	1.639
	3	0.587	0.839	1.329	1.741	1.622
	4	0.587	0.368	0.273	0.193	0.108
	5	0.574	1.043	1.658	2.194	2.008
CO_2 concentrations (B/t)	1	–	–	–	–	–
	2	727.1000	1240.688	1870.777	2276.013	2611.204
	3	727.000	1240.660	1870.716	2275.918	2611.055
	4	727.000	1239.703	1866.841	2268.378	2600.205
	5	727.000	1241.217	1872.151	2278.275	2614.221
Emission control rate of GHG	1	0.010	0.010	0.010	0.010	0.010
	2	0.000	0.000	0.000	0.000	0.000
	3	0.010	0.010	0.010	0.010	0.010
	4	0.010	0.010	0.010	0.010	0.010
	5	0.032	0.033	0.032	0.024	0.010
Radiative forcing (W/m^2)	1	–	–	–	–	–
	2	1.617	5.567	8.246	9.406	10.218
	3	1.617	5.567	8.246	9.405	10.218
	4	1.617	5.562	8.233	9.386	10.193
	5	1.617	5.570	8.250	9.412	10.225
Change in the atmospheric temperature (°C)	1	–	–	–	–	–
	2	0.200	2.517	4.375	5.307	5.921
	3	0.200	2.517	4.375	5.307	5.921
	4	0.200	2.515	4.369	5.297	5.907
	5	0.200	2.518	4.377	5.310	5.925
Change in the lower-ocean temperature (°C)	1	–	–	–	–	–
	2	0.100	0.298	0.881	1.608	2.337
	3	0.100	0.298	0.881	1.608	2.337
	4	0.100	0.298	0.880	1.606	2.334
	5	0.100	0.298	0.881	1.609	2.339

Source: Islam [11].

Sustainability: According to some scientists [27], a sustainable rule in the global warming area, similar to the rules 'safe minimum standard' or 'constant national capital', is a temperature increase of 0.1°C per decade. Therefore, model run 4 generates a relatively more sustainable growth path. The model solution with the constraint that the temperature increase per decade would be less than or equal to 0.1°C was infeasible or unsustainable.

Figure 1 Dynamic paths for CO_2 emissions



5.2 Economic variables and parameters

The output, consumption, per capita consumption and per capita output are higher under model run 1 (no greenhouse effect) than under model runs 2, 3 and 4. This suggests that the differences between model run 1 and the other model runs may be interpreted as the costs (about 1–2%) of the greenhouse effect on the Australian economy.

The greatest increase in per capita income and per capita consumption, over all simulation periods, is in model run 5 and the second highest increase is in model run 1. The initial level of savings and investment increases in model run 5, as the zero discount rate causes per capita consumption to be smaller over the initial periods. The level of saving increases to 39% and remains higher than the other model runs (20% for other models) over the modelling period. The effect of this model run is to increase the available present capital for future production resulting in lower rates of interest. Model 5's interest rate is lower over the entire time period compared to other model runs with positive discount rates. These results are in no way conclusive whether Australia should choose a zero discount rate or not.

Table 3 Results for Australian economic variables

		Period				
	Run	*1*	*10*	*20*	*30*	*40*
Output (A$ trillion)	1	0.114	0.429	1.660	4.521	7.660
	2	0.114	0.423	1.593	4.252	7.095
	3	0.114	0.423	1.593	4.252	7.095
	4	0.114	0.423	1.593	4.253	7.094
	5	0.114	0.539	2.033	5.436	8.783

Table 3 Results for Australian economic variables (continued)

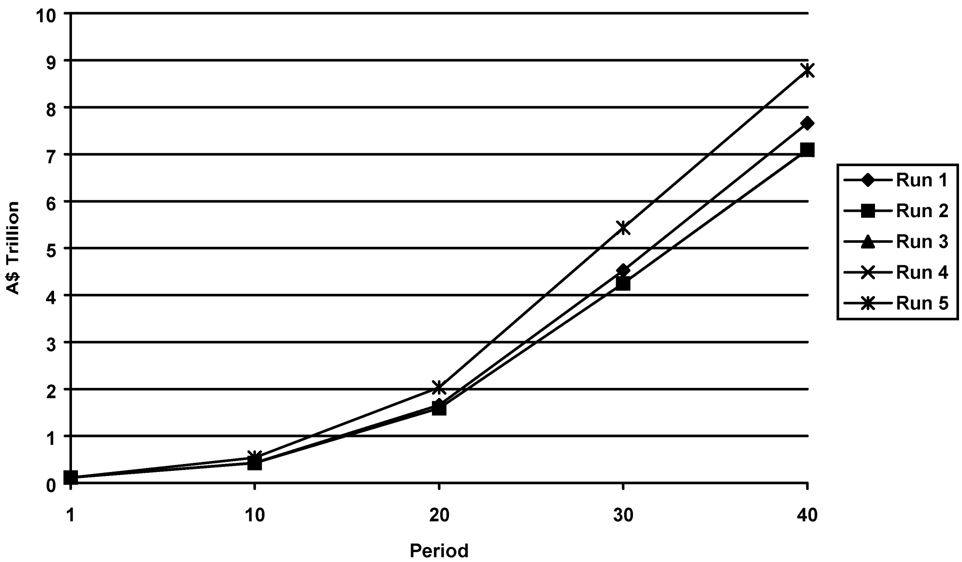
	Run	*Period* 1	10	20	30	40
Consumption (A$ trillion)	1	0.091	0.323	1.267	3.481	7.125
	2	0.091	0.319	1.217	3.274	6.598
	3	0.091	0.319	1.217	3.274	6.598
	4	0.091	0.319	1.217	3.275	6.598
	5	0.069	0.331	1.277	3.463	8.783
Capital stock (A$ trillion)	1	0.687	1.436	5.697	15.843	17.859
	2	0.687	1.423	5.489	14.934	15.575
	3	0.687	1.423	5.489	14.934	16.576
	4	0.687	1.423	5.489	14.938	16.558
	5	0.687	2.830	11.014	30.134	30.501
Saving rate (*% of GDP*)	1	0.201	0.246	0.236	0.230	0.070
	2	0.201	0.246	0.236	0.230	0.070
	3	0.201	0.264	0.236	0.230	0.070
	4	0.201	0.246	0.236	0.230	0.070
	5	0.391	0.385	0.372	0.363	0.112**
Investment (A$ trillion)	1	0.023	0.106	0.392	1.040	0.536
	2	0.023	0.104	0.377	0.978	0.497
	3	0.023	0.104	0.376	0.978	0.497
	4	0.023	0.104	0.377	0.978	0.497
	5	0.045	0.208	0.756	1.973	1.084
Per capita income (A$ 000)	1	6.689	12.156	28.494	57.249	80.649
	2	6.689	12.005	27.351	53.837	74.700
	3	6.689	12.005	27.351	53.838	74.702
	4	6.689	12.006	27.354	53.851	74.690
	5	6.689	15.272	34.901	68.829	92.469
Per capita consumption (A$ 000)	1	5.334	9.160	21.757	44.077	75.009
	2	5.334	9.047	20.889	44.083	69.465
	3	5.334	9.047	20.889	41.456	69.466
	4	5.334	9.047	20.891	41.465	69.461
	5	4.051	9.376	21.918	43.850	92.469
Interest rate per annum	1	0.002	0.048	0.045	0.043	0.094
	2	0.002	0.048	0.045	0.043	0.093
	3	0.002	0.048	0.045	0.043	0.093
	4	0.002	0.048	0.045	0.043	0.093
	5	0.002	0.010	0.008	0.007	0.044

Note: Table 3 gives a view of the eight economic variables over 4/5 periods for the three policy options.

**Refers to period 39 result.

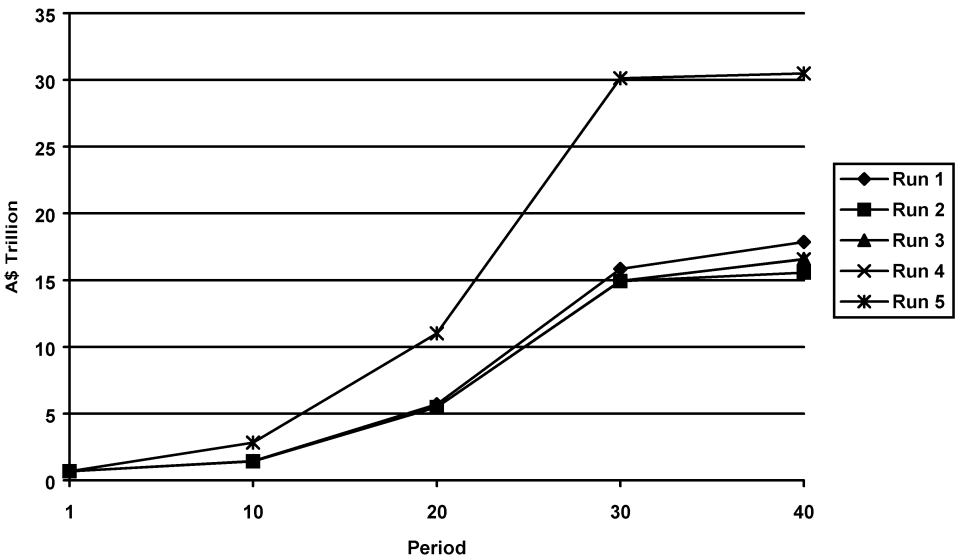
Source: Islam [11].

Figure 2 Dynamic paths for output



Note: Model runs 2, 3 and 4 are almost identical.

Figure 3 Dynamic paths for capital stock



A strong view in this area is that from society's point of view a zero discount rate is justified as it ensures intergenerational equity and impartiality and is consistent with social contracts. However, in ADICE, the path of savings and consumption simulated by model run 5 (39%) may appear to be unrealistic and unacceptable. But these results may not be unacceptable to those (for example [28]) who view that the society as a whole should have a higher savings rate than individuals because of the external benefits of public savings.

5.3 Analysis of results of different model runs: sustainability implications

In model run 1, the greenhouse effect is not included. Model run 1 shows greater per capita income and no effects on the environmental and climate conditions of the planet. Model run 2 simulates no emission control and the Australian environment is left to the market to determine the level of emissions. The level of GHG emissions produces relatively higher polluted trajectories.

Model run 4 simulates a decrease in the ratio of uncontrolled GHG emissions growth rate to GDP. Consumption is increasing in a sustainable way while the level of GHG emissions is positive, but the rate of change is decreasing, diminishing the GHG emissions (sustainable economic growth path). According to some scientists, a sustainable rule in the global warming area, similar to the rules 'safe minimum standard' or 'constant national capital', is a temperature increase of 0.1°C per decade. Therefore, model run 4 generates a relatively more sustainable growth path.

Model run 5 generates greater per capita income and output and generates greater levels of GHG emissions and a higher savings rate.

Of all the five model runs, the most realistic and realisable model run is model run 3, while the model run that shows the most promise in abating the GHG effect is model run 4; increasing the ability of the new technologies that will diminish GHG emissions resulting in sustainable economic growth.

6 Global warming policies for Australia

The specification of policy formulation in this study is based on a non-cooperative global warming international policy regime: the policy results show the optimum Australian abatement policies, given that the rest of the world is not undertaking any policy. However, problems related to the formulation of international policy for global warming such as free riding and carbon leakage are not resolved in this package of Australian policies. Moreover, the results do not address issues like uncertainty, irreversibility, possibility of catastrophic impact and international equity.

6.1 Policy results

ADICE determines an optimum precautionary policy package for global warming in Australia. Policy options for the Australian economy for limiting GHG emissions and the impacts of climate change include the efficient management of the production and consumption of energy, reduction in deforestation, technical progress for substitution of the use of energy by other inputs, especially by knowledge, reforestation, etc. The instruments which are available include the following: carbon taxation, subsidies on carbon reduction and energy efficiency improvements, equity-based trading permit, environmental laws, public awareness and institution building. In ADICE, two policy controls are explicitly specified: carbon tax and investment. It is assumed that emissions are controlled by technological, organisational and economic measures, and ADICE determines the optimum emission rate. The optimum values of the policy variables under the five different model runs are reported in Table 4.

Table 4 Optimum values of policy variables

		Period				
	Run	*1*	*10*	*20*	*30*	*40*
Emission control rate of GHG	1	–	–	–	–	–
	2	0.000	0.000	0.000	0.000	0.000
	3	0.010	0.010	0.010	0.010	0.010
	4	0.010	0.010	0.010	0.010	0.010
	5	0.032	0.033	0.032	0.024	0.010
Carbon tax (A$/t)	1	–	–	–	–	–
	2	0.000	0.100	0.000	0.000	0.000
	3	0.026	0.104	0.000	0.000	0.000
	4	0.026	0.104	0.000	0.000	0.000
	5	0.568	1.565	3.537	4.329	0.000
Investment (A$ trillion)	1	0.023	0.106	0.392	1.040	0.536
	2	0.023	0.104	0.377	0.978	0.497
	3	0.023	0.104	0.376	0.978	0.497
	4	0.023	0.104	0.377	0.978	0.497
	5	0.045	0.208	0.756	1.973	1.084

Source: Islam [11].

All the optimal emission control rates are within reasonable bounds. The only two policies (use) that offer reductions in GHG emissions are model runs 4 and 1. Model run 4 shows a reduction of 45.3% (0.587–0.321/0.587) in GHG emissions from 1990 levels by the year 2005. The level of investment required achieving this level of reduction increases over time. The carbon tax level (which can be considered as an environmental risk premium in the Australian economy), under model run 4 is A$0.026 per ton of carbon, while model run 5 shows a higher level of emission reduction and a higher level of carbon tax.

ADICE results imply that the Australian Government's planning target of achieving 20% reduction of 1988 CO_2 emissions by the year 2005 is feasible.

6.2 *Cost–benefit analysis: the choice of optimal abatement policies*

Table 5 shows the cost and benefits of abatement policies in the various model runs.

It is evident that in the Australian case the benefit of the abatement cost is substantially higher than its cost. This result is different from most other previous studies of the costs and benefits of GHG abatement policy where the benefits are not as obvious (see [29,30]). The benefits may even be higher if secondary benefits and double dividend of abatement are included in the abatement benefits. These results also confirm the Rio strategies of global warming, where undertaking abatement policies by individual countries for the interests of the individual countries was stressed. In spite of the limitations of cost–benefit analysis often raised by economists [31], it may be argued that the cost–benefit estimates of global warming reality in Australia favour the control of GHGs. It appears, therefore, that some reduction of emissions on a unilateral basis may not be harmful to Australia. However, an analysis of the implications of Australia following the provisions of the Kyoto protocol type multilateral agreements [32] has not been undertaken here.

Table 5 Cost–benefit analysis of the five model runs

	Run	*Period* 1	10	20	30	40
Benefit of abatement/ Damage avoided ($)	1	0.0	0.0	0.0	0.0	0.0
	2	0.0	4000000000	45000000000	176900000000	367700000000
	3	0.0	4000000000	45000000000	177000000000	368000000000
	4	0.0	4000000000	45000000000	176000000000	366000000000
	5	0.0	4000000000	58000000000	226000000000	456000000000
Cost of abatement ($)	1	0.0	0.0	0.0	0.0	0.0
	2	0.0	0.0	0.0	0.0	0.0
	3	13192	48875	183991	490778	819041
	4	13192	48876	183932	490906	818919
	5	370739	1915918	6698298	8219407	1013847

Source: Islam [11].

7 Conclusions

The present study shows that useful national climate-change modelling is possible. Although climate–economic change forecasts are uncertain, the present study also shows that reasonably good predictions can be generated from suitably specified climate–economic models and can be used for policy formulation. For ensuring an optimistic future of Australia, ADICE suggests that intelligently formulated policies are necessary to achieve the optimistic prospects. The temperature change forecasts of ADICE are in line with other studies, Australian and international. The main ingenuity of ADICE is in the long-term projections of the Australian macroeconomic and climate variables, and more importantly, in prescribing the optimum emission control and investment policies, which have been suggested by no other previous studies.

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Appendix A: The full ADICE model

Equations of the model

Maximise:

Objective function: $\sum_{t=1}^{t_T} U[c(t), L(t)]\,(1+\rho)^{-t}$ (1)

Definition of utility: $U[c(t), L(t)] = L(t)\text{Log}\, c(t)$ (2)

Subject to:

Production function: $Q(t) = \Omega(t)\, A(t)\, K(t)^{\gamma} L(t)^{1-\gamma}$ (3)

Growth rate of technology: $g_A(t) = g_A(t-1)(1-\delta_A)$ (4)

Growth rate of population: $g_{\text{pop}}(t) = g_{\text{pop}}(t-1)(1-\delta_{\text{pop}})$ (5)

Capital balance equation: $K(t) = (1-\delta_K)K(t-1) + I(t-1)$ (6)

Output composition equation: $Q(t) = C(t) + I(t)$ (7)

Emissions equation: $E(t) = [1-\mu(t)]\sigma(t)Q(t)$ (8)

Emissions–output ratio: $\sigma(t) = (1+g_\sigma)\sigma(t-1)$ (9)

Growth of emissions–output ratio: $g_\sigma(t) = g_\sigma(t-1)(1-\delta_A)$ (10)

Emissions accumulation equation:

$$M(t) - 590 = \beta[E(t-1) + E_{row}(t)] + (1 - \delta_M)\,[M(t-1) - 590] \quad (11)$$

Radioactive forcing equation: $F(t) = 4.1\{\log[M(t)/590]/\log(2)\} + O(t)$ (12)

Climate change equation:

$$T(t) = T(t-1) + (1/R_1)\{F(t) - \lambda T(t-1) - (R_2/\tau_{12})\,[T(t-1) - T^*(t-1)]\}$$
$$T^*(t) = T^*(t-1) + (1/R_2)\{(R_2/\tau_{12})[T(t-1) - T^*(t-1)]\} \quad (13)$$

Damage function: $D(t) = Q(t)\theta_1\, T(t)\theta_2$ (14)

Emissions reducing cost function: $\mathrm{TC}(t) = Q(t)b_1\mu(t)b_2$ (15)

Relationship showing the impact of emissions reductions and climate change on output: $\Omega(t) = (1 - b_1\mu(t)b_2)/[1 + \theta_1 T(t)\theta_2]$ (16)

Carbon tax: $C_{tax} = -1000 \times ee \cdot m(t)/kk \cdot m(t)$ (17)

Major variables in the model

Exogenous variables	
$A(t)$	level of technology
$L(t)$	labour inputs
$O(t)$	forcings of exogenous GHG
$E_{row}(t)$	Rest of the world emissions ($E_{world}(t) = E_{row}(t) + E(t)$)
t	time
Parameters	
α	elasticity of marginal utility of consumption
b_1, b_2	parameters of emission reduction costs function
β	marginal atmospheric retention ratio of GHGs (*w*)
γ	elasticity of output with respect to capital
δ_K	rate of depreciation of the capital stock
δ_M	rate of transfer of GHGs from upper to lower reservoir (*w*)
λ	feedback parameter in climate model (*w*)
ρ	pure rate of social time preference
R_1	thermal capacity of the upper ocean layer (*w*)
R_2	thermal capacity of deep oceans (*w*)
$\sigma(t)$	GHG emissions/output ratio
τ_{12}	transfer rate from upper to lower reservoir (*w*)
θ_1, θ_2	parameters of damage function
Endogenous variables	
$C(t)$	total consumption
$c(t)$	per capita consumption
$D(t)$	damage from greenhouse warming
$E(t)$	emissions of GHGs (CO_2 and CFCs only)
$F(t)$	radiative forcing from GHGs (*w*)
$\Omega(t)$	output scaling factor due to emission controls and to damages from climate change

$K(t)$	capital stock
$M(t)$	mass of GHGs in atmosphere (w)
$Q(t)$	gross domestic product
$T(t)$	atmospheric temperature relative to base period (w)
$T^*(t)$	deep-ocean temperature relative to base period (w)
$TC(t)$	total cost of reducing GHG emissions
$u(t) = u[c(t)]$	utility of per capita consumption
Policy variables	
$I(t)$	investment
$\mu(t)$	rate of emission reduction
C_{tax}	carbon tax
Initial values of parameters in the ADICE model	
α	1 [elasticity of marginal utility with respect to consumption]
b_1	0.0686 [fraction of output per unit emission control]
b_2	2.887 [exponent of control cost]
β	0.64 [pure number] (w)
γ	0.35 [elasticity of output with respect to capital]
δ_K	0.08 [per year]
δ_M	0.0833 [per decade]
δ_A	0.02 [per decade]
g_{pop} (1990)	0.050 [per year]
g_σ(1990)	–0.1168 [per decade]
K(1990)	0.687107 [trillion A$, 1989 prices]
λ	1.41 [°C/W-m^2] (w)
M(1990)	727 [billion tons CO_2 equivalent, carbon weight]
I(1990)	17.068 [million persons]
ρ	0.03 [per year]
$1/r_1$	0.226 [°C-m^2/W-decades] (w)
r_2/τ_{12}	0.44 [W/°C-m^2] (w)
Q(1990)	0.266047 [billion A$, current prices]
σ(1990)	0.519 [billion tons CO_2 equivalent per trillion dollars, 1989 prices]
T(1990)	0.2 [°C] (w)
T^*(1990)	0.1 [°C] (w)
θ_1	0.00148 [fraction of output per °C squared]
θ_2	2 [exponent of damage function]
δ_{pop}	0.050 [per decade]
g_A(1990)	0.0206 [per year]

(w) Represents world variable and value. In the absence of this label the assumption is that variables are Australian variables.

Source: [7,17,19,32].