Cost Benefit Ratio Analysis of Stock and Flow Adaptation: an Extension to AD-DICE Model

Adhit Chandy George

June 21, 2024

Abstract

Through extending the AD-DICE model by de Bruin, Dellink and Tol (2009), this term paper tries to find out the economic benefits of adaptation policies and compare the benefits between flow and stock adaptation and the baseline AD-DICE model.

1 Introduction

Climate change and the climate disasters are considered worldwide as one of the most pressing issues of our day. IPCC Report 2023 clearly states that "*The Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 1.1°C above 1850-1900 in 2011-2020. Global greenhouse gas emissions have continued to increase, with unequal historical and ongoing contributions arising from unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production across regions, between and within countries, and among individuals*". The repercussions caused by this human accelerated changes in the atmosphere temperature has already affected several ecosystems and vulnerable bio systems including coral reefs and human settlements closer to sea shores. Around the world, people in their daily lives are experiencing sudden changes in weather patters and extreme weather situations. In this context understanding how to deal with climate change and the imminent and following climate disasters is an extremely important topic for a safe and sustainable life in the future.

The most important method of combating climate change is by reducing the emissions of green house gases including carbon dioxide. While this method is being adopted by the world governments and businesses, the awaiting climate disasters due to the already emitted greenhouse gases are not to be taken lightly. Archer (2016) in his book argues that "*the lifetime of fossil fuel CO2 in the atmosphere is a few centuries, plus 25 percent that lasts essentially forever*". Therefore the measures to deal with the already emitted carbon and the impending climate disasters also become an area of extreme importance in this context.

Adaptation as measure to combat climate change can be seen as a solution for both long and short climate disasters that we will face. Based on the effect of adaptation, we can divided it into two types where the first one which can be called the Flow Adaptation are the type of adaptation actions which can be done in a short period of time and the benefits and costs of these adaptation measures are incurred in the same period as well. The second type of adaptation actions are the ones which have long term benefits which can be incurred over multiple periods of time and are referred to as Stock Adaptations. The cost of climate damage as well as the cost and benefit of adaptation measures can be modeled and calculated using Integrated Assessment Models (IAMs) which has helped us in understanding the interaction between climate, nature and economy. One of the most important of these models is DICE (Dynamic Integrated Climate and the Economy) model which was designed by the Nobel laureate William Nordhaus. Several revisions and different extensions based on this model are available in this research area now.

In this term paper, I am trying to work with an extension of the DICE model by de Bruin, Dellink and Tol (2009) named AD-DICE model where the authors have tried to implement the adaptation measure into the damage component of the original DICE model. The extension that I am implementing will differentiate between the flow and stock adaptation which was not differentiated in the AD-DICE version. The main idea of the extension is from Agrawala et al. (2011), while the mathematical part and implementation of the extension is done in a different way than mentioned in that paper.

2 Overview of AD-DICE model

2.1 Theory

In the DICE model and the AD-DICE model, the final optimizing aim of the routine is to maximize the utility. Utility is a function of consumption and in each time period, the amount of consumption is defined by the endogenously available income reduced by the costs of climate change (residual damage, mitigation costs and protection cost). The climate change damages are represented by the damage function that depends on the temperature increase compared to 1900 levels. The new element added to the AD-DICE model by the authors is the inclusion of adaptation and the adaptation is included through a level parameter which determines what level of adaptation is introduced in the model. The damage prior to taking any adaptation measures is defined here as the gross damages and the damages occurring after the implementation of some adaptation measures is termed as residual damages. The cost incurred during the adaptation procedure is called the adaptation costs and the total damage is the sum of residual damages and the adaptation costs. This total damage costs is reduced from the income every period and affects the consumption and utility of the people.

2.2 Implementation

The implementation of AD-DICE model is done based on the OptMimiDICE2016R2 julia package by Felix Schaumann available on the GitHub. The model used here is a optimizing enabled model version for the MimiDICE2016 julia package and we need to use this package since adaptation is implemented as a policy variable in the AD-DICE model. Since the main changes are made to the damage part of the equations in DICE model, we can recreate the AD-DICE model by editing the equations in the damage component of the OptMimiDICE2016R2 package.

The Gross Damage function in the DICE model is used in the AD-DICE model with a minor change in the value of the damage exponent α_3. The equation for gross damage at each time period GD_t is given by:

$$GD_t = (\alpha_1 TATM_t + \alpha_2 TATM_t^{\alpha_3})Y_t$$

where the $TATM_t$ represents the temperature increase compared to 1900 levels, α_1 is the damage coefficient, α_2 is the damage quadratic term ($\alpha_2 > 0$) and α_3 is the damage exponent ($\alpha_3 > 1$). The residual damage RD_t is implemented through the equation:

$$RD_t = GD_t(1 - P_t), \qquad 0 \leq P_t \leq 1$$

This equation ensures that when the protection level is 0, residual damage will be equal to the gross damage and when protection level is 1, gross damage will be 0. Implementing any level of protection comes at a cost and is represented by the protection cost PC_t. de Bruin, Dellink and Tol (2009) reports that the optimal level of P_t ranges between 0.09 to 0.45 with an average of 0.33, that is, 33% of gross damages are reduced by using adaptation.

$$PC_t = (\gamma_1 P_t^{\gamma_2})Y_t \qquad \gamma_1 > 0, \gamma_2 > 1$$

where γ_1 is the protection coefficient and γ_2 is the protection exponent. Finally, the total damage is calculated by the sum of residual damages RD_t and protection costPC_T.

$$D_t = RD_t + PC_t$$

The above given equations are implemented in the OptMimiDICE2016R2 package to get a working model of AD-DICE which we can later extend to include our additions. After the implementation the calibrated parameters for the AD-DICE models are added into the model through Mimi and Julia. The calibrated model values from the de Bruin, Dellink and Tol (2009) are given in Table 1.

Parameter	α_1	α_2	α_3	γ_1	γ_2
Value	0.0012	0.0023	2.32	0.115	3.60

Table 1: Parameter values from AD-DICE in the optimal scenario calibration

3 Extension

There are two main types of adaptations named stock and flow adaptation. In the AD-DICE model only flow adaptation is considered and he extension idea for the AD-DICE model is implicitly given by de Bruin, Dellink and Tol (2009), "...*both the costs and benefits of adaptation are "instantaneous", i.e. they fall within the same time period, that is within the same decade.* This clearly shows that the adaptation procedure used in the AD-DICE model is limited in the sense that it only accommodates the flow adaptations whose benefits and costs are incurred in the same period. Flow adaptations can include measures such as cloud dispersion, irrigation, atmospheric aerosol injection, water conservation programs etc. while the examples of stock adaptations include infrastructural adaptations like water reservoirs, forest management and reforestation,etc. In reality, policy makers are interested in both flow and stock adaptation after looking at the economic benefits and the possible reductions in damages as result of the combined use of stock and flow adaptation measures. This idea is then implemented by Agrawala et al. (2011) along with a comparison to the AD-WITCH model. But implementation of the original model by Agrawala et al. (2011) is a very tedious process as it involves many parameters which has to be calibrated and this is out of scope for this term paper. But even then, the idea of stock and flow adaptation is quite interesting in itself and here I try to implement this model using a different mathematical approach to look at the economic of benefits of using a mix of stock and flow adaptation measures.

3.1 Theory

The basic gross damage equation remains the same in this extended model as well while changes have been made to the calculation of residual damages and protection cost from the original AD-DICE model. Furthermore, new variables and parameters are also introduced to incorporate the flow and stock adaptation in a meaningful manner.

The total budget used for the flow adaptation per period is taken from the AD-DICE model and is shared between flow adaptation and investment in stock adaptation using a parameter ω_1. This is then used to calculate the investment in stock adaptation IA_t and flow adaptation spending. Since we have a stock adaptation component which provided benefits for long periods of time, we can calculate the value of the cumulative stock adaptation with some depreciation rate δ over all the time periods t. The value of stock adaptation in period $t+1$ will be the cumulative stock adaptation until period t reduced by the depreciation rate. Here we are using the same capital depreciation rate used in de Bruin, Dellink and Tol (2009) which is 5% or $\delta = 0.05$.

Next we try to calculate the adaptation benefits in terms of currency units by assigning effectiveness coefficients to the amount of flow adaptation cost and on the cumulative stock adaptations. This is a very basic approach in which we assume that the relationship is linear and do not assume any substitutability or elasticities. (Agrawala et al. (2011) uses other complicated methods which are out of scope of this paper). Both the effectiveness coefficients are found initially by using the benefit cost ratio calculation, since these could be calculated using simple algebraic manipulation of equations from the AD-DICE model for the flow investments and can be found using literature reviews for the stock adaptations. The resulting adaptation benefits in terms of currency units can be used to calculate the residual damage by simply subtracting this amount from the gross damage.

We also use a simplified approach to calculate the protection cost per period, just by adding the allocated share of budget for flow adaptation and investment in stock adaptation per period. This assumes that the the relationships between the expenditures and costs to be linear. The advantages of using this method includes easier implementation and understanding and suitability for initial modelling when detailed cost behaviour data is lacking.

3.2 Implementation

This extension is also implemented based on the OptMimiDICE2016R2 and some major changes and various new parameters and variables are introduced to the damage component in the package. The new variables which are introduced are stock adaptation SAD_t, investment in stock adaptation IA_t, flow adaptation FAD_t, cumulative stock adaptation $SADC_t$ and the new parameters are depreciation parameter for stock adaptation δ, effectiveness coefficient for flow adaptation λ_{1t}, effectiveness coefficient for stock adaptation λ_2, share parameter ω_t which allocates certain share of total budget in adaptation to flow adaptation and total budget parameter B_t.

Just as in the AD-DICE and normal DICE models the gross damage parameter is defined here with the equation:

$$GD_t = (\alpha_1 TATM_t + \alpha_2 TATM_t^{\alpha_3})Y_t$$

where the $TATM_t$ represents the temperature increase compared to 1900 levels, α_1 is the damage coefficient, α_2 is the damage quadratic term ($\alpha_2 > 0$) and α_3 is the damage exponent ($\alpha_3 > 1$). The investment in stock adaptation is done by the leftover share of budget from the flow adaptation and is represented by:

$$IA_t = (1 - \omega_t)B_t$$

where $(1-\omega_t)$ represents the share of the budget allocated for the investment in stock adaptation and B_t represents the total budget per period t. Similarly the budget allocated for the flow investment is given by:

$$FAD_t = \omega_t * B_t, \qquad 0 \leq \omega \leq 1$$

The cumulative stock adaptation is calculated by:

$$SAD_t^{\text{cum}} = \sum_{i=0}^{t} IA_i(1 - \delta)^{t-i}$$

Here we consider the depreciation rate δ to be similar to the 0.05 as in the original AD-DICE model. The total benefits from the combined flow and stock adaptation is given by the equation:

$$ADAPT_t = \lambda_{1t} FAD_t + \lambda_2 SAD_t^{\text{cum}}$$

where the λ_{1t} and λ_2 are effectiveness coefficients of flow adaptation and cumulative stock adaptation respectively. The λ_{1t} takes the value of a vector while the $\lambda_2 = 0.19$ based on calculations (see Appendix). Since we have the $ADAPT_t$ in currency terms, we can now easily use this to find the protection cost PC_t.

$$PC_t = FAD_t + IA_t$$

This form assumes the relationship to be linear and is easier for us to understand. But in reality this linear form might not be able to describe the relationships observed. But using a more complex cost relationship would mean that we have to introduce more parameters which needed to be calibrated for results. Residual damages can also be calculated from $ADAPT_t$ and GD_t:

$$RD_t = GD_t - ADAPT_t$$

Finally the damage function takes the form as in the original AD-DICE model with:

$$D_t = RD_t + PC_t$$

3.3 Calibration

Running a full calibration routine is a complex tasks and requires lots of expertise in the field along with availability of good quality data and observations. For the purpose of this term paper, I have tried to calibrate only one parameter λ_1. It is a manual calibration which made use of basic algebra and the idea is to set $\omega_t = 1$ so that all the budget (which is the same budget in original AD-DICE model) is allocated for the flow adaptations. This will modify the $ADAPT_t$ equation as: $ADAPT_t = \lambda_{1t} FAD_t$. Now we will have two equations from AD-DICE and our extension such that:

$$RD_t = GD_t - 0.33GD_t, \qquad \textit{from AD-DICE}$$

$$RD_t = GD_t - \lambda_{1t} FAD_t, \qquad \textit{from extended model}$$

Equating these two equations will give us new values for λ_1.

$$\lambda_1 = \frac{GD_t \times 0.33}{FAD_t}$$

Through trial and error, an exponent of 1/1.2 has been added for better fit.

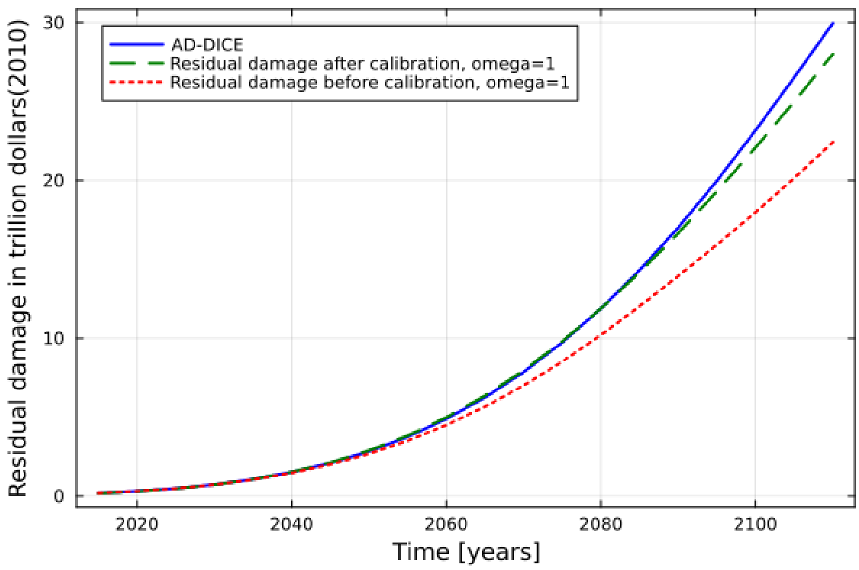

Figure 1: Before and after calibration with $\omega_t = 1$

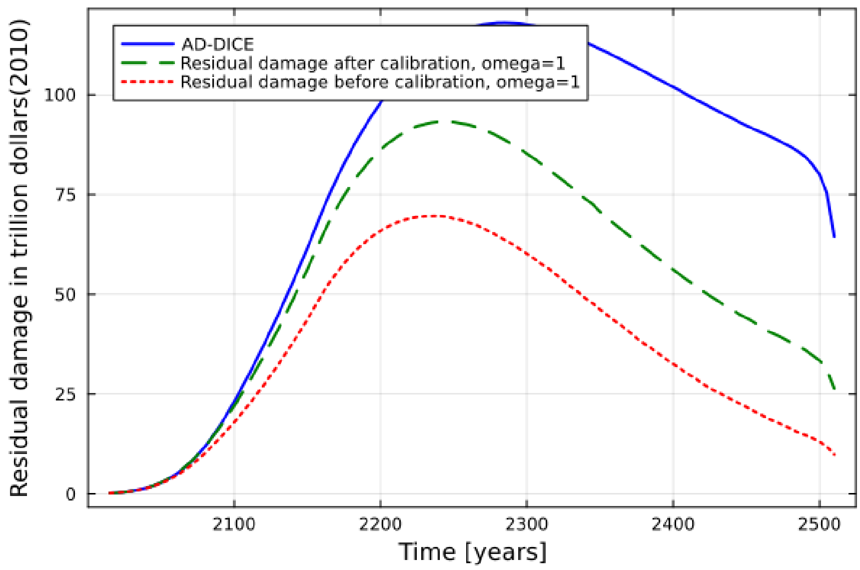

Figure 2: Before and after calibration with $\omega_t = 1$, long term

As shown in Figure 1, the calibration procedure has made the baseline calculations more in line with the AD-DICE model even though it is clear from Figure2 that the long term results are still not aligned with the original AD-DICE.

4 Results

The results in this extended study is mainly pertaining to the economic benefit with respect gained from employing different policy scenarios of adaptations. The results will look at three scenarios of the extended model where, $\omega_t = 1$ (full budget allocated for flow adaptation), $\omega_t = 0.5$ (half of the budget allocated for flow adaptation and the other half for investment in stock adaptation), $\omega_t = 0$ (full budget is allocated for investment in stock adaptation) and is compared to the baseline AD-DICE model. Figure 3 & Figure 4 shows the benefits incurred in long run and short run for various ω_t values in the extended model and for the original AD-DICE model in trillions of US dollars (2010). From this we see that the benefits from the original AD-DICE model outweighs the all the outcomes from the extended model in both the long run and in the short run. But among the results from the extended model, the flow adaptation can be preferred in the short run while stock and mixed approach can be preferred for the long run planning. From both the AD-DICE model and the extended model, it is clear that preferring only the flow adaptation for the long run not a good idea since both these curves shows substantial negative trends towards from around 2250 onwards while the benefits from stock adaptation only scenario and mixed adaptation scenario both have an increasing benefit.

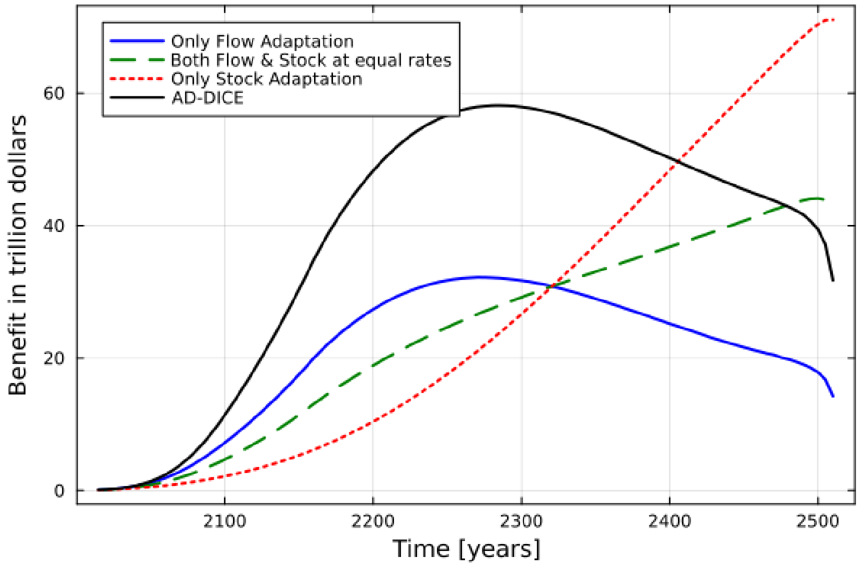

Figure 3: Benefits in the long run with different ω_t values and for AD-DICE

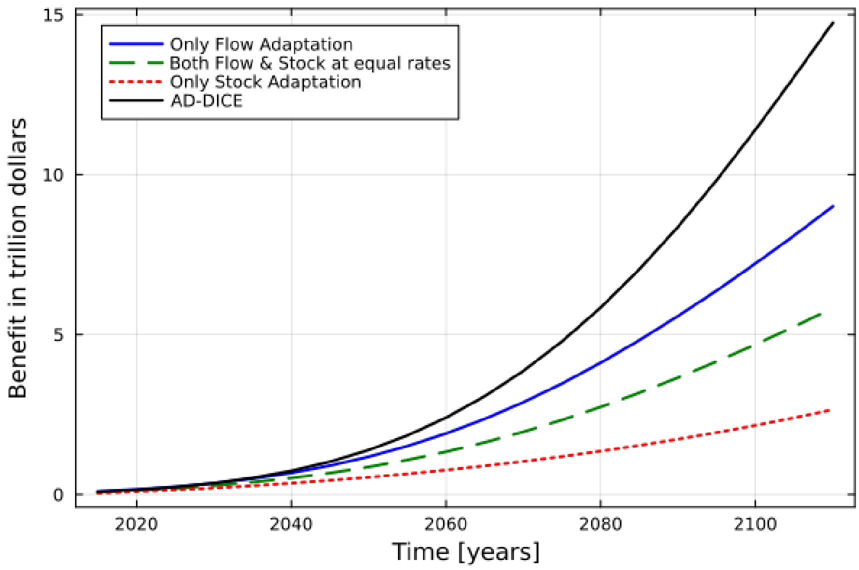

Figure 4: Benefits in with different ω_t values and for AD-DICE

The main findings of this extension is related to the cost benefit ratio of adaptation measures. The cost benefit ratio can be calculated using the equation: *CBR* = *ProtectionCost/Benefits*. A CBR of less than 1 is desired as this means that the benefits incurred from the investment is higher than the cost. In this case our model gives us both the protection costs and the benefits ($ADAPT_t$). Figure 5 show the cost benefit ratio of the different adaptation scenarios. In the beginning of the time period in the model, it is highly beneficial to invest in more stock adaptation since it has the highest cost benefit ratio. Interestingly, by the end of the time period, it become more beneficial to use adaptation measures the benefit from the stock adaptation requires long periods of time to manifest.

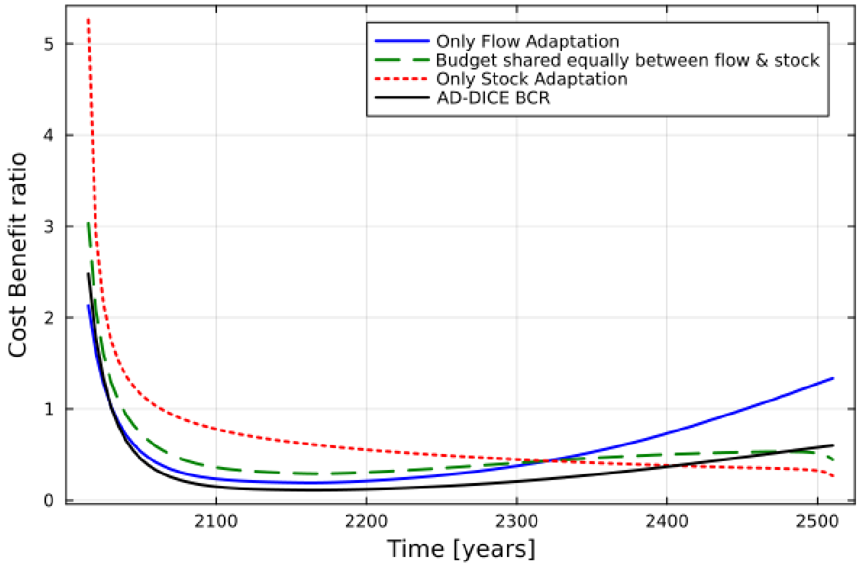

Figure 5: Benefits in with different ω_t values and for AD-DICE

The Table 2 given below shows the average CBR across the time period for all the given periods and from this table it is clear that the highest average CBR is for investing only in the stock adaptation followed by the only flow adaptation. This is due to the opposing trend of CBRs of both these components in the time frame. While only stock adaptation investment has a higher CBR in the beginning, the flow adaptation investments have higher CBRs towards the end of the time frame. The CBR of the AD-DICE model is 0.33 which is the protection level specified in the AD-DICE model.

ω_t **Value**	$\omega_t = 1$	$\omega_t = 0.5$	$\omega_t = 0$	AD-DICE
Scenarios	only flow adaptation	both flow and stock adaptation	only stock adaptation	only flow (Baseline AD-DICE)
Mean CBR	0.5534	0.5016	0.6503	0.3335

Table 2: Mean CBR for different scenarios

The table 3 shows the total Benefit-Cost Ratio(BCR) of the investments made throughout the 100 year period. It is the inverse of the CBR and hence a BCR of value greater than 1 is desirable for profitable investments in adaptation measures. from this it is clear that the highest return is availed from the stock adaptation while a slightly lower BCR from a mix of flow and stock adaptations. The least amount of BCR in the extended model is achieved when only using the flow adaptation which signifies the importance of stock adaptation investments.

ω_t **Value**	$\omega_t = 1$	$\omega_t = 0.5$	$\omega_t = 0$	AD-DICE
Scenarios	only flow adaptation	both flow and stock adaptation	only stock adaptation	only flow (Baseline AD-DICE)
Total BCR	1.9813	2.2413	2.5013	3.7145

Table 3: Total BCR for different scenarios *(higher is better)*

5 Conclusion

The extension underscores the significance of integrating both flow and stock adaptations in climate policy frameworks. While flow adaptations are beneficial for immediate impacts, stock adaptations are crucial for sustainable, long-term resilience. Policymakers should consider a balanced approach, investing in both types of adaptations to optimize economic benefits and enhance protection against climate impacts. This extended model provides a foundational step towards more comprehensive and effective adaptation strategies, though further refinement and calibration are necessary for precise policy implementation.

The extension made in this term project is in no way an ideal extension as it has omitted several key factors which are important in deciding the dynamics between the climate, economy and climate damages. The complex dynamics of the price systems and the complex methods in which the benefits may accrue are completely omitted in this modelling approach. But understanding modeling as an effort to simplify the world in which we live and to derive somewhat meaningful insights along with good understanding of the Julia programming language and Mimi Framework has been the major personal achievements for me through this project.

References

Agrawala, Shardul, Francesco Bosello, Carlo Carraro, Kelly De Bruin, Enrica De Cian, Rob Dellink and Elisa Lanzi. 2011. "PLAN OR REACT? ANALYSIS OF ADAPTATION COSTS AND BENEFITS USING INTEGRATED ASSESSMENT MODELS." *Source: Climate Change Economics* 2:175–208.

Archer, David. 2016. *The Long Thaw: How Humans Are Changing the Next 100,000 Years of Earth's Climate*. Princeton: Princeton University Press.
URL: *https://doi.org/10.1515/9781400880775*

Core Writing Team, H. Lee and J. Romero (eds.). 2023. *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: IPCC.
URL: *https://doi.org/10.59327/IPCC/AR6-9789291691647.001*

de Bruin, Kelly C., Rob B. Dellink and Richard S. J. Tol. 2009. "AD-DICE: an implementation of adaptation in the DICE model." *Climatic Change* 95:63–81.
URL: *http://link.springer.com/10.1007/s10584-008-9535-5*

Shaumann, Felix and David Anthoff. Year. "OptMimiDICE2016R2.jl." GitHub repository.
URL: *https://github.com/felixschaumann/OptMimiDICE2016R2.jl*

UNFCCC. 2011. "ASSESSING THE COSTS AND BENEFITS OF ADAPTATION OPTIONS AN OVERVIEW OF APPROACHES.".
URL: *https://unfccc.int/resource/docs/publications/pub*$_nwp_costs_benefits_adaptation.pdf$

Appendix

1. **Value of λ_1 (effectiveness of Flow adaptation per period)**

   In the original AD-DICE model, the residual damages are calculated as follows:

   $$RD_t = GD_t(1 - P_t)$$

   From this, we can find the benefits of flow adaptation in trillion-dollar terms. The benefits will be $BF_t = GD_t \times P_t = GD_t - RD_t$. Dividing it with the adaptation cost will give the effectiveness coefficient $\lambda 1$.

2. **Value of λ_2 (effectiveness of Stock adaptation per period)**

   From a list of case studies published in the UNFCCC (2011), it is found that the cost benefit ratio with an average of 3.8 per dollar invested. Considering that the long term projects have lifespans of 100 years, we can divide it into 20, 5 year periods. Then the benefit per time period is: $\frac{3.8}{20} = 0.19$ i.e, $\lambda_2 = 0.19$.

Statutory Declaration

I hereby declare that this term paper is my own original work and that I have acknowledged all sources and references accurately. I have utilized various resources for assistance, including ChatGPT, an AI language model developed by OpenAI, for help with coding, explanations on functional forms, and conceptual clarifications.
Furthermore, I acknowledge the original authors of the referenced papers, including de Bruin, Dellink, and Tol (2009), and Agrawala et al. (2011), whose work has significantly contributed to the foundation and extension of the AD-DICE model discussed in this paper. Their research has been instrumental in developing the concepts and methodologies employed in this study.
I have ensured that all sources, including the websites and the cited papers, have been appropriately credited and that any direct quotations or paraphrased content are properly referenced. This term paper adheres to the academic standards and guidelines for authenticity and integrity.

Adhit Chandy George
Matriculation Number: 7598886
21 June 2023