BEFORE THE OFFICE OF ADMINISTRATIVE HEARINGS

FOR THE MINNESOTA PUBLIC UTILITIES COMMISSION

STATE OF MINNESOTA

In the Matter of the Further Investigation in to

Environmental and Socioeconomic Costs

Under Minnesota Statute 216B.2422, Subdivision 3

OAH Docket No. 80-2500-31888

MPUC Docket No. E-999-CI-14-643

Sur-Rebuttal Testimony

Professor Robert Mendelsohn

September 10, 2015

PROFESSOR ROBERT MENDELSOHN

OAH 80-2500-31888

MPUC E-999/CI-14-643

TABLE OF CONTENTS

REBUTTAL TESTIMONY OF ROBERT MENDELSOHN

Q: Are you the same Robert Mendelsohn who has testified previously in this proceeding?

A: Yes, I am.

Q: How do you intend to present your testimony?

A: I have read the rebuttal testimony of Dr. Michael Hanemann and Dr. Stephen Polasky and would like to respond. Although there are many technical details in their testimony that I believe are not accurate, I restrict myself in this response to the major issues that they raise.

I. INTRODUCTION.

Q: What do you understand to be the position of Drs. Hanemann and Dr. Polasky?

A: Both Dr. Hanemann and Dr. Polasky support the SCC 2015 (in 2007 USD) estimates that the IWG came to in 2010 of $26, in 2013 of $43, and in 2015 of $36 per ton. These values have been changed because of technical issues with the models and IWG estimation, not because of changes in the underlying science over this time period. It appears that both Dr. Hanemann and Dr. Polasky are not actually verifying that they support a specific value of the SCC but rather they support the opinion of the IWG.

Q: What is your opinion of their position?

A: Dr. Hanemann and Dr. Polasky defer to the IWG as an expert panel on climate change and therefore support their conclusions and all their methods. Nonetheless, they personally raise many arguments which suggest that they do not agree with the IWG but rather feel that the true SCC (damage from carbon emissions) is much higher. They feel that many climate damages were not included, that the discount rate should be lower than 3%, and that a risk premium should be added to the damage. They raise no counterbalancing arguments to suggest the IWG figure is correct. Their arguments do not support the conclusion to which they have come.

II. BENEFITS OF CO2 FERTILIZATION

Q: Drs. Hanemann and Polasky have stated that your conclusions as to the benefits of carbon fertilization for agriculture are unsupported. How do you respond?

A: Carbon fertilization is an important factor if one is concerned about crops. Economists have not been able to measure carbon fertilization effects using cross-sectional methods because the level of CO_2 is effectively the same across the planet. Changes in CO_2 over time unfold slowly and systematically, making it hard to separate their effect from other changes over time. Nonetheless there is compelling evidence from hundreds of controlled laboratory experiments that confirm doubling CO_2 increases crop yields (Kimball 1983). For most crops, yields increase 30% if CO_2 doubles. Dr. Polasky and especially Dr. Hanemann complain that the beneficial effect of CO_2 on crops is too complicated and too uncertain to include at all. (Polasky Rebuttal 53:19-54:4; Hanemann Rebuttal 12:5-18.)

But Dr. Hanemann and Dr. Polasky are not consistent in how they treat complexity and uncertainty. With CO_2 fertilization they argue complexity and uncertainty implies one should dismiss fertilization effects. With warming, they argue complexity and uncertainty imply one should give the impact more weight, not less weight. (Polasky Rebuttal 54:4-55:2; Hanemann Rebuttal 5:17-6:12.) However, the evidence supporting the idea that temperature is harmful and the evidence supporting the idea that carbon fertilization is beneficial are very similar. Both effects are revealed in laboratory experiments and they are both likely to be a factor in the real world.

One other point that Dr. Hanemann and Dr. Polasky gloss over is the critical importance of adaptation which will mute the harmful consequences of climate change. Taking into account adaptation, there is every reason to believe that global agricultural supply will be robust against the climate change possible over the next century. If a modest mitigation program is undertaken consistent with a current SCC of $5/ton, it is not clear that global agricultural supply will be at risk at all. Although there will be places in the planet where agriculture will decline, there will also be places in the planet such as Minnesota where agriculture will be more productive.

Q: Dr. Hanemann contends that these are only laboratory results and that, outside the laboratory, the stress of higher temperatures would outweigh the carbon fertilization benefit. How do you respond?

A: I do not understand why Dr. Hanemann dismisses scientific studies because they are done in a laboratory. Controlled experiments are a very important way to demonstrate cause and effect. Dr. Hanemann complains that the real world is too complicated and uncertain to extrapolate from laboratory results. But the fact that the real world is uncertain and complicated is a major problem for all studies, not just laboratory studies.

The fact that carbon fertilization is likely to be more important than temperature impacts over the next century is well documented. For example, one can look at the results of Dr. Hanemann's own research on agriculture in the United States. Schlenker, Hanemann, and Fischer (2005) examine just the part of the United States east of the 100th meridian and show that the harmful climate effect of doubling CO_2 on United States agriculture would lead to a 15% loss. However, the fertilization effect of doubling CO_2 would directly cause an increase in yields of 30%. His own research demonstrates that the carbon fertilization effects are larger than the temperature effects in the eastern United States. If one includes the entire country, the net benefit is even larger (Mendelsohn, Nordhaus and Shaw 1994; Mendelsohn and Dinar 2003).

Q: What about the results for ecosystems rather than crops?

A: Carbon fertilization is an important factor if one is concerned about ecosystems. There is substantial evidence that carbon dioxide fertilizes trees. The evidence takes several forms. Laboratory experiments reveal young trees grow more rapidly with higher CO_2 concentrations. Field observations reveal a large increase in the growth rates of mature trees that can only be explained by the combination of carbon fertilization and climate change (Boisvenue and Running 2006). Carbon models reveal that the historic changes in the earth's CO_2 levels over time can only be explained if carbon in fact fertilizes land based ecosystems (Pan 2012). Ecosystem models depend on CO_2 fertilization to explain the observed biomass growth over time (Haxeltine and Prentice 1996).

Q: Dr. Hanemann questions whether there is any evidence that climate change could possibly be beneficial to ecosystems. How do you respond?

A: The science is quite clear on this point. Dynamic quantitative vegetation models consistently predict the net effect of rising CO_2 levels and global warming on global ecosystems is that net primary productivity will increase, standing biomass will increase, and forestland will increase (Gerber, Fortunat, and Prentice 2004; Sitch et al. 2008). Rising net primary productivity implies more growth. More biomass implies that forests would be more fully stocked. More forests imply shifts in biome types that humans generally would consider desirable. On the basis of all these physical changes predicted by science, I argue that the net change in ecosystems from global warming is likely to be beneficial over the next century. I have not quantified the magnitude of these benefits in dollar values but the fact that these are beneficial changes is clear.

Q: What about the effects in Minnesota?

A: As I explained in my direct testimony, Minnesota will likely be a net beneficiary of warming, because of increased agricultural and ecosystem productivity. The primary downside risk for Minnesota ecosystems is that the forests may shrink over time and be replaced by grassland. Even this loss is muted because the land will be suitable for agriculture. Drs. Hanemann and Polasky do not appear to have addressed or disputed my conclusions regarding Minnesota.

Q: Dr. Rom has suggested that there may be adverse human health effects from warming. How are these treated in the DICE model?

A: Potential health effects are already captured in the DICE model damage function. My run of DICE did not alter how human health impacts are included in the damage function. The exact future impacts of warming on health are uncertain, but many of the citations that Dr. Rom relies upon have not taken into account public health and pollution control measures that are likely in the future as incomes rise across the world. Because these future preventive measures are ignored in these studies, it is likely that the current Integrated Assessment Models overestimate future health effects.

III. BASIS FOR MODIFYING THE DICE DAMAGE FUNCTION

Q: Dr. Hanemann criticizes your modification of the so-called "damage function" in DICE. (Hanemann Rebuttal 40:25-42:12.) What is that, and why and how did you modify the damages function in DICE, rather than leaving it as Dr. Nordhaus wrote it?

A: Both experimental results in laboratories and climate impact research suggest that the effect of long term temperature and precipitation on the performance of most sectors is a hill-shaped response function. If temperatures are too cool, they will be harmful. If temperatures are too warm, they will also be harmful. There is an optimal temperature for every sector. The effect of climate change consequently depends on the temperature at which each location starts and ends and how important the changes are in each sector. A relatively cool state such as Minnesota will at first benefit from warming and will only be harmed if there is a large warming. Crops will get more productive. Heating savings will at first outweigh additional cooling costs. However, a relatively warm country such as Brazil will be hurt by warming immediately because it is already too hot in most of Brazil. Brazilian crops will become less productive. Increased cooling costs will far outweigh the small heating savings they might get.

Whether the planet gains from warming or loses depends on how it affects the many locations across the world. The expectation is that mid- to-high latitude countries will largely gain from initial warming and low-latitude countries will largely be harmed (Mendelsohn, Morrison, Schlesinger and Andronova 2000; Mendelsohn, Schlesinger, and Williams 2000; Mendelsohn, R. and L. Williams 2004; Mendelsohn, R., A. Dinar, and L. Williams 2006; IPCC 2013b). Taking all of these arguments into account, the net effect of warming of 1.5°C to 2°C (above preindustrial temperature) is expected to cause only minimal damage if any.

Professor Nordhaus acknowledges in his recent book *The Climate Casino* that most market sectors will in fact adapt to climate changes of 2°C and annual effects in these sectors will be relatively small. His belief that global damage will be orders of magnitude higher is entirely concerned with catastrophes such as ice sheet melting, ecosystem collapse, ocean acidification, and ocean circulation collapse. There is no scientific evidence that any of these effects will occur in 2050 if temperatures reach 2°C. If they occur at all, all of these potential catastrophic events would take many more decades (and sometimes centuries) to unfold and probably require much higher temperatures. Although the annual damage of unchecked warming in the far future can be great, the annual impact in the near future cannot plausibly be this large.

I have consequently modified the damage function of DICE to calibrate to all the evidence about climate damage that has been accrued. I have tried to make very simple modifications in DICE that are easy to verify. The first modification is to assume climate damage would not start until temperatures reach 1.5°C warmer than preindustrial temperatures. That is equivalent to assuming global climate damage would start when observed temperatures are 0.7°C warmer than today. An alternative modification is to assume that global damage does not start until temperatures are 2.0°C warmer than preindustrial or 1.2°C warmer than today. These calculations do not assume that warming below the thresholds is beneficial. Merely that damage does not begin until the temperature threshold is reached.

Q: What was the evidence supporting your adjustment?

A: My argument was based on more than two decades of empirical study, drawing on my own expertise as well as peer-reviewed research in the field. I have repeatedly cited peer-reviewed works in my initial testimony, the discovery responses I have provided in this proceeding, and in my rebuttal testimony. For example, some of my work includes:

1. Dinar, A., R. Hassan, R. Mendelsohn, and J. Benhin, *Climate Change and Agriculture in Africa: Impact Assessment and Adaptation Strategies* (EarthScan, London, 2008).
2. Ariel Dinar and Robert Mendelsohn (eds), *Handbook of Climate Change and Agriculture* (Edward Elgar Publishing, England, 2011).
3. Dinar, A., R. Mendelsohn, R. Evenson, J. Parikh, A. Sanghi, K. Kumar, J. McKinsey, and S. Lonergan. Measuring the Impact of Climate Change on Indian Agriculture World Bank Technical Paper No. 402, Washington D.C. 1998.
4. Fleischer, A., I. Lichtman, and R. Mendelsohn. 2008. "Climate Change, Irrigation, and Israeli Agriculture: Will Warming Be Harmful?" Ecological Economics 67: 109-116.
5. Goklany, I., 2012, Humanity Unbound How Fossil Fuels Saved Humanity from Nature and Nature from Humanity, Cato Policy Analysis No. 715, 33 pp.
6. Helms, S., R. Mendelsohn, and J. Neumann. 1996. "The Impact of Climate Change on Agriculture", Climatic Change 33: 1-6.
7. Kala, N. P. Kurukulasuriya, and R. Mendelsohn. 2012. "How Will Climate Change Shift Agro-Ecological Zones and Impact African Agriculture" Environment and Development Economics 17: 663-687.
8. Kurukulasuriya, P. and R. Mendelsohn. 2008. "Crop Switching as an Adaptation Strategy to Climate Change" African Journal Agriculture and Resource Economics 2: 105-126.

9. Kurukulasuriya, P. and R. Mendelsohn. 2008. “A Ricardian Analysis of The Impact of Climate Change on African Cropland” African Journal Agriculture and Resource Economics 2:1-23.

10. Kurukulasuriya, P., R. Mendelsohn, R. Hassan, J. Benhin, M. Diop, H. M. Eid, K.Y. Fosu, G. Gbetibouo, S. Jain, , A. Mahamadou, S. El-Marsafawy, S. Ouda, M. Ouedraogo, I. Sène, N. Seo, D. Maddison and A. Dinar. 2006. “Will African Agriculture Survive Climate Change?” World Bank Economic Review 20: 367-388.

11. Massetti, E. and R. Mendelsohn. 2011. “The Impact of Climate Change on US Agriculture: a Cross Section, Multi-Period, Ricardian Analysis” in A.Dinar and R. Mendelsohn (eds) Handbook of Climate Change and Agriculture, Edward Elgar Publishing, England.

12. Mendelsohn, R., W. Nordhaus and D. Shaw. 1996. "Climate Impacts on Aggregate Farm Values: Accounting for Adaptation", *Agriculture and Forest Meteorology* **80:** 55-67.

13. Mendelsohn, R., W. Nordhaus and D. Shaw. 1994. "Measuring the Impact of Global Warming on Agriculture", *American Economic Review* **84:** 753-771.

14. Mendelsohn, R. and J. Neumann (eds.) 1999. *The Impact of Climate Change on the United States Economy* Cambridge University Press, Cambridge, UK

15. Mendelsohn, R. “Assessing The Market Damages From Climate Change” in J. Griffin (ed) *Global Climate Change: The Science, Economics, and Politics* Edward Elgar Publishing, UK, 2003, pp92-113.

16. Robert Mendelsohn, “The Impact of Climate Change on Agriculture in Asia,” 13 J. Integrative Agric. S2095 (2013).

17. Mendelsohn et al., *The Impact of Global Warming on Agriculture: A Ricardian Analysis*, 84 AM. ECON. REV. 753, 769 (1994).

18. Mendelsohn, R. 2001. *Global Warming and the American Economy: A Regional Analysis*. Edward Elgar Publishing, England.

19. Mendelsohn, R. 2009. "The Impact of Climate Change on Agriculture in Developing Countries" Journal of Natural Resources Policy Research 1: 5-19.

20. Mendelsohn, R., P. Christensen, and J. Arellano-Gonzalez. 2010. "The Impact of Climate Change on Mexican Agriculture: A Ricardian Analysis" Environment and Development Economics 15: 153-171.

21. Mendelsohn, R and A. Dinar. 2009. *Climate Change and Agriculture: An Economic Analysis of Global Impacts, Adaptation, and Distributional Effects.* Edward Elgar Publishing, England.

22. Mendelsohn, R. and A. Dinar. 2003. "Climate, Water, and Agriculture", Land Economics 79, 328-341.

23. Mendelsohn, R. and A. Dinar. 1999. "Climate Change, Agriculture, and Developing Countries: Does Adaptation Matter?", The World Bank Research Observer 14: 277-293.

24. Mendelsohn, R. and M. Reinsborough. 2007. "A Ricardian Analysis of US and Canadian Farmland" Climatic Change 81: 9-17.

25. Mendelsohn, R. 2007. "What Causes Crop Failure?" Climatic Change 81: 61-70.

26. Mendelsohn, R., A. Basist, A. Dinar, and P. Kurukulasuriya. 2007. "What Explains Agricultural Performance: Climate Normals or Climate Variance?" Climatic Change 81: 85-99.

27. Mendelsohn, R., A. Basist, A. Dinar, and P. Kurukulasuriya. 2007. “Climate and Rural Income” Climatic Change 81: 101-118.

28. Mendelsohn, R., A. Dinar and A. Sanghi. 2001. "The Effect of Development on the Climate Sensitivity of Agriculture", Environment and Development Economics 6: 85-101.

29. Mendelsohn, R. W. Nordhaus, and D. Shaw. “The impact of climate variation on US agriculture” in R. Mendelsohn and J. Neumann (eds) The Impact of Climate Change on the United States Economy. Cambridge University Press, Cambridge, UK, 1999.

30. Mendelsohn, R. and W. Nordhaus. 1996. "The Impact of Global Warming on Agriculture: Reply to Cline", American Economic Review 86: 1312-1315.

31. Mendelsohn, R., W. Nordhaus and D. Shaw. 1996. "Climate Impacts on Aggregate Farm Values: Accounting for Adaptation", Agriculture and Forest Meteorology 80: 55-67.

32. Mendelsohn, R., W. Nordhaus and D. Shaw. 1994. "Measuring the Impact of Global Warming on Agriculture", American Economic Review 84: 753-771.

33. Mendelsohn R. 2011. “Economic Estimates of the Damages Caused by Climate Change” in J.S. Dryzek, R.B. Norgaard, and D. Schlosberg (eds) Oxford Handbook of Climate Change and Society, Oxford University Press, Oxford, UK pp 177-189.

34. Mendelsohn, R. 2011. “The Impact of Climate Change on Land” Chapter 4 In G. Ingram and Y. Hong (ed) Climate Change, and Land Policies, Lincoln Institute of Land Policy, Cambridge MA. p.62-83.

35. Mendelsohn, R. 2007. “The Impacts of Climate Change on Africa” in Schlesinger, M., Kheshgi, H., Smith, J. and de la Chesnaye, F., Reilly, J., Wilson, T. and Kolstad, C. (eds.)

Human-Induced Climate Change: An Interdisciplinary Assessment Cambridge University Press, Cambridge, UK p.161-166.

36. Mendelsohn, R. and L. Williams. 2007. "Dynamic Forecasts of the Sectoral Impacts of Climate Change" in Schlesinger, M., Kheshgi, H., Smith, J. and de la Chesnaye, F., Reilly, J., Wilson, T. and Kolstad, C. (eds.) Human-Induced Climate Change: An Interdisciplinary Assessment Cambridge University Press, Cambridge UK p107-118.

37. Mendelsohn, R. 2007. "Past Climate Change Impacts on Agriculture", Chapter 60 in R. Evenson and P Pingali (eds) Handbook of Agricultural Economics: Volume 3 Elsevier, North Holland p3009-3031.

38. Mendelsohn, R. and A. Dinar. 2005. "Exploring Adaptation to Climate Change in Agriculture: The Potential of Cross-Sectional Analysis" Agriculture and Rural Development Notes, World Bank, Washington, D.C.

39. Mendelsohn, R. 2005. "The Social Cost of Greenhouse Gases: Their Values and Their Policy Implications" in H. Dieter (ed) Climate Change Policy Oxford Economic Press p134-151.

40. Mendelsohn, R. "Measuring the Impacts from Climate Change" Hamilton Roddis Memorial Lecture Series, University of Wisconsin-Madison, Madison, WI, 2001.

41. Ng, W. and R. Mendelsohn. 2006. "The Impact of Sea-Level Rise on Non-Market Lands in Singapore" Ambio 35: 289-296.

42. Sanghi, A. and R. Mendelsohn. 2008. "The Impacts Of Global Warming On Farmers In Brazil And India" Global Environmental Change 18: 655-665.

43. Seo, N. and R. Mendelsohn. 2008. “A Ricardian Analysis of the Impact of Climate Change on South American Farms” Chilean Journal Of Agricultural Research 68(1): 69-79.

44. Seo, N. and R. Mendelsohn. 2008. "Measuring Impacts and Adaptation to Climate Change: A Structural Ricardian Model of African Livestock Management" Agricultural Economics 38: 150-165.

45. Seo, N. and R. Mendelsohn. 2008. “Climate Change Impacts on Latin American Farmland Values: The Role of Farm Type” Revista de Economia e Agronegocio 6: 159-176.

46. Seo, N. and R. Mendelsohn. 2008. “Climate Change Impacts and Adaptations on Animal Husbandry in Africa” African Journal Agriculture and Resource Economics 2: 65-82.

47. Seo, N. and R. Mendelsohn. 2008. “An Analysis of Crop Choice: Adapting to Climate Change in Latin American Farms” Ecological Economics 67: 109-116.

48. Seo, N., R. Mendelsohn, A. Dinar, R. Hassan, and P. Kurukulasuriya. 2009. ”A Ricardian Analysis of the Distribution of Climate Change Impacts on Agriculture across Agro-Ecological Zones in Africa” Environmental and Resource Economics 43: 313-332.

49. Seo, S.N., R. Mendelsohn, and M. Munasinghe. 2005. “Climate Change Impacts on Agriculture in Sri Lanka” Environment and Development Economics 10: 581-596.

50. Seo, N., R. Mendelsohn, P. Kurukulasuriya, and A. Dinar. 2008. “Long Term Adaptation: Selecting Farm Types Across Agro-Ecological Zones in Africa” World Bank Policy Research Working Paper 4602. Washington D.C.

51. Seo, N. and R. Mendelsohn. 2008. “A Structural Ricardian Analysis of Climate Change Impacts on African Farmers” World Bank Policy Research Working Paper 4603. Washington D.C.

52. Joel Smith and Robert Mendelsohn (eds.), *The Impact of Climate Change on Regional Systems: A Comprehensive Analysis of California* (Edward Elgar Publishing, Northampton, MA, 2006).

53. Sohngen, B., R. Mendelsohn and R. Sedjo. 2002. "A Global Model of Climate Change Impacts on Timber Markets" Journal of Agricultural and Resource Economics 26: 326-343.

54. Sohngen, B. and R. Mendelsohn. 1998. “Valuing The Market Impact of Large-Scale Ecological Change: The Effect of Climate Change on US Timber", American Economic Review 88: 686-710.

55. Wood, S. and R. Mendelsohn. 2014. “The impact of climate change on agricultural net revenue: a case study of Fouta Djallon, West Africa” Environment and Development Economics 19: 1-17.

56. Wang, J., R. Mendelsohn, A. Dinar, J. Huang, 2010. “How Chinese Farmers Change Crop Choice To Adapt To Climate Change” Climate Change Economics 1: 167-186.

57. Wang, J., R. Mendelsohn, A. Dinar, J. Huang, S. Rozelle and L. Zhang. 2009. “The Impact of Climate Change on China’s Agriculture” Agricultural Economics 40: 323-337.

58. Wang, X. and R. Mendelsohn. 2003. “An Economic Analysis of Using Crop Residues for Energy in China” Environment and Development Economics 8 467-480.

In addition, as noted in my report, I have drawn on the work of others to support my views and research. I cited the following sources in my initial report:

1. Gerber, S., F. Joos, and I .C. Prentice. 2004. "Sensitivity of a dynamic global vegetation model to climate and atmospheric CO2" *Global Change Biology* 10: 1223–1239.
2. Kimball, B. A. 1983. "Carbon Dioxide and Agricultural Yields: An Assemblage and assessment of 430 prior observations" *Agronomy Journal* 75: 779-788.

Q: Dr. Hanemann criticizes your reliance on Gerber et al. (2004). Can you respond to that?

A: Dr. Hanemann points out that the phrase "net benefit" does not actually appear in Gerber's work, which "contains no assessment of benefits to the ecosystem." I actually cited Gerber for a different proposition, namely that "the carbon fertilization of trees has also led to an overall increase in ecosystem productivity and standing biomass" (Direct Testimony, Ex. 2 (Report) at 12). I argue that an "overall increase in ecosystem productivity and standing biomass" would be a "net benefit" to society. The phrase "net benefit" does not appear in Gerber's work because that is *my* conclusion, not his, based on the net changes that ecosystem models predict from climate change.

Q: In your initial report, you said that "Global temperature today is about 0.8°C warmer than the preindustrial temperature. According to DICE2013, there should already be a global damage from climate change in 2015 equal to $173 billion annually. Clearly damage this great would be conspicuous. In practice, however, it is very difficult to detect this

annual global damage today, even with careful scientific measurements." Dr. Hanemann replied by saying that "$173 billion amounts to about 0.23% of global GDP" and thus it is not surprising that it is hard to detect. How do you respond to him?

A: One reason why I adjust the damage function in DICE is that DICE predicts annual climate damages of $173 billion today and yet I can find no net damages today. Dr. Hanemann argues that it is understandable one cannot find damages of $173 billion because this is a very small fraction of global GDP. (Hanemann Rebuttal 41:24-42:7.) However, I am not using changes in global GDP to measure damage. I am looking at individual effects in the sectors that are expected to be damaged by climate change in locations across the planet where these effects should occur. Although there are damages in select places and sectors, there are benefits in other places and other sectors. It is not possible to detect any net damage. Annual damages of $173 billon every year ought to be detectable.

Q: Are there other reasons to modify the damage function of DICE?

A: Another reason to adopt a modified lower damage function involves looking into the near future. In 2050, just 35 years from now, the DICE model predicts temperatures will be 2°C warmer than preindustrial assuming no mitigation. The global GDP according to DICE will be $199 trillion in 2050, so the annual damage in 2050 from climate change is predicted to be $2.1 trillion. It is simply implausible that there would be over $2 trillion of damage every year from such a small amount of warming. Looking at the sum of the damage across each sector of the economy with a 2°C warming, the net damage should be minimal. The current DICE model predicts $2 trillion of damage in 2050 alone and yet the mechanism that will deliver such damage in 35 years is not yet known. It is not clear how warming one more degree than today could possibly have an impact this large. Obviously, any assumption introduced into DICE that makes the predicted damage even higher is even more unlikely. By adjusting DICE so that the annual global damage starts at a slightly higher temperature, I was trying to update the model to reflect what we now understand about climate damage.

IV. ADAPTATION

Q: What is your conclusion about the ability of humans to adapt to climate change?

A: In response to Dr. Hanemann's arguments against using the optimization mode for DICE (Hanemann Rebuttal 84:12-85:3), I must explicitly address the issue of adaptation. I have studied climate adaptation and climate impacts intensively over the last 20 years. Along with colleagues from around the world, I have published 7 books and 66 refereed articles on climate change and adaptation. Adaptation is an essential and inevitable aspect of climate change. There is extensive evidence that people have already adapted to the climate that they live in across the planet. Humans inhabit climates that vary by as much as 20°C by adopting very different life styles to survive where they live. Migrants quickly learn to survive in places they move to despite the fact that the climate can be quite different. There is every reason to believe that people, firms, and farms will adapt as climate changes. The adaptation is in their interest. They do not need additional incentives. Adaptation will make them better off.

Q: Is adaptation important?

A: Adaptation is important precisely because it reduces damage. The early studies of climate change did not take adaptation into account and so predicted very large "potential" damages. The early impact studies (and even some recent studies) predict that cities would take no precautions against rising sea levels and simply be inundated, farmers would not adjust their crops despite evidence of decades of crop failure, people would not cool their houses to avoid dying from heat waves, and water would not be reallocated if it became scarce. Although these assumptions were made for simplicity, the assumption of no adaptation overstates the likely damage that climate change would cause.

Q: How does adaptation relate to your modification of the damage function of DICE and how does your modified model compare to others?

A: The no-adaptation models effectively assume that climate change occurs overnight with no warning. The climate change is a surprise. Assuming that climate change occurs overnight is not consistent with the science of climate change. The science of climate change argues that these changes will gradually unfold over centuries. It is predicted to be a very slow process because it takes a very long time (several decades) to accumulate sufficient greenhouse gases in the atmosphere and it takes an even longer time for equilibrium temperatures to be reached (many hundreds of years). Climate is also not likely to be a surprise because climate models predict how it will change in the future. We know many decades in advance how climate is likely to change. Finally, it is not likely to be a surprise because we are constantly measuring climate. Today we may be uncertain about the climate change in 2065 (fifty years from now) but a person in 2065 will already know what the climate is like at that time from the observations over the last 30 years (2035-2065).

If climate is not a surprise and it has important impacts, it is very obvious that people will react. If they can do something easily that will lessen the damage, they will make the change. For example, we react all the time to temperature by wearing more clothes at night than in the heat of the day. We change our behavior on wet days versus dry. We have different behaviors in summer and winter. There is every reason to believe we will make changes with respect to a gradual warming as well.

Adaptation will cause the actual damage from climate change to be a small fraction of potential damage. Studies of every sector that is expected to be damaged by climate change reveal that adaptation will substantially reduce damage.

Q: What are some examples of adaptation with respect to agriculture?

A: In agriculture, climate affects the choice of farm type in Latin America (Seo and Mendelsohn 2008b) and Africa (Kurukulasuriya et al. 2006). Crop choice is very sensitive to climate in Africa (Kurukulasuriya and Mendelsohn 2008), Latin America (Seo and Mendelsohn 2008d), and in China (Wang et al. 2010). The mix of animal species is sensitive to climate in Africa (Seo and Mendelsohn 2008c; 2008a) and Latin America (Seo, McCarl, and Mendelsohn 2010). Climate also affects whether a farmer irrigates or not (Mendelsohn, R. and A. Dinar. 2003; Kurukulasuriya, Kala, and Mendelsohn 2011). Making all of these changes will help farmers cope with warming. They effectively encourage managed systems to mimic ecosystems and shift plants and animals poleward and to higher altitudes so that they can remain in the same climate zone. That is how ecosystems have adapted in the past to wide swings in global temperature and that is how we will adapt forestry and agriculture as well.

Q: What are some examples of adaptation with respect to droughts and water management?

A: Water will be reallocated from low-valued to high-valued uses substantially reducing damage (Hurd et al. 1999; Hurd and Harrod 2001; Hurd et al. 2004; Lund, Cai, and Characklis 2006). By shifting water to high-valued uses such as municipal and industrial activities, these activities can be protected from possible swings in water supply. By carefully doing the same thing within agriculture, the damage from reductions in irrigation water can be limited. Dams can be constructed to shift water to high-valued (summer) periods from low-valued (winter) periods if needed.

Q: What are some examples of adaptation with respect to sea level rise?

A: Cities will be protected by sea walls from sea level rise (Yohe 1991; Yohe et al. 1996; Yohe and Schlesinger 1998; Neumann and Livesay 2001; Ng and Mendelsohn 2006; Hallegatte et al. 2010; 2013). It is much cheaper to build sea walls around developed coastlines compared to the damage of having developed coastlines inundated. Although some especially low lying pieces of land may be lost to inundation in cities, most urban territory will be protected.

Miami? S. Florida?

Q: What are some examples of adaptation with respect to temperature increases?

A: Firms and households will adopt more cooling as temperatures rise (Rosenthal and Gruenspecht 1995; Morrison and Mendelsohn 1998; Mendelsohn 2001; Mansur, Mendelsohn, and Morrison 2008; Mideksa and Kallbekken 2010; Deschênes and Greenstone 2011). This increased cooling may be especially important to low-latitude developing countries as their rising incomes permit consumers to respond with more cooling (Depaula and Mendelsohn 2010).

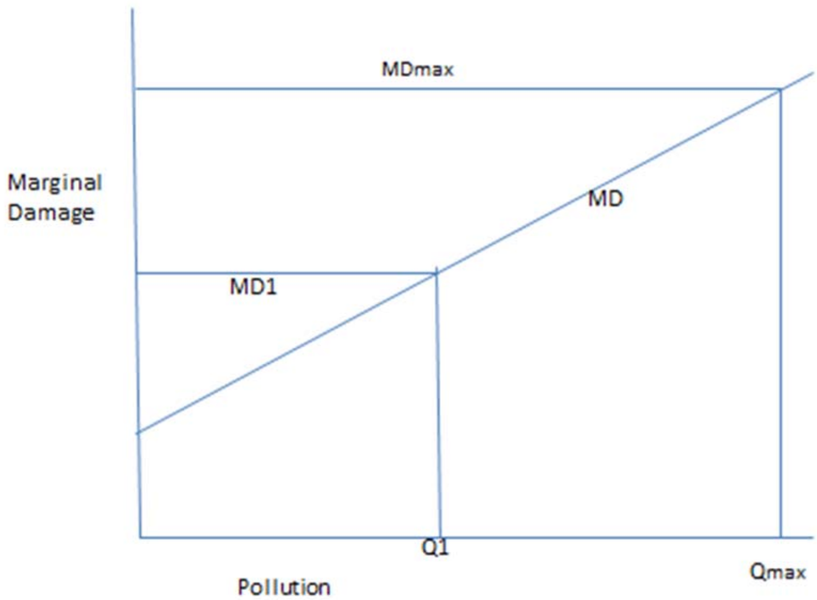
Cooling and public health measures will substantially reduce heat wave deaths (Deschênes and Greenstone 2011). Following the heat wave in Europe in 2003 that killed thousands, cooling and public health measures were taken leading to almost no deaths in subsequent heat wave events (Fouillet et al. 2008). Public health measures will substantially reduce vector borne disease risks (World Bank 2010). Most of these public health measures will be put in place simply because vulnerable countries will be wealthier.

V. HOW TO MEASURE THE SOCIAL COST OF CARBON

Q: Drs. Hanemann and Polasky say that you were wrong to calculate the Social Cost of Carbon by trying to measure the cost assuming an "optimal" level of emissions. Can you briefly explain the method by which you measured the SCC?

A: As I explained in my direct testimony, a damages model for determining the externality value of carbon should measure the marginal damage associated with each policy choice. This is a familiar procedure that environmental economists use for all pollutants, not just carbon dioxide:

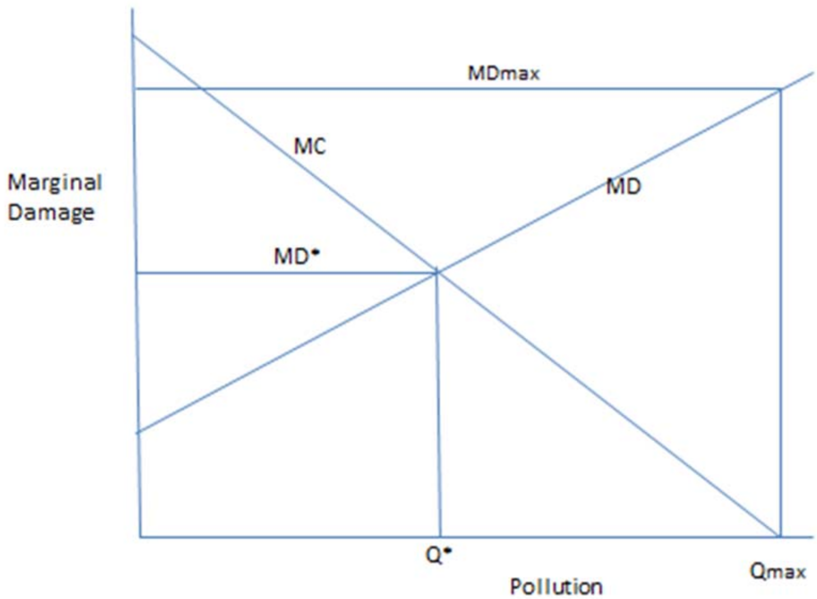
Figure 1: Marginal Damage Function



If there is no mitigation and emissions are at Q_{max}, the marginal damage in Figure 1 would be MD_{max}. This is the damage one would observe if there was no emissions policy. If the policy was Q_1, the correct marginal damage would be MD_1. The marginal damage therefore depends upon the level of mitigation that will be caused by the policy.

A policy is efficient when the planned policy equates marginal cost to the social cost of carbon. The purpose of implementing a social cost of carbon (measurement of marginal damage) is to equate the marginal cost of abatement to the marginal damage. This optimal policy will maximize the net benefits to society. Figure 2 illustrates this point by adding a marginal cost of mitigation function to Figure 1. The optimal policy, MD*, equates marginal cost and marginal damage. The correct place to measure the SCC is at the optimal mitigation level Q*. The SCC at this point is equal to MD*. The purpose of using the SCC in decision making is to get the prices right. If one is interested in having the best effect, one must use the right price.

Figure 2 Optimal SCC where MD*=MC



Q: Why did you use this method?

A: This is the conventional and universally accepted methodology for measuring externality values. If the government intends to use the SCC to determine the appropriate amount of money to spend on mitigation, the government should equate marginal cost to the SCC. The only measure of the SCC that makes sense in this case is MD*.

Q: What method do Drs. Hanemann and Polasky favor?

A: Both Dr. Hanemann and Dr. Polasky support the IWG's decision to measure the SCC at Q_{max}, rather than MD*. They feel that it is reasonable that the IWG measured the SCC assuming that there will never be any future climate mitigation (globally through 2300). They hold this view even though the purpose of the SCC is to encourage mitigation.

Drs. Hanemann and Polasky argue against measuring the SCC at the optimal point that minimizes the present value of the sum of cost and damage. Dr. Polasky recognizes that every environmental economics textbook teaches that the ideal solution to pollution problems minimizes the sum of damage and cost. He understands that this principle offers important guidance to policy makers and in general leads to the choice of MD*. However, Dr. Polasky does not realize that the IWG ignores this maxim by assuming zero mitigation.

Q: What is the effect of the approach taken by the IWG?

A: Instead of taking into account what effect the SCC (carbon price) would have on future mitigation, the IWG assumed it would have no effect. The SCC measurement made by the IWG is accurate only as long as it is never used. The moment that Minnesota or the federal government uses the IWG SCC estimate to enact policy, the IWG SCC value immediately becomes an overestimate of the damage from CO_2 By assuming zero future mitigation, the IWG is exaggerating the damage of carbon emissions. This is a grievous mistake.

Q: Dr. Hanemann rejects the concept of minimizing the present value of the sum of cost and damage because actual policy is not perfect and therefore "optimal" solutions are not "realistic". How do you respond to that?

A: Economics is not intended to mimic public policy, it is intended to guide it. There would be no need for economists (or policy advisors in general) if all they ever did was affirm current policy. Dr. Hanemann is in fact antagonistic to the suggestion that it is desirable to promote optimal policies. He states that "the simplifications embedded in the optimization version of DICE are not innocuous … [they] generate a lower estimate of the social cost of carbon."

(Hanemann Rebuttal44:1-2.) Given that the optimization is in fact a desirable choice, one can turn these words around. The simplification that the IWG uses by assuming no mitigation is not innocuous but is intended to generate a higher estimate of the social cost of carbon.

Q: Dr. Polasky also argues that assuming optimal emissions reduction is unrealistic because it represents a global collective action problem that is difficult to solve. How do you respond to that?

A: Again, economics is not intended to mimic public policy, it is intended to guide it. It is intended to identify the most efficient, optimal policy.

Moreover, Dr. Polasky's concerns would argue for creating a separate Minnesota-specific cost of carbon. Minnesota alone cannot alter the path of climate change. It simply does not emit enough emissions to make a difference all by itself. If Minnesota adopts the SCC values recommended by the IWG, Minnesota is providing a gift to the rest of the world. If Minnesota's share of global damage was equal to its share of global GDP, the state will get only 1% of the benefits of this action but will pay 100% of the cost. In fact, the actual share of benefits is likely to be even smaller because Minnesota is cooler than most of the world. Small amounts of warming are beneficial to farmers and residents of Minnesota. Minnesota is not vulnerable to sea level rise or tropical cyclones that will afflict coastal regions. Vector borne diseases will not reach Minnesota.

VI. THE IWG'S CALCULATION OF THE SCC

Q: Both Dr. Hanemann and Dr. Polasky feel that the choice of DICE, FUND, and PAGE were good choices by the IWG because the models are respected and frequently cited. How do you respond to that?

A: DICE and FUND are frequently cited and do in fact have excellent reputations. They enjoy these reputations because they are internally consistent models that could calculate the optimal solution to climate change. The models made consistent choices about the discount rate, the growth of the economy, and emissions.

But the IWG did not use these models for the purpose for which they were designed. The IWG did not calculate optimal SCC values. The IWG altered the FUND and DICE models by changing the assumptions concerning discounting, emissions, and GDP. The altered models were no longer internally consistent. The SCC values generated by the IWG are not consistent with the published results by the authors of DICE and FUND. The published DICE and FUND SCC estimates are much lower than the IWG estimates. As Dr. Tol mentions in his testimony, the SCC results for FUND in 2014 are just $6.6/ton.

Q: In your opening report you stated that the PAGE model (one of the three IAMs considered by the IWG) is "not well grounded in economic theory." Dr. Polasky argues that the IWG properly considered PAGE? Do you agree?

A: I believe that the PAGE model should never have been included in the calculation of the SCC. Dr. Polasky takes issue with dropping PAGE because having one more model is better than having fewer. However, adding a flawed model to two well-crafted models does not improve the average value of the model forecasts. The version of the PAGE model used by the IWG explicitly does not include adaptation. Failing to include adaptation vastly overstates the damage that climate change will cause.

Q: Did the IWG make other mistakes in calculating the SCC?

A: Climate sensitivity, how much equilibrium temperature changes with a doubling of CO_2, is one of the key uncertainties introduced by the IWG. It is also unknown how quickly actual temperatures will actually adjust to the equilibrium temperature. It could be several decades or a thousand years. The IWG assumed that climate sensitivities varied independently of how quickly transient temperatures adjust to the equilibrium temperature. However, the world now has hundreds of years of evidence revealing the relationship between transient temperatures and greenhouse gas concentrations. If the true climate sensitivity is higher (lower), it must also be true that it takes longer (less time) for temperatures to reach equilibrium levels. Both must be adjusted together to replicate the transient temperatures we have actually observed. It is not clear that the IWG made these adjustments properly in its Monte Carlo experiment.

VII. <u>DISCOUNT RATES</u>

Q: IWG and Dr. Hanemann and Dr. Polasky are of the opinion that constant discount rates of less than 3% are reasonable to use with climate change. How do you respond?

A: Discount rates reflect the value of time. The interest rate is the market value of time. The interest rate and the discount rate do not measure the relative harmfulness of climate change. The damage predicted by climate change measures harm. Why then are advocates for more stringent climate mitigation arguing for a low discount rate? The cost of current mitigation is borne today but the benefits of that mitigation take several decades to begin and they may last centuries. If we use the value of time (the interest rate) from the market place, the value of these far future benefits in today's dollars is worth much less. That is why the economics of climate change suggest mitigation should start modestly and rise over time. The IWG, Dr. Hanemann, and Dr. Polasky are consequently urging adoption of a discount rate below the market interest rate. However, using below-market interest rates effectively increases the overall cost of climate change by forcing every generation to spend too much on mitigation and specifically forcing the current generation to spend more on mitigation than future generations. This is not in the interest of all generations and very much not in the interest of those alive today. As I stated in my direct testimony and report, the discount rate that is internal to DICE changes over time as the economy changes, matching the growth in per capita consumption over time. The model estimates a current discount rate of 5%. The rate of GDP growth is assumed to slow over time, and therefore the DICE model predicts that the discount rate would concomitantly fall over time.

Q: What do other economists think?

A: A top group of economic experts (including Kenneth Arrow, Geoffrey Heal, William Nordhaus, Robert Pindyck, and Martin Weitzman) have argued that the correct way to value intergenerational discounting is to use the Ramsey formula that adjusts the discount rate for the rate at which income (consumption) grows over time (Arrow et al. 2014). If the rate of income growth slows over time, then the discount rate should fall accordingly. The choice of discount rate and the projection of income cannot be treated independently. The IWG violates this principle by choosing a constant rate of discount. Although the IWG assumes that income growth declines over time, they do not use a declining discount rate. Instead they arbitrarily choose a low discount rate. This is not consistent with economic theory.

Q: Dr. Polasky criticizes your use of a declining interest rate. How do you respond?

A: Dr. Polasky criticizes the analysis I have done with the DICE model because I have used a declining discount rate tied to the growth of income over time. What Dr. Polasky appears not to understand is that this is the original DICE model formulation written by Dr. Nordhaus. The IWG modified the DICE model to remove declining discount rates. The IWG did not run the DICE model as it was originally designed.

Q: How do you respond to Dr. Hanemann's criticism of your treatment of interest rates?

A: Dr. Hanemann argues we should use a discount rate for mitigation that is higher than the market rate of interest only if the damage from climate change is correlated with overall market performance. (Hanemann Rebuttal 86:32-34.) He is apparently not aware that this is in fact the case. Higher GDP growth leads to more emissions and higher damage per emission. Climate damage is clearly positively correlated with income. Dr. Hanemann provides a solid argument why the discount rate should be higher than 5% (the current market interest rate).

Q: Drs. Hanemann and Polasky say that your estimates of the SCC are too low because they do not reflect the uncertainties surrounding the climate issue. How do you respond to that?

A: Because greenhouse gases are expected to remain in the atmosphere far into the future, because their effect on temperature is uncertain, because the impact of temperature change on the economy and nonmarket sectors is uncertain, and because it is uncertain how effects will be distributed across the planet, uncertainty haunts the measurement of climate damage.

The fact that the IWG assumed zero mitigation exaggerates the consequence of uncertainty. This assumption implies that no matter how bad climate change turns out to be, society will not react and mitigate. Future mitigation policies will certainly respond to how serious climate change reveals itself to be. If climate damage turns out to be more serious than we currently believe, the obvious policy response is to mitigate more. If damage is less than expected, we will mitigate less. The resulting expected damage across all possible outcomes is much lower. Evaluating uncertainty in an optimal regime causes uncertainty to have a much smaller effect than with a zero mitigation policy.

Q: What about the argument that we have a duty to act to protect future generations from climate change?

A: Dr. Hanemann believes it is a moral issue to use a low discount rate. Otherwise, future generations will be handicapped by our choices. Because the discount rate is the value of time, it is important to use the same value for all decisions. If one believes that the discount rate should be lower, it should be lower for all decisions. Society should invest more in all capital. We should invest more in infrastructure, schools, hospitals, research, and weapons. We should also invest more in private capital. We should have more factories, more malls, more houses, and more cars. The problem with this argument is that we actually have this choice today and reject it. We individually choose the market interest rate in our everyday investment and saving decisions. The capital stock today already reflects a global balancing between current versus future consumption.

The government could choose a lower interest rate but it also rejects this choice. The government could lower interest rates by subsidizing savings. However, the government chooses to tax savings. This increases the interest rate. There is simply no evidence to suggest that either private or social decisions reflect a desire for low discount rates.

Economists are not trained in philosophy. In order to make a "moral" argument, it is necessary to connect the argument to a well-developed philosophical rationale. Dr. Hanemann does not explain why a low discount rate is "morally" preferable. There is an allusion that it is necessary to protect future generations. But we already do that with the market rate of interest. Forcing the current generation to adopt a lower interest rate would imply that it is necessary for us to sacrifice even more for the future. Would each future generation also agree to sacrifice for remaining "future generations"? Why is that desirable if it makes every single generation worse off?

VIII. <u>LEAKAGE</u>

Q: Will there be consequences in surrounding states if Minnesota adopts a higher value for the SCC?

A: As Anne Smith has testified, leakage is likely to be an issue when a single state issues a pollution regulation that is very different from its neighbors. The supply of electricity to Minnesota is closely linked with neighboring states through the Midwest power grid. As Minnesota reduces carbon emissions and eliminates low cost coal plants, utilities in neighboring states have a financial incentive to send their electricity to Minnesota. If Minnesota insists that imported electricity be low carbon, the utilities will send only their low carbon electricity to

Minnesota. To replace this lost electricity, the utilities in neighboring states will then use new high carbon sources for their domestic state market (which is completely legal in their state). The net change in regional emissions will be smaller than the change in emissions in Minnesota.

Q: How do you respond to Dr. Hanemann on this point?

A: Dr. Hanemann feels one should ignore this leakage. (Hanemann Rebuttal 30:26-31:2.) Dr. Polasky recognizes that the SCC estimates of the IWG must be applied only to net carbon emissions. (Polasky Rebuttal 29:8-15.) The IWG also acknowledges that the SCC estimate should only be applied to net emissions in their 2015 response to comments. (Polasky Rebuttal 29:17-30:5.) Given that Minnesota is trying to determine what value to place on the gross (not net) carbon emissions actually made by Minnesota utilities, it is necessary that the IWG estimate be adjusted for leakage. For example, if there is a rate of leakage of 25%, each ton removed in Minnesota will actually lead to only 0.75 tons falling globally. The actual damage avoided would be only 75% of the IWG SCC in this case. This 75% value should be applied to carbon emissions from utilities in Minnesota. It is therefore critical that the size of the leakage be calculated and included in the final calculation. The greater the difference between the price of carbon in Minnesota and the rest of the region, the more leakage one should expect.

IX. <u>CONCLUSION</u>

Q: Have the rebuttal reports you have read affected your conclusion?

A: Based on my analysis of the case before Minnesota and decades of research on climate impacts and adaptation, the original estimate of the damage of a ton of CO_2 made by the PUC of $5/ton remains a reasonable value to place on carbon. It is consistent with values being used by other states and countries implementing carbon regulations. It is sufficiently close to the values used by neighboring states to limit leakage. It is already clear that this price is working and encouraging Minnesota utilities to reduce their carbon emissions as they have done the last several years.

Advocates of more stringent mitigation have argued that the SCC could be much higher than $5/ton. However, the SCC could also be much lower. In advocating for the current SCC value of $5/ton, I have assumed the same climate sensitivity value (3.0 °C) as was used by the Interagency Working Group (IWG) based on earlier reports of the Intergovernmental Panel on Climate Change (IPCC). But recent evidence, as discussed in the testimony of Professors Lindzen, Happer, and Spencer, suggests that the climate sensitivity assumed by the IWG is overstated. As Dr. Roy Spencer notes, the historical observed warming has been much less than climate models predicted. Indeed, even the IPCC's Fifth Assessment reduced the low end of the likely range from 2.0 to 1.5, with high confidence. All of this raises questions about whether the climate sensitivity value of 3.0 used by the IWG is too high. If the climate sensitivity is 1.5 (as Dr. Lindzen and others have suggested and as now lies within the IPCC's assessed likely range of "high confidence"), the SCC lies between $0.30 and $0.80/ton, as shown in Table 2 of my Report. If the climate sensitivity value is 2.0, the SCC lies between $1.10 and $2.00/ton, as shown in Table 2. Given the strong scientific evidence above, a reasonable and the "best available measure" for the SCC is between $0.30 and $2.00/ton.

If Minnesota takes a risk and chooses a much higher value for the SCC, the state will immediately run into problems. 1) Leakage will most certainly occur. Tons removed by Minnesota will be compromised by tons added by other states. 2) Minnesota will impose a large fiscal burden on their residents. 3) Minnesota will set an example that other states and countries cannot afford to follow. Not only will Minnesota be paying more than their share for climate mitigation, but more importantly the effort will be futile. No one else will follow and there will be no measurable effect on climate.

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