Precaution and a Dismal Theorem:

Implications for Climate Policy and Climate Research

Gary W. Yohe[1, 5] and Richard S. J. Tol[2, 3, 4]

[1] Woodhouse/Sysco Professor of Economics, 238 Church St., Wesleyan University, Middletown, CT 06459 USA

[2] Economic and Social Research Institute, Dublin, Ireland

[3] Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands

[4] Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA

[5] Contact author: phone: 860-685-3658; fax: 860-685-2781; e-mail: gyohe@wesleyan.edu

Working Paper FNU-145

Economic efficiency has long been a gold standard for evaluating policies. In the context of climate change, the search for efficient solutions to the policy problem has evolved into using elaborate, regionally disaggregated integrated assessment models to judge the relative expected benefits and costs of various policy options across a wide range of possible futures. In many cases, studies in what is fundamentally a utility-optimising design, use Monte Carlo simulations to set expected marginal benefits equal to expected marginal cost. This is why calculations of the social cost of carbon (SCC) have become so popular.

This approach has, of course, been criticized because many of the potential impacts of climate change (particularly non-market impacts and low-probability but high consequence ramifications of abrupt climate change) cannot easily be quantified in economic terms. This has lead to arguments in favor of taking a precautionary approach to climate policy – defining the boundaries of "tolerable" climate impacts and working from there. In this context, policy designers ask the economists to calculate only the paths that avoid the proscribed boundaries of climate change at minimum expected cost.[1]

---

[1] Because tolerable boundaries are typically defined in terms of temperature limits and because temperature change depends, to a first approximation, on cumulative emissions over long periods of time, the appropriate economic response can be visualized by solving for an initial shadow price for carbon (and other warming gases) with the expectation that it would increase over time at an endogenously determined rate of interest.

Critics of this approach have focused primarily on the arbitrary definition of what is or is not tolerable and the potential for inefficient or inconsistent thresholds.

This debate is now informed by a "Dismal Theorem" offered by Weitzman (2007). It shows that profound uncertainty about fundamental parameters like climate sensitivity (reflected as a "thick upper tail" in their distributions for which the probability only falls with a power of the size of the event) cannot be overcome for any positive rate of risk aversion and any positive rate of pure time preference for any distribution whose moment generating function is infinite (e.g., power-law or lognormal distribitions) and includes the potential for catastrophic climate impacts (here defined as a prolonged period of falling welfare per capita). If so, the impact grows exponentially while the probability falls with a power law and the expected impact becomes unbounded. The theorem is derived from our inability to observe the events in the tails with enough frequency to learn anything useful about relatively likelihoods of associated catastrophic consequences. It follows that uncertainty dominates any calculation of expected climate damage because Bayesian learning about the critical variables (even with very strong time discounting) is never strong enough to keep expected marginal damages finite.

The Dismal Theorem clearly casts doubt on results derived from a cost-benefit approach to climate policy, at least if the equity implications of declining marginal utility are recognized; indeed, it suggests that a warning label be attached to integrated assessment models that rely on the cost-benefit approach – something like "Warning: To be applied only to non-extreme climate change possibilities". The Dismal Theorem marginalizes the debate over the social cost of carbon and the associated discussions about what makes estimates high or low. All of the existing estimates are infinitely too small. It similarly renders the current obsession of the scientific community for reaching consensus on central tendencies of climate change obsolete.[2] The action is in the dismal tails.

On the positive side, the result indicates that the value of some types of information is far greater (and perhaps infinitely greater) than the value of other information, and so it offers some guidance on where to devote scarce research resources in climate and policy science. Moreover, it seems to offer sound theoretic footing for a generalized precautionary approach designed explicitly to examine the definition of tolerable climate change. More careful examination of these implications suggests that another warning label need to be written, but more on that later.

Before proceeding to make that point, it is important to focus on one important condition of the Dismal Theorem – that decision makers view the world with some

---

[2] Evidence of this obsession can be found in the most recent report of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Note, for example, their removal of potential contributions of Greenland Ice Sheet melting and collapse of the West Antarctic Ice Sheet from sea level rise estimates. Even though these contributions were included in the estimates published in the Third Assessment Report, they were deleted in the Fourth because there was no model based scientific consensus of what is going on ([IPCC (2007a)]. In the logic of the Dismal Theorem, this makes the ice sheets more policy relevant, not less.

aversion to risk (and thus some aversion to inequality).[3] We could get around the Dismal Theorem by simply asserting that policy makers should always proceed as if they were completely risk-neutral. Doing so would, however, mean rewriting much of current economic policy; and doing so only in the climate arena would mean that the United Nations Framework Convention on Climate Change would have to be completely overhauled.

It follows that there is no easy way to dismiss the implications of the Dismal Theorem for climate policy and climate science. To explore these implications a little more fully, it is appropriate to contemplate its applicability in a few different cases. Tol (2003), for example, worked within a cost-benefit framework that recognized multiple regions with and without equity weighting. Even without recognizing the consequences of thick tails in the distribution of climate sensitivity, his Monte Carlo simulations noted the (small but non-zero) probability that marginal utility could grow infinitely large in one or more regions where even “routine” climate change, particularly declining precipitation, drove economic activity to subsistence levels. As long as these regions were given non-zero weight in the expected utility calculation, their plight would dominate the policy calculus because expected marginal damages would approach infinity. This was, perhaps, a precursor of the Dismal Theorem.

Yohe (2003) suggested that this problem could be overcome by implementing a second policy instrument designed to maintain economic activity above subsistence levels everywhere – a foreign aid program designed simply to prevent economic collapse anywhere in real time. Tol and Yohe (2007) examined this suggestion within the original modeling framework and found that, with sufficient aid, the issue of infinite marginal damage could be avoided. While this work did not envision events characterized in the fat tails of climate sensitivity, it nonetheless suggests that timely social or economic interventions that effectively “lop off the thick tails” could undercut the Dismal Theorem if the impacts of its profound uncertainty were regional.

If, however, the impacts of the profound uncertainty were felt globally so that no country or region would have the wherewithal to underwrite the subsistence of another, then the Dismal Theorem could still persist. It is here, therefore, that a generalized precautionary principle – the logical implication of the Dismal Theorem - comes into play.

Can the Dismal Theorem inform the boundaries of precaution? To answer this question, it is important to note that policy makers are not confined to Bayesian learning, that is, observe and infer, about the climate sensitivity and other critical parameters in climate models. They could, equally as well, rely on developing scientific understanding of the fundamental processes that could produce catastrophic impacts from whatever climate change happens to materialize. Even if they cannot rely on the scientific community to characterize “true scenarios” about what might happen, they could ask it to

[3] This assumption is captured simply by allowing the marginal utility of consumption to rise indefinitely as consumption falls to a subsistence level (and to fall as consumption rises beyond the range currently experienced by developed economies).

(1) explore the triggers of global catastrophe, (2) identify the parameters of fundamental change that define those triggers, (3) contribute to the design of monitoring mechanisms that can track the pace of change relative to the triggers, and (4) conduct small- and large-scale experiments in models, laboratories and perhaps the real world to learn more about the relevant processes. Assuming that their rate of change could be calibrated to something like the pace of change in global mean temperature, it would then be possible to calibrate the likelihood of setting off an "intolerable" trigger by holding warming below particular targets.

Three possibilities emerge. In the first, setting off a trigger is reversible, and avoidable if perhaps draconian intervention into the economic sectors were forthcoming. Given the great momentum of the climate system, though, the catastrophe would have to be coped with for a certain period. The precautionary principle would tell us to hedge against both the cost of such draconian intervention and the transient costs of "temporary" catastrophe by initiating more modest intervention well in advance of setting off the trigger. In the second case, the catastrophe is irreversible. Here, the precautionary principle tells us to hedge more strongly against "falling off the cliff" – presumably a hedging strategy that would impose more stringent emissions reductions much earlier than otherwise contemplated. In this case, calls for geoengineering a solution are likely. In the third case, the catastrophe is irreversible and unavoidable – and we should enjoy the good times while they last.

To put this into a "not-implausible" context, consider the collapse of the Atlantic thermohaline circulation (the THC) as an example of a potentially catastrophic event on a global scale. The higher the climate sensitivity, the more likely it becomes and the sooner it might occur. The implications of such a collapse are unknown, particularly in the socio-economic context, but the planet has experienced another climate equilibrium in which it does not exist. Three different explanations of the process by which it might collapse [Keller, et al, forthcoming] have been advanced, but each would point to its own critical parameter for monitoring. Because we do not know the precise process, we do not know the triggering threshold, particularly when calibrated in terms of an increase in global mean temperature. We do know that the THC can collapse in a matter of decades once the trigger is pulled and that reversal, if possible, would take as long as a century to achieve [Schlesinger, et al. (2005) and Yin, et al. (2006)].

Integrated assessment models cannot accommodate any of these profound uncertainties, particularly in the context of a thick tail in the distribution of climate sensitivity. They could, though, investigate the least cost approach to any hedging strategy designed to restrict the likelihood of collapse below any particular limit that the policy community were to chose, but *only if* the scientific community could clarify (1) the triggering mechanism, (2) estimate the lag time between that trigger and a climatological commitment to crossing the threshold, (3) devise mechanisms for monitoring circulation intensity with enough precision to inform the likelihood of commitment, and (4) allow statisticians to calculate probabilities of type 1 and type 2 errors along a range of transient futures based on those monitoring exercises – the same information required to identify the boundaries of tolerable risk. None of these tasks involves Bayesian learning about climate sensitivity, and that is reassuring. None of it is simple either, of course; but faced with an impossibility theorem, tackling a difficult problem is the lesser of two evils.

It should now be clear why the scientific community must move beyond trying to nail down consensus about the central baseline tendencies of climate change and embrace (though not exclusively) an organized effort designed to examine the "dark tails" of our possible futures. Only then can we begin to define the boundaries of tolerable change on the basis of rigorous analyses of decision-making criteria that accounts, explicitly, for the profound uncertainty that characterizes our understanding of the climate system.

What about the social cost of carbon? Cast in the context of an informed and rigorously defined precautionary approach to policy design, the social cost of carbon is the marginal cost of mitigation at any point in time – the shadow price of the precautionary temperature constraint that would just avoid the catastrophe from happening, and thus approximately the scarcity rent that minimizes the expected cost of meeting the target. This is not necessarily an easy calculation, but there is some good news. Climate sensitivity would not be an issue because the social cost of carbon would be tied to the marginal cost of meeting a concentration target (though climate sensitivity would be involved in the discussions that identify the target). The discount rate would not be an issue because the rate applied to other public investments and not the one that ponders the ethical complications of intergenerational equity now applies. Indeed, this calculation would exclude some of the sources of uncertainty that explain the enormous range of social cost of carbon estimates [Chapter 20, IPCC (2007b)]. However, issues like valuation and equity weighting do not go away, as they are essential ingredients to the definition of what constitutes a catastrophe.

We hope to have shed some preliminary light on the "So what?" implications of the Dismal Theorem on the design of climate policy and climate research. We now turn to the warning label that we promised. The Dismal Theorem is derived from taking limits, so it is tempting to take its conclusion to its logical extremes. One might, for example, read the Dismal Theorem as saying that the value of some improved information about what might be going on in the thick tail of the climate sensitivity distribution is infinite. If that is so, then we need to do as much as we can to sharpen the climate signal by, for example, burning as much coal as quickly as we can. One might also apply the generalized precautionary principle to all social issues for which there are unfortunate consequences in the fat tails of the distributions of critical variables because expected marginal damages are infinite for all of them. But then, how should we set priorities for distributing the planet's finite resources in the social interest? The economic tradeoffs would simply be undefined. Thus, we offer a concluding warning label on the Dismal Theorem: "Warning: Not to be taken to its logical extreme in application to real world problems."

{2168 words}

Acknowledgements

The authors gratefully acknowledge the contributions of Martin Weitzman in the preparation of this paper, as well as the comments offered by participants in the Climate Change Impacts workshop in Snowmass, Colorado in the summer of 2007. All remaining errors reside with the authors.

References

Intergovernmental Panel on Climate Change (IPCC) (2007a), *Climate Change 2007: The Science. Contribution of Working Group I to the Fourth Assessment Report*, Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate Change (IPCC) (2007b), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report,* Cambridge University Press, Cambridge, UK.

Keller, K., Yohe, G.W., and Schlesinger, M.E., and Yohe, G.W., (forthcoming), "Managing the Risk of Climate Thresholds: Uncertainties and Information Needs", *Climatic Change.*

Schlesinger, M. E. et al., "Assessing the Risk of Collapse of the Atlantic Thermohaline Circulation" in *Avoiding Dangerous Climate Change: A Scientific Symposium on Stabilisation of Greenhouse Gases* (eds. Schellnhuber, J., Cramer, W., Nakicenovic, N., Wigley, T. & Yohe, G.) Cambridge University Press, U. K. Meteorological Office, Exeter, U.K., 2005, 37-47.

Tol, R. S. J. (2003), "Is the uncertainty about climate change too large for expected cost-benefit analysis?", *Climatic Change*, **56**, 265-289.

Tol, R. S. J. and G. W. Yohe (2007), "Infinite Uncertainty, Forgotten Feedbacks, and Cost-Benefit Analysis of Climate Change", *Climatic Change*, **83**, 429-442.

Weitzman, M.L. (2007), "The Role of Uncertainty in the Economics of Catastrophic Climate Change", manuscript.

Yin, J., Schlesinger, M.E., Andronova, N.G., Malyshev, S., and Li, B. (2006), Is a Shutdown of the Thermohaline Circulation Irreversible?", *Journal of Geophysical Research*

Yohe, G. W. (2003), "More trouble for cost-benefit analysis", *Climatic Change*, **56**, 235-244.

Working Papers

Research Unit Sustainability and Global Change

Hamburg University and Centre for Marine and Atmospheric Science

Yohe, G.W. and R.S.J. Tol (2007), *Precaution and a Dismal Theorem: Implications for Climate Policy and Climate Research*, **FNU-145** (submitted)

Tol, R.S.J. (2007), *The Social Cost of Carbon: Trends, Outliers and Catastrophes*, **FNU-144** (submitted)

Tol, R.S.J. (2007), *The Matthew Effect Defined and Tested for the 100 Most Prolific Economists*, **FNU-143** (submitted)

Berrittella, M., K. Rehdanz, R.S.J. Tol and J. Zhang (2007), *The Impact of Trade Liberalisation on Water Use: A Computable General Equilibrium Analysis*, **FNU-142** (submitted)

Lyons, S., K. Mayor and R.S.J. Tol (2007), *Convergence of Consumption Patterns during Macroeconomic Transition: A Model of Demand in Ireland and the OECD*, **FNU-141** (submitted)

Osmani, D. and R.S.J. Tol (2007), *Towards Farsightedly Stable International Environmental Agreements*, **FNU-140** (submitted)

Rehdanz, K. and S. Stöwhase (2007), *Cost Liability and Residential Space Heating Expenditures of Welfare Recipients in Germany*, **FNU-139** (submitted)

Schleupner, C. and P.M. Link (2007), *Potential impacts on bird habitats in Eiderstedt (Schleswig-Holstein) caused by agricultural land use changes*, **FNU-138** (submitted)

Link, P.M. and C. Schleupner (2007), *Agricultural land use changes in Eiderstedt: historic developments and future plans*, **FNU-137** (submitted)

Anthoff, D., R.J. Nicholls and R.S.J. Tol (2007), *Global Sea Level Rise and Equity Weighting*, **FNU-136** (submitted)

Schleupner, C. (2007), *Wetland Distribution Modelling for Optimal Land Use Options in Europe*, **FNU-135** (submitted)

Mayor, K. and R.S.J. Tol (2007), *The Impact of the EU-US Open Skies Agreement on International Travel and Carbon Dioxide Emissions*, **FNU-134** (forthcoming, *Journal of Air Transport Management*)

Schneider, U.A., M. Obersteiner, and E. Schmid (2007), *Agricultural adaptation to climate policies and technical change*, **FNU-133** (submitted)

Lychnaras, V. and U.A. Schneider (2007), *Dynamic Economic Analysis of Perennial Energy Crops - Effects of the CAP Reform on Biomass Supply in Greece*, **FNU-132** (submitted)

Mayor, K. and R.S.J. Tol (2007), The Impact of the UK Aviation Tax on Carbon Dioxide Emissions and Visitor Numbers, **FNU-131** (forthcoming, *Transport Policy*)

Ruane, F. and R.S.J. Tol (2007), *Refined (Successive) h-indices: An Application to Economics in the Republic of Ireland*, **FNU-130** (forthcoming, *Scientometrics*)

Yohe, G.W., R.S.J. Tol and D. Murphy (2007), *On Setting Near-Term Climate Policy as the Dust Begins the Settle: The Legacy of the Stern Review*, **FNU-129** (*Energy & Environment*, **18** (5), 621-633)

Maddison, D.J. and K. Rehdanz (2007), *Happiness over Space and Time*, **FNU-128** (submitted).

Anthoff, D. and R.S.J. Tol (2007), *On International Equity Weights and National Decision Making on Climate Change*, **FNU-127** (submitted).

de Bruin, K.C., R.B. Dellink and R.S.J. Tol (2007), *AD-DICE: An Implementation of Adaptation in the DICE Model*, **FNU-126** (submitted).

Tol, R.S.J. and G.W. Yohe (2007), *The Stern Review: A Deconstruction*, **FNU-125** (submitted).

Keller, K., L.I. Miltich, A. Robinson and R.S.J. Tol (2007), *How Overconfident Are Current Projections of Anthropogenic Carbon Dioxide Emissions?*, **FNU-124** (submitted, *Energy Journal*).

Cowie, A., U.A. Schneider and L. Montanarella (2006), *Potential synergies between existing multilateral environmental agreements in the implementation of Land Use, Land Use Change and Forestry activities*, **FNU-123** (submitted)

Kuik, O.J., B. Buchner, M. Catenacci, A. Goria, E. Karakaya and R.S.J. Tol (2006), *Methodological Aspects of Recent Climate Change Damage Cost Studies*, **FNU-122** (submitted, *Climate Policy*)

Anthoff, D., C. Hepburn and R.S.J. Tol (2006), *Equity Weighting and the Marginal Damage Costs of Climate Change*, **FNU-121** (submitted)

Tol, R.S.J. (2006), *The Impact of a Carbon Tax on International Tourism*, **FNU-120** (*Transportation Research D: Transport and the Environment*, **12** (2), 129-142).

Rehdanz, K. and D.J. Maddison (2006), *Local Environmental Quality and Life Satisfaction in Germany*, **FNU-119** (forthcoming, *Ecological Economics*)

Tanaka, K., R.S.J. Tol, D. Rokityanskiy, B.C. O'Neill and M. Obersteiner (2006), *Evaluating Global Warming Potentials as Historical Temperature Proxies: An Application of ACC2 Inverse Calculation*, **FNU-118** (submitted, *Climatic Change*)

Berrittella, M., K. Rehdanz and R.S.J. Tol (2006), *The Economic Impact of the South-North Water Transfer Project in China: A Computable General Equilibrium Analysis*, **FNU-117** (submitted)

Tol, R.S.J. (2006), *Why Worry about Climate Change? A Research Agenda*, **FNU-116** (submitted)

Hamilton, J.M. and R.S.J. Tol (2006), *The Impact of Climate Change on Tourism in Germany, the UK and Ireland: A Simulation Study*, **FNU-115** (*Regional Environmental Change*, **7** (3), 161-172)

Schwoon, M., F. Alkemade, K. Frenken and M.P. Hekkert (2006), *Flexible transition strategies towards future well-to-wheel chains: an evolutionary modelling approach*, **FNU-114** (submitted).

Ronneberger, K., L. Criscuolo, W. Knorr and R.S.J. Tol (2006), *KLUM@LPJ: Integrating dynamic land-use decisions into a dynamic global vegetation and crop growth model to assess the impacts of a changing climate. A feasibility study for Europe*, **FNU-113** (submitted)

Schwoon, M. (2006), *Learning-by-doing, Learning Spillovers and the Diffusion of Fuel Cell Vehicles*, **FNU-112** (submitted).

Strzepek, K.M., G.W. Yohe, R.S.J. Tol and M. Rosegrant (2006), *The Value of the High Aswan Dam to the Egyptian Economy*, **FNU-111** (submitted, *Ecological Economics*).

Schwoon, M. (2006), *A Tool to Optimize the Initial Distribution of Hydrogen Filling Stations*, **FNU-110** (*Transportation Research D: Transport and the Environment*, **12** (2), 70-82).

Tol, R.S.J., K.L. Ebi and G.W. Yohe (2006), *Infectious Disease, Development, and Climate Change: A Scenario Analysis*, **FNU-109** (forthcoming, *Environment and Development Economics*).

Lau, M.A. (2006), *An analysis of the travel motivation of tourists from the People's Republic of China*, **FNU-108** (submitted).

Lau, M.A. and R.S.J. Tol (2006), *The Chinese are coming – An analysis of the preferences of Chinese holiday makers at home and abroad*, **FNU-107** (submitted, *Tourism Management*).

Röckmann, C., R.S.J. Tol, U.A. Schneider, and M.A. St.John (2006), *Rebuilding the Eastern Baltic cod stock under environmental change - Part II: The economic viability of a marine protected area.* **FNU-106** (submitted)

Ronneberger, K., M. Berrittella, F. Bosello and R.S.J. Tol (2006), *KLUM@GTAP: Introducing biophysical aspects of land-use decisions into a general equilibrium model. A coupling experiment*, **FNU-105** (submitted).

Link, P.M. and Tol, R.S.J. (2006), *Economic impacts on key Barents Sea fisheries arising from changes in the strength of the Atlantic thermohaline circulation*, **FNU-104** (submitted).

Link, P.M. and Tol, R.S.J. (2006), *The Economic Impact of a Shutdown of the Thermohaline Circulation: An Application of FUND*, **FNU-103** (submitted, *Climatic Change*).

Tol, R.S.J. (2006), *Integrated Assessment Modelling*, **FNU-102** (submitted).

Tol, R.S.J. (2006), *Carbon Dioxide Emission Scenarios for the USA*, **FNU-101** (forthcoming, *Energy Policy*).

Tol, R.S.J., S.W. Pacala and R.H. Socolow (2006), *Understanding Long-Term Energy Use and Carbon Dioxide Emissions in the USA*, **FNU-100** (submitted).

Sesabo, J.K, H. Lang and R.S.J. Tol (2006), *Perceived Attitude and Marine Protected Areas (MPAs) establishment: Why households' characteristics matters in Coastal resources conservation initiatives in Tanzania*, **FNU-99** (submitted).

Tol, R.S.J. (2006), *The Polluter Pays Principle and Cost-Benefit Analysis of Climate Change: An Application of* FUND, **FNU-98** (submitted)

Tol, R.S.J. and G.W. Yohe (2006), *The Weakest Link Hypothesis for Adaptive Capacity: An Empirical Test*, **FNU-97** (*Global Environmental Change*, **17**, 218-227)

Berrittella, M., K. Rehdanz, R.Roson and R.S.J. Tol (2005), *The Economic Impact of Water Pricing: A Computable General Equilibrium Analysis*, **FNU-96** (submitted, *Water Policy*)

Sesabo, J.K. and R. S. J. Tol (2005), *Technical Efficiency and Small-scale Fishing Households in Tanzanian coastal Villages: An Empirical Analysis*, **FNU-95** (submitted)

Lau, M.A. (2005), *Adaptation to Sea-level Rise in the People's Republic of China – Assessing the Institutional Dimension of Alternative Organisational Frameworks*, **FNU-94** (submitted)

Berrittella, M., A.Y. Hoekstra, K. Rehdanz, R. Roson and R.S.J. Tol (2005), *The Economic Impact of Restricted Water Supply: A Computable General Equilibrium Analysis*, **FNU-93** (*Water Research*, **42**, 1799-1813)

Tol, R.S.J. (2005), *Europe's Long Term Climate Target: A Critical Evaluation*, **FNU-92** (*Energy Policy*, **35** (1), 424-434)

Hamilton, J.M. (2005), *Coastal Landscape and the Hedonic Price of Accommodation*, **FNU-91** (Ecological Economics, **62** (3-4), 594-602)

Hamilton, J.M., D.J. Maddison and R.S.J. Tol (2005), *Climate Preferences and Destination Choice: A Segmentation Approach*, **FNU-90** (submitted)

Zhou, Y. and R.S.J. Tol (2005), *Valuing the Health Impacts from Particulate Air Pollution in Tianjin*, **FNU-89** (submitted)

Röckmann, C. (2005), *International Cooperation for Sustainable Fisheries in the Baltic Sea*, **FNU-88** (forthcoming, in Ehlers,P./Lagoni,R. (Eds.): *International Maritime Organisations and their Contribution towards a Sustainable Marine Development*.)

Ceronsky, M., D. Anthoff, C. Hepburn and R.S.J. Tol (2005), *Checking the price tag on catastrophe: The social cost of carbon under non-linear climate response* **FNU-87** (submitted, *Climatic Change*)

Zandersen, M. and R.S.J. Tol (2005), *A Meta-analysis of Forest Recreation Values in Europe*, **FNU-86** (submitted)

Heinzow, T., R.S.J. Tol and B. Brümmer (2005), Offshore-Windstromerzeugung in der Nordsee -eine ökonomische und ökologische Sackgasse? **FNU-85** (*Energiewirtschaftliche Tagesfragen*, **56** (3), 68-73)

Röckmann, C., U.A. Schneider, M.A. St.John, and R.S.J. Tol (2005), *Rebuilding the Eastern Baltic cod stock under environmental change - a preliminary approach using stock, environmental, and management constraints*, **FNU-84** (*Natural Resources Modelling*, **20** (2), 223-262)

Tol, R.S.J. and G.W. Yohe (2005), *Infinite uncertainty, forgotten feedbacks, and cost-benefit analysis of climate policy,* **FNU-83** (*Climatic Change,* **83**, 429-442)

Osmani, D. and R.S.J. Tol (2005), *The case of two self-enforcing international agreements for environmental protection*, **FNU-82** (submitted)

Schneider, U.A. and B.A. McCarl, (2005), *Appraising Agricultural Greenhouse Gas Mitigation Potentials: Effects of Alternative Assumptions*, **FNU-81** (submitted)

Zandersen, M., M. Termansen, and F.S. Jensen, (2005), *Valuing new forest sites over time: the case of afforestation and recreation in Denmark,* **FNU-80** (submitted)

Guillerminet, M.-L. and R.S.J. Tol (2005), *Decision making under catastrophic risk and learning: the case of the possible collapse of the West Antarctic Ice Sheet*, **FNU-79** (submitted, *Climatic Change*)

Nicholls, R.J., R.S.J. Tol and A.T. Vafeidis (2005), *Global estimates of the impact of a collapse of the West Antarctic Ice Sheet: An application of FUND,* **FNU-78** (submitted, *Climatic Change*)

Lonsdale, K., T.E. Downing, R.J. Nicholls, D. Parker, A.T. Vafeidis, R. Dawson and J.W. Hall (2005), *Plausible responses to the threat of rapid sea-level rise for the Thames Estuary,* **FNU-77** (submitted, *Climatic Change*)

Poumadère, M., C. Mays, G. Pfeifle with A.T. Vafeidis (2005), *Worst Case Scenario and Stakeholder Group Decision: A 5-6 Meter Sea Level Rise in the Rhone Delta, France,* **FNU-76** (submitted, *Climatic Change*)

Olsthoorn, A.A., P.E. van der Werff, L.M. Bouwer and D. Huitema (2005), *Neo-Atlantis: Dutch Responses to Five Meter Sea Level Rise,* **FNU-75** (submitted, *Climatic Change*)

Toth, F.L. and E. Hizsnyik (2005), *Managing the inconceivable: Participatory assessments of impacts and responses to extreme climate change*, **FNU-74** (submitted, *Climatic Change*)

Kasperson, R.E. M.T. Bohn and R. Goble (2005), *Assessing the risks of a future rapid large sea level rise: A review,* **FNU-73** (submitted, *Climatic Change*)

Schleupner, C. (2005), *Evaluation of coastal squeeze and beach reduction and its consequences for the Caribbean island Martinique,* **FNU-72** (submitted)

Schleupner, C. (2005), *Spatial Analysis As Tool for Sensitivity Assessment of Sea Level Rise Impacts on Martinique,* **FNU-71** (submitted)

Sesabo, J.K. and R.S.J. Tol (2005), *Factors affecting Income Strategies among households in Tanzanian Coastal Villages: Implication for Development-Conservation Initiatives,* **FNU-70** (submitted)

Fisher, B.S., G. Jakeman, H.M. Pant, M. Schwoon. and R.S.J. Tol (2005), *CHIMP: A Simple Population Model for Use in Integrated Assessment of Global Environmental Change*, **FNU-69** (*Integrated Assessment Journal*, **6** (3), 1-33)

Rehdanz, K. and R.S.J. Tol (2005), *A No Cap But Trade Proposal for Greenhouse Gas Emission Reduction Targets for Brazil, China and India*, **FNU-68** (submitted, *Climate Policy*)

Zhou, Y. and R.S.J. Tol (2005), *Water Use in China's Domestic, Industrial and Agricultural Sectors: An Empirical Analysis*, **FNU-67** (*Water Science and Technoloy: Water Supply*, **5** (6), 85-93)

Rehdanz, K. (2005), *Determinants of Residential Space Heating Expenditures in Germany*, **FNU-66** (*Energy Economics **29***)

Ronneberger, K., R.S.J. Tol and U.A. Schneider (2005), *KLUM: A Simple Model of Global Agricultural Land Use as a Coupling Tool of Economy and Vegetation,* **FNU-65** (submitted, *Climatic Change*)

Tol, R.S.J. (2005), *The Benefits of Greenhouse Gas Emission Reduction: An Application of* FUND, **FNU-64** (submitted, *Global Environmental Change*)

Röckmann, C., M.A. St.John, U.A. Schneider, F.W. Köster, F.W. and R.S.J. Tol (2006), *Testing the implications of a permanent or seasonal marine reserve on the population dynamics of Eastern Baltic cod under varying environmental conditions,* **FNU-63-revised** (*Fisheries Research,* **85**, 1-13)

Letsoalo, A., J. Blignaut, T. de Wet, M. de Wit, S. Hess, R.S.J. Tol and J. van Heerden (2005), *Triple Dividends of Water Consumption Charges in South Africa*, **FNU-62** (*Water Resources Research*, **43**, W05412)

Zandersen, M., Termansen, M., Jensen,F.S. (2005), *Benefit Transfer over Time of Ecosystem Values: the Case of Forest Recreation,* **FNU-61** (submitted)

Rehdanz, K., Jung, M., Tol, R.S.J. and Wetzel, P. (2005), *Ocean Carbon Sinks and International Climate Policy*, **FNU-60** (*Energy Policy*, **34**, 3516-3526)

Schwoon, M. (2005), *Simulating the Adoption of Fuel Cell Vehicles*, **FNU-59** (submitted)

Bigano, A., J.M. Hamilton and R.S.J. Tol (2005), *The Impact of Climate Change on Domestic and International Tourism: A Simulation Study*, **FNU-58** (submitted, *Integrated Assessment Journal*)

Bosello, F., R. Roson and R.S.J. Tol (2004), *Economy-wide estimates of the implications of climate change: Human health*, **FNU-57** (*Ecological Economics,* **58**, 579-591)

Hamilton, J.M. and M.A. Lau (2004) *The role of climate information in tourist destination choice decision-making*, **FNU-56** (forthcoming, Gössling, S. and C.M. Hall (eds.), Tourism and Global Environmental Change. London: Routledge)

Bigano, A., J.M. Hamilton and R.S.J. Tol (2004), *The impact of climate on holiday destination choice*, **FNU-55** (*Climatic Change*, **76** (3-4), 389-406)

Bigano, A., J.M. Hamilton, M. Lau, R.S.J. Tol and Y. Zhou (2004), *A global database of domestic and international tourist numbers at national and subnational level*, **FNU-54** (*International Journal of Tourism Research*, **9**, 147-174)

Susandi, A. and R.S.J. Tol (2004), *Impact of international emission reduction on energy and forestry sector of Indonesia*, **FNU-53** (submitted)

Hamilton, J.M. and R.S.J. Tol (2004), *The Impact of Climate Change on Tourism and Recreation*, **FNU-52** (forthcoming, Schlesinger et al. (eds.), Cambridge University Press)

Schneider, U.A. (2004), *Land Use Decision Modelling with Soil Status Dependent Emission Rates*, **FNU-51** (submitted)

Link, P.M., U.A. Schneider and R.S.J. Tol (2004), *Economic impacts of changes in fish population dynamics: the role of the fishermen's harvesting strategies*, **FNU-50** (submitted)

Berritella, M., A. Bigano, R. Roson and R.S.J. Tol (2004), *A General Equilibrium Analysis of Climate Change Impacts on Tourism*, **FNU-49** (*Tourism Management*, **27** (5), 913-924)

Tol, R.S.J. (2004), *The Double Trade-Off between Adaptation and Mitigation for Sea Level Rise: An Application of* FUND, **FNU-48** (*Mitigation and Adaptation Strategies for Global Change*, **12** (5), 741-753)

Erdil, E. and Yetkiner, I.H. (2004), *A Panel Data Approach for Income-Health Causality*, **FNU-47**

Tol, R.S.J. (2004), *Multi-Gas Emission Reduction for Climate Change Policy: An Application of* FUND, **FNU-46** (*Energy Journal* (Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue), 235-250)

Tol, R.S.J. (2004), *Exchange Rates and Climate Change: An Application of* FUND, **FNU-45** (*Climatic Change*, **75**, 59-80)

Gaitan, B., Tol, R.S.J, and Yetkiner, I. Hakan (2004), *The Hotelling's Rule Revisited in a Dynamic General Equilibrium Model*, **FNU-44** (submitted)

Rehdanz, K. and Tol, R.S.J (2004), *On Multi-Period Allocation of Tradable Emission Permits*, **FNU-43** (submitted)

Link, P.M. and Tol, R.S.J. (2004), *Possible Economic Impacts of a Shutdown of the Thermohaline Circulation: An Application of* FUND, **FNU-42** (*Portuguese Economic Journal*, **3**, 99-114)

Zhou, Y. and Tol, R.S.J. (2004), *Evaluating the costs of desalination and water transport*, **FNU-41** (*Water Resources Research*, **41** (3), W03003)

Lau, M. (2004), *Küstenzonenmanagement in der Volksrepublik China und Anpassungsstrategien an den Meeresspiegelanstieg*,**FNU-40** (*Coastline Reports* (1), 213-224.)

Rehdanz, K. and D.J. Maddison (2004), *The Amenity Value of Climate to German Households*, **FNU-39** (submitted)

Bosello, F., Lazzarin, M., Roson, R. and Tol, R.S.J. (2004), *Economy-wide Estimates of the Implications of Climate Change: Sea Level Rise*, **FNU-38** (*Environmental and Resource Economics*, **37**, 549-571)

Schwoon, M. and Tol, R.S.J. (2004), *Optimal CO_2-abatement with socio-economic inertia and induced technological change*, **FNU-37** (*Energy Journal*, **27** (4), 25-60)

Hamilton, J.M., Maddison, D.J. and Tol, R.S.J. (2004), *The Effects of Climate Change on International Tourism*, **FNU-36** (*Climate Research*, **29**, 255-268)

Hansen, O. and R.S.J. Tol (2003), *A Refined Inglehart Index of Materialism and Postmaterialism*, **FNU-35** (submitted)

Heinzow, T. and R.S.J. Tol (2003), *Prediction of Crop Yields across four Climate Zones in Germany: An Artificial Neural Network Approach*, **FNU-34** (submitted, *Climate Research*)

Tol, R.S.J. (2003), *Adaptation and Mitigation: Trade-offs in Substance and Methods*, **FNU-33** (*Environmental Science and Policy*, **8** (6), 572-578)

Tol, R.S.J. and T. Heinzow (2003), *Estimates of the External and Sustainability Costs of Climate Change*, **FNU-32** (submitted)

Hamilton, J.M., Maddison, D.J. and Tol, R.S.J. (2003), *Climate change and international tourism: a simulation study*, **FNU-31** (*Global Environmental Change*, **15** (3), 253-266)

Link, P.M. and R.S.J. Tol (2003), *Economic impacts of changes in population dynamics of fish on the fisheries in the Barents Sea*, **FNU-30** (*ICES Journal of Marine Science*, **63** (4), 611-625)

Link, P.M. (2003), *Auswirkungen populationsdynamischer Veränderungen in Fischbeständen auf die Fischereiwirtschaft in der Barentssee*, **FNU-29** (*Essener Geographische Arbeiten*, **35**, 179-202)

Lau, M. (2003), *Coastal Zone Management in the People's Republic of China – An Assessment of Structural Impacts on Decision-making Processes*, **FNU-28** (*Ocean & Coastal Management*, No. 48 (2005), pp. 115-159.)

Lau, M. (2003), *Coastal Zone Management in the People's Republic of China – A Unique Approach?*, **FNU-27** (*China Environment Series*, Issue 6, pp. 120-124; http://www.wilsoncenter.org/topics/pubs/7-commentaries.pdf)

Roson, R. and R.S.J. Tol (2003), *An Integrated Assessment Model of Economy-Energy-Climate – The Model Wiagem: A Comment*, **FNU-26** (*Integrated Assessment*, **6** (1), 75-82)

Yetkiner, I.H. (2003), *Is There An Indispensable Role For Government During Recovery From An Earthquake? A Theoretical Elaboration*, **FNU-25**

Yetkiner, I.H. (2003), *A Short Note On The Solution Procedure Of Barro And Sala-i-Martin for Restoring Constancy Conditions*, **FNU-24**

Schneider, U.A. and B.A. McCarl (2003), *Measuring Abatement Potentials When Multiple Change is Present: The Case of Greenhouse Gas Mitigation in U.S. Agriculture and Forestry*, **FNU-23** (submitted)

Zhou, Y. and Tol, R.S.J. (2003), *The Implications of Desalination to Water Resources in China - an Economic Perspective*, **FNU-22** (*Desalination*, **163** (4), 225-240)

Yetkiner, I.H., de Vaal, A., and van Zon, A. (2003), *The Cyclical Advancement of Drastic Technologies*, **FNU-21**

Rehdanz, K. and Maddison, D. (2003) *Climate and Happiness*, **FNU-20** (*Ecological Economics*, **52** 111-125)

Tol, R.S.J., (2003), *The Marginal Costs of Carbon Dioxide Emissions: An Assessment of the Uncertainties*, **FNU-19** (*Energy Policy,* **33** (16), 2064-2074).

Lee, H.C., B.A. McCarl, U.A. Schneider, and C.C. Chen (2003), *Leakage and Comparative Advantage Implications of Agricultural Participation in Greenhouse Gas Emission Mitigation*, **FNU-18** (submitted).

Schneider, U.A. and B.A. McCarl (2003), *Implications of a Carbon Based Energy Tax for U.S. Agriculture*, **FNU-17** (submitted).

Tol, R.S.J. (2002), *Climate, Development, and Malaria: An Application of* FUND, **FNU-16** (forthcoming, *Climatic Change*).

Hamilton, J.M. (2003), *Climate and the Destination Choice of German Tourists*, **FNU-15** (revised and submitted).

Tol, R.S.J. (2002), *Technology Protocols for Climate Change: An Application of* FUND, **FNU-14** (*Climate Policy*, **4**, 269-287).

Rehdanz, K (2002), *Hedonic Pricing of Climate Change Impacts to Households in Great Britain*, **FNU-13** (*Climatic Change* **74**).

Tol, R.S.J. (2002), *Emission Abatement Versus Development As Strategies To Reduce Vulnerability To Climate Change: An Application Of* FUND, **FNU-12** (*Environment and Development Economics*, **10**, 615-629).

Rehdanz, K. and Tol, R.S.J. (2002), *On National and International Trade in Greenhouse Gas Emission Permits*, **FNU-11** (*Ecological Economics*, **54**, 397-416).

Fankhauser, S. and Tol, R.S.J. (2001), *On Climate Change and Growth*, **FNU-10** (*Resource and Energy Economics*, **27**, 1-17).

Tol, R.S.J.and Verheyen, R. (2001), *Liability and Compensation for Climate Change Damages – A Legal and Economic Assessment*, **FNU-9** (*Energy Policy*, **32** (9), 1109-1130).

Yohe, G. and R.S.J. Tol (2001), *Indicators for Social and Economic Coping Capacity – Moving Toward a Working Definition of Adaptive Capacity*, **FNU-8** (*Global Environmental Change*, **12** (1), 25-40).

Kemfert, C., W. Lise and R.S.J. Tol (2001), *Games of Climate Change with International Trade*, **FNU-7** (*Environmental and Resource Economics*, **28**, 209-232).

Tol, R.S.J., W. Lise, B. Morel and B.C.C. van der Zwaan (2001), *Technology Development and Diffusion and Incentives to Abate Greenhouse Gas Emissions*, **FNU-6** (submitted).

Kemfert, C. and R.S.J. Tol (2001), *Equity, International Trade and Climate Policy*, **FNU-5** (*International Environmental Agreements*, **2**, 23-48).

Tol, R.S.J., Downing T.E., Fankhauser S., Richels R.G. and Smith J.B. (2001), *Progress in Estimating the Marginal Costs of Greenhouse Gas Emissions*, **FNU-4**. (*Pollution Atmosphérique – Numéro Spécial: Combien Vaut l'Air Propre?*, 155-179).

Tol, R.S.J. (2000), *How Large is the Uncertainty about Climate Change?*, **FNU-3** (*Climatic Change*, **56** (3), 265-289).

Tol, R.S.J., S. Fankhauser, R.G. Richels and J.B. Smith (2000), *How Much Damage Will Climate Change Do? Recent Estimates*, **FNU-2** (*World Economics,* **1** (4), 179-206)

Lise, W. and R.S.J. Tol (2000), *Impact of Climate on Tourism Demand*, **FNU-1** (*Climatic Change*, **55** (4), 429-449).