Center for Climate Change and
Environmental Forecasting
U.S. Department Of Transportation

Climate Tipping Points:
Current Perspectives and State of Knowledge

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Introduction

With respect to climate, tipping points are delicate thresholds where a relatively slight rise in Earth's temperature can cause a more dramatic change in climate systems. Tipping points represent one issue in the larger discussion of global climate change where the effects of the changes are better understood than the points in time at which they occur.

During the development of the Environmental Impact Statement (EIS) for the National Highway Traffic Safety Administration (NHTSA) Corporate Average Fuel Economy standards (CAFE) proposed rulemaking in 2008, many commenters requested that NHTSA consider the issue of tipping points in its analysis of global warming.[1] The issue of tipping points was also specifically pointed out by the courts in *Center for Biological Diversity v. NHTSA*[2] as one that NHTSA had failed to address in analyzing environmental impacts. This paper is derived from the research[3] NHTSA conducted in response to these comments and direction from the 9th Circuit Court to meet the requirements of the National Environmental Policy Act (NEPA) on a tipping point, or multiple tipping points, in the climate system and associated global processes as well as new research since this EIS was drafted. It is provided as a consolidation of reliable and current research on the issue of tipping points to facilitate discussions of how to approach the issue of tipping points in future analysis. The description of NHTSA's experience incorporating tipping points into its environmental impact statement for the proposed CAFE rule in 2008 may have limited utility to other cases.

This paper first discusses the uses of the term tipping point, since it is used in various ways in describing climate systems, then explores the Intergovernmental Panel on Climate Change's (IPCC) views on tipping points in the 4th Assessment Report, the U.S. Climate Change Science Program (CCSP) approach to the issue, current research from the paleoclimatic[4] record, and a paper published by Lenton, et al[5] that explores tipping points in multiple systems. It concludes with a brief discussion of the relevance of tipping points to decision makers in the NEPA process, highlighting NHTSA's Final EIS (FEIS) on the CAFE Standards rulemaking.

This paper is based on IPCC and CCSP research, along with recent, peer-reviewed published papers (Hansen et al. 2007a, 2007b: Lenton et al. 2008) and is not intended to

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[1] The EPA announced the availability of the FEIS through the Federal Register on October 16, 2008 (page 61859) and the FEIS is available on the DOT Dockets website, with all of the submitted comments, at http://www.regulations.gov/fdmspublic/component/main?main=DocumentDetail&o=090000648076416f

[2] 538 F.3d 1172 (C.A. 9th Cir, 2008)

[3] A number of people contributed to the development of this portion of the EIS including Michael Johnsen, Mark Flugge, Michael MacCracken, John Venezia, Randy Freed, Michael Savonis, and Kevin Wang.

[4] Paleoclimatology is the study of climate change through the physical evidence left on earth of historical global climate change prior to the widespread availability of records to temperature, precipitation, and other data. *See generally* http://www.giss.nasa.gov/research/paleo/.

[5] See Lenton, T.M., H. Held, E. Kriegler, J.W. Hall, W. Lucht, S. Rahmstorf, and H. J. Schnellhuber. 2008. Tipping Elements in the Earth's Climate System. *Proceedings of the National Academy of Sciences of the United States of America (PNAS*). 105(6):1786–1793.

establish general policy as to how the issue of tipping points should be assessed within the NEPA process or within the U.S. Department of Transportation (DOT).

Defining and Using the Term "Tipping Point"

The phrase "tipping point" is most typically used in the context of climate change and its consequences to describe situations where the climate system—encompassing the atmosphere, oceans, land, cryosphere[6], and biosphere—reaches a point at which there is a disproportionately large, singular response (e.g., a phase transition) as a result of only a moderate additional change in the inputs to the system (e.g., an increase in the CO_2 concentration). Exceeding one or more tipping points could potentially result in abrupt changes in the climate or any component of the climate system. A tipping point is defined in Alley et al. (2002)[7] to "occur when the climate system is forced to cross some threshold, triggering a translation to a new state at a rate determined by the climate system itself and faster than the cause." These changes would produce impacts at a rate and intensity far greater than slow and steady changes currently being observed (and in some cases, planned for) in the climate system.

The phrase "tipping point" has also been used more broadly outside of the climate modeling community. In addition to climate scientists, many others—including biologists, marine chemists, engineers, and policymakers—are concerned about tipping points and the potential for abrupt change as the same type of non-linear responses exist in the resource areas and domains affect by the Earth's climate. For example, ocean acidity resulting from an elevated atmospheric concentration of CO_2 might reach a point that causes a dramatic decline in coral ecosystems. Consideration of possible tipping points often is not restricted to just physical climate changes, but also encompasses discussion of sharp changes in other parts of Earth's systems affected by climate.

In the CCSP Synthesis and Assessment Product 3.4 Report *Abrupt Climate Change*[8] the CCSP forgoes the term 'tipping point' and defines abrupt climate change as:

> *A large scale change in the climate system that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades, and causes substantial disruptions in human and natural systems*.

This definition defines the process and the end result rather than the actual transitional tipping point in a system. Using the broad definition of the term tipping point to include both climate change and its consequences across climate-affected physical, environmental and societal systems, the scale of spatial responses can range across the spectrum. These changes can be global, continental or subcontinental changes in a major

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[6] The cryosphere refers to the portions of the Earth's surface that is frozen water which includes permafrost, floating ice, glaciers, and snow cover.
[7] Alley, R.B., et al., 2002: Abrupt Climate Change: Inevitable Surprises. US National Research Council Report, National Academy Press, Washington, DC, 230 pp. Quotation from p. 14.
[8] This report was in draft form at the time of the drafting of this document and is discussed generally and not specifically referenced.

component (e.g., dramatically altering the Asian monsoon, the melting of summer Arctic sea ice, or the melting of the Greenland Ice Sheet), or regional (e.g., drying of the southwestern United States leading to increased fire frequency), or local (e.g., loss of the Sierra Nevada snowpack). The definition of tipping point used by Lenton et al. (as discussed in a later subsection) specifically applies only to large-scale—that is, subcontinental or larger—features of the system, whereas public interest and discussion are likely to encompass a wider range of scales, as IPCC's analysis, discussed below, suggests. Lenton et al. "offer a formal definition, introducing the term 'tipping element' to describe subsystems of the Earth system that are at least subcontinental in scale and can be switched—under certain circumstances—into a qualitatively different state by small perturbations. The tipping point is the corresponding critical point—in forcing and a feature of the system—at which the future state of the system is qualitatively altered."

The temporal scales considered are also important in understanding tipping points. On crossing a tipping point, the changes in the climate-affected system are no longer controlled by the time scale of the heat absorption by greenhouse gases (GHG) (often referred to as climate forcing), but rather are determined by its internal dynamics, which can either be much faster than the forcing, or significantly slower. The much faster case—abrupt climate change—might be said to occur when:

- the rate of change is sharply greater than what has prevailed over previous decades;
- the state of the system exceeds the range of variations experienced in the past; and/or,
- the rate has accelerated to a pace that significantly exceeds the resources and ability of nations to respond to it.

In recent years, the concept of a tipping point—or a set of tipping points—in the planet's climate system has been attracting increased attention among climate scientists and resource managers. The following subsections present perspectives from key analyses of the issue as well as other relevant research— the IPCC, the CCSP, paleoclimatic evidence, and Lenton et al. (2008). The section concludes with a brief comparative evaluation of the different perspectives and available research.

IPCC Perspectives on Tipping Points

In the IPCC Fourth Assessment Report, the IPCC addresses the issue of tipping points in the discussion of "major or abrupt climate changes" and highlights three large systems: the meridional overturning circulation (MOC) system that drives Atlantic Ocean circulation, the collapse of the West Antarctic Ice Sheet, and the loss of the Greenland Ice Sheet (Meehl et al. p. 818). The IPCC also mentions additional systems, as noted below, that may have tipping points but does not include estimates for these additional systems.

Various climate and climate-affected systems that might undergo abrupt change, contribute to climate surprises, or experience irreversible impacts are described in the

IPCC Working Group I report (see Chapter 10, Box 10-1). The systems that the IPCC described include:

- Atlantic MOC (AMOC) and other ocean circulation changes;
- Arctic sea ice;
- Glaciers and ice caps;
- Greenland and West Antarctic Ice Sheets;
- Vegetation cover; and
- Atmospheric and ocean-atmosphere regimes.

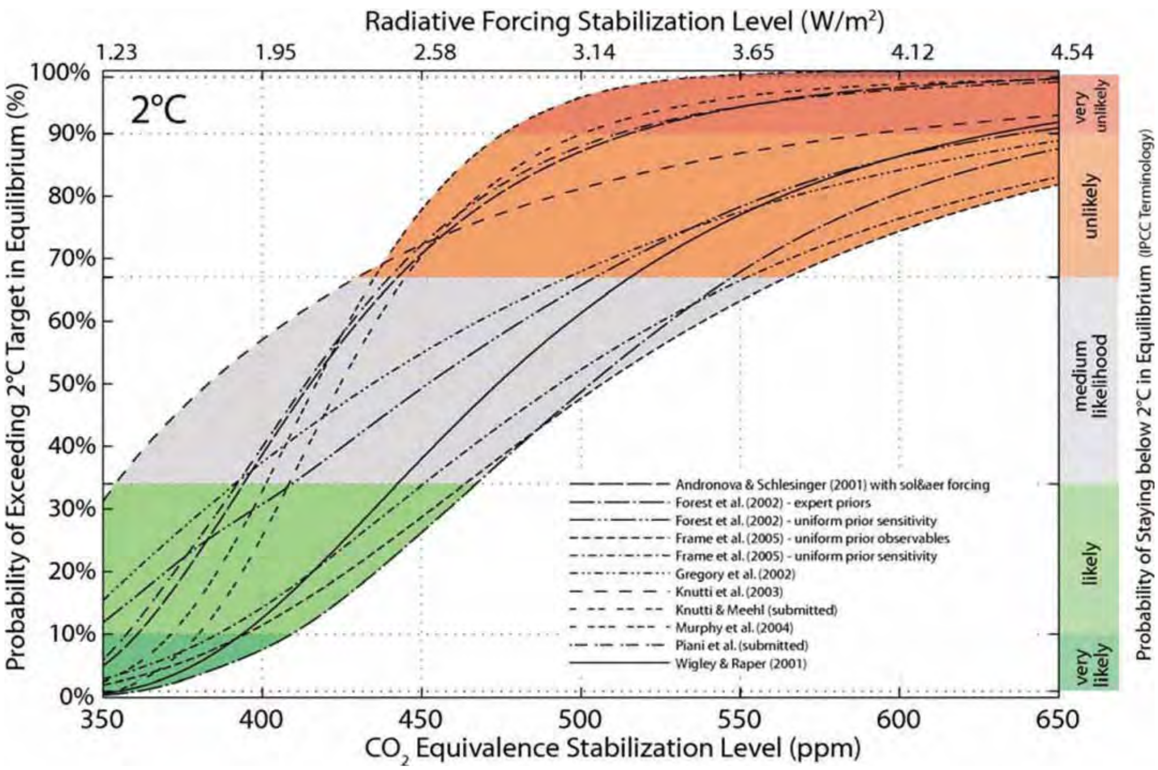
The coverage of the tipping point issue in the IPCC Working Group II report provides insight into the uncertainties surrounding tipping points, their systemic and impact thresholds, and the value judgments required to select critical levels, for example of global warming (see IPCC WGII section 2.3.1). The presence of these thresholds can also present their own physical and ecological limits as well as informational and cognitive barriers to adaptation (see IPCC WGII section 17.4.2).

Certain thresholds have been used in analyses of emission scenarios and analyses of stabilization targets to assess scenarios under which certain impacts might be avoided (see IPCC WGII section 19.4.2). For example, several authors hypothesize that a large-scale climatic event or other impacts such as widespread coral-reef bleaching, deglaciation of West Antarctica, and the collapse of the MOC would be likely if atmospheric CO_2 concentrations stabilize at levels exceeding 450 parts per million (ppm).

Instead of using a CO2 concentration level, tipping points for various effects are often expressed in terms of temperature increases with respect to either present or pre-industrial levels. Research indicates upward trends in temperatures over the last 100 years and global warming is a major component of all climate change discussion (IPCC 2007b). In an example where the research provided by the IPCC has been used in trying to determine a tipping point threshold in policy research by targeting a specific temperature increase, the European Union (EU) has established a policy using IPCC data points for CO2 concentrations in seeking to limit global average temperature increase to less than 2° Celsius (C) compared to pre-industrial levels in order to “limit the impacts of climate change and the likelihood of massive and irreversible disruptions of the global ecosystem.” The temperature increases are a function of atmospheric GHG concentrations (usually expressed in units of CO_2 equivalent), which are in turn a function of GHG emissions.

Figure 1, from the IPCC Working Group II report, shows the likelihood of a given CO_2 equivalent concentration leading to a temperature increase of 2ºC above preindustrial levels. It also shows that to have a 50% likelihood of staying below 2ºC the CO_2 equivalent concentration has to be stabilized at less than 450 ppm CO_2 equivalent. It should be noted that while the EU has made a goal of avoiding a temperature increase of 2ºC above preindustrial levels in order to avoid the most dramatic problems, this is not the same as saying there is a tipping point at 2ºC, nor does the IPCC indicate that a 2ºC increase triggers a tipping point scenario. Indeed, the IPCC states that tipping points and thresholds are poorly determined (O'Neill and Oppenheimer 2002; Lowe et al. 2006; Corfee-Morlot and Höhne 2003) which presents challenges for developing a 450 ppm or 2ºC level hypothesis at this time.

Figure 1. Probability of exceeding an equilibrium global warming of 2°C above pre-industrial (1.4°C above 1990 levels), for a range of CO_2-equivalent stabilization levels. Source: IPCC WGII, section 19.4.2, p. 801 (citing Hare and Meinshausen 2005).



Even though the EU uses this threshold and there is uncertainty in these systems, the IPCC ultimately concludes in their assessment that some of these systems, such as the melting of the Greenland Ice Sheet and changes in the AMOC, are unlikely to reach their tipping point within the 21st century (Meehl et al. p. 818).

CCSP Perspectives on Tipping Points

The U.S. Climate Change Science Program (CCSP) also reaches a similar conclusion as the IPCC in its report *Scientific Assessment of the Effect of Global Change on the United States*.[9] The CCSP report summarizes scientific studies that suggest that there are several "triggers" of abrupt climate change and that "anthropogenic forcing could increase the risk of abrupt climate change." However, "future abrupt changes cannot be predicted with confidence" because of the insufficiencies of current climate models, which are, to a

[9] *See generally* http://www.climatescience.gov/. (CCSP, 2008)

large extent, a reflection of limits of present understanding.[10] The CCSP has explored the issue of tipping points in two papers: Synthesis and Assessment Product (SAP) 3.4 and SAP 4.2. This issue also surfaces in other CCSP documents, but these two papers focus specifically on this issue.

The CCSP analysis considers the susceptibility of the same three systems to abrupt change as highlighted by the IPCC: the MOC system that drives Atlantic Ocean circulation, the collapse of the West Antarctic Ice Sheet, and the loss of the Greenland Ice Sheet.[11] The CCSP analysis also discusses thresholds in non-climate systems influenced by CO_2 emissions, such as the acidification of the oceans, where there may be a threshold beyond which existing coral reef ecosystems cannot survive.[12] The CCSP report concludes that these impacts, including climate-related thresholds, may occur in groups as thresholds are crossed, but more research is needed to quantify the impacts of crossing particular thresholds and to determine when these thresholds will be reached.[13]

The CCSP explores abrupt climate change in new research. In the SAP 3.4, *Abrupt Climate Change*, (CCSP, 2008b) the CCSP provides an in-depth examination of the potential for abrupt climate change, picking up where Alley, et al (2002)[14] and the IPCC AR4 left off. The CCSP utilizes paleoclimatic data, modeling, and recent studies in the development of findings in four major topic areas:

1) Rapid changes in glaciers and ice sheets;
2) Widespread and sustained changes to the hydrologic cycle;
3) Abrupt change in the AMOC; and
4) Rapid release to the atmosphere of methane trapped in permafrost on continental margins.

The report concludes that sea level projections could be substantially higher than the IPCC AR4 report due to the recent rapid changes at the edges of the Greenland and West Antarctic ice sheets which are showing an accelerated rate of flow and thinning. The hydrological variability section focuses on precipitation patterns over North America reinforcing the drying of the American Southwest, but the report finds no clear evidence to date of human-induced global climate change on North American precipitation, though subtropical aridity is likely to intensify and persist due to future global warming. The CCSP report finds the possibility of a collapse of the AMOC in the 21st century unlikely, however the findings show that the AMOC is very likely to decrease over the 21st century by about 25-20%.

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[10] *See* U.S. Climate Change Science Program, Synthesis and Assessment Product 3.1 (Climate Models: An Assessment of Strengths and Limitations), Final Report (July 2008) *available at* http://climatescience.gov/Library/default.htm#sap
[11] CCSP Scientific Assessment of the Effect of Global Change on the United States, pp. 95–97
[12] CCSP Unified Synthesis Product “Global Climate Change Impacts in the United States” First Draft, July 2008
[13] *Ibid*.
[14] Alley, R.B., et al., 2002: Abrupt Climate Change: Inevitable Surprises. US National Research Council Report, National Academy Press, Washington, DC.,244 pp.

Finally, the report finds that it is very likely that climate change will accelerate the pace of methane releases from melting permafrost and the warming of the sea floor, as well at high-latitude wetlands. It is possible that northern high latitudes of CH4 emissions could double, all processes are not represented in the models so larger or smaller releases are quite possible. The acceleration of methane releases from the hydrate sources is likely but difficult to estimate. Since methane is a potent GHG, these releases produce a positive feedback system that could, in large enough amounts, accelerate global warming.

In January, 2009, the CCSP released SAP 4.2, *Thresholds of Climate Change in Ecosystems*, (CCSP, 2009). This document focuses on the impacts to ecosystems and the tipping points within ecosystems. The document provides suggestions for decision-makers in the land and resource management field. A new tipping point definition, specific to ecosystems, is also introduced here:

> *"An ecological threshold is the point at which there is abrupt change in an ecosystem quality, property, or phenomenon, or where small changes in one or more external conditions produce large and persistent responses in an ecosystem"*

These changes are said to propagate in a "…domino-like fashion that is potentially irreversible."[15] (CCSP, 2009). The report provides several examples of ecosystems that have crossed climate-induced thresholds as case studies, as summarized:

1) *Alaska*: The spruce bark beetle outbreak and consequent forest die-off are associated with milder winters and warmer temperatures that allow the bark beetles to survive winter, overlaid with a 9-year drought stress that weakened spruce tree resistance to beetle infestation. There are also ecological thresholds associated with the wetlands in interior Alaska and fisheries in the Bering Sea.

2) *Coral Reefs*: Many factors contribute to the current trend of degradation of coral reefs over the past 3 decades in the tropical Atlantic and Indo-Pacific Oceans that are not associated with climate change (but, rather, other human-induced changes such as pollution) but global changes in climate and oceanic characteristics from increased atmospheric CO2 concentrations are now becoming more important. These include sea-level rise, the decline in pH of seawater, and the increase in seawater temperatures.

3) *Prairie Pothole Wetlands*: Drier conditions threaten the wetland network in the mid-section of the U.S. that is one of the most ecologically valuable freshwater resources of the Nation.

4) *Southwestern Forests*: This case study indicates that these forests are susceptible to climate-induced water stress which can trigger rapid, extensive and dramatic forest dieback. The water-stress kills trees and also makes them more susceptible to insect outbreaks. These ecosystems become less productive as a result which affects numerous other ecological processes.

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[15] While SAP 4.2 focuses on North American ecosystems, this description could be helpful in understanding other climate tipping points.

While this report was focused on a more detailed level than other reports, (specific North American ecosystems versus larger-scale global systems) SAP 4.2 is notable for providing recommendations for management and policy for decision-makers in the natural resource management field including suggesting the need to instigate institutional change to increase adaptive capacity[16].

Paleoclimatic Evidence on Tipping Points

Perhaps the most relevant feature of the paleoclimatic record cited by IPCC, CCSP, Hansen, and others is the indication of the extent of sea-level rise from previous ice-sheet melt, and the corresponding temperature for geologic time periods. For example, geological evidence indicating the presence of elevated beaches suggests that global sea level was 4 to 6 meters (m) higher than present during the last interglacial period, which peaked about 125,000 years ago.[17] At that time, paleoclimatic reconstructions suggest that the global average temperature was about 1 degree Celsius warmer than during the present interglacial period.[18] Ice cores in the ice sheets to determine their ages, supplemented by simulations of ice-sheet extent, suggest that large-scale retreat of the southern half of the Greenland Ice Sheet and other Arctic ice fields likely contributed roughly 2 to 4 m of sea-level rise during the last interglacial period, with most of the remainder likely coming from the Antarctic ice sheet.[19]

Paleoclimatic reconstructions also indicate the occurrence of abrupt changes in the terrestrial, ice, and oceanic climatic records. For example, the ice-core records suggest that temperatures atop the Greenland ice sheet warmed by 8–16º C within a few decades during Dansgaard-Oeschger events,[20] which were most likely caused by the North Atlantic Ocean being covered as a result of catastrophic outflows of accumulated glacial meltwater from the North American ice sheet that was present during glacial times.[21]

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[16] Adaptive capacity in the sense of learning how to manage ecosystems in response to changes in atmospheric CO2 concentrations and climate patterns.

[17] Jansen, E., J. Overpeck, K.R. Briffa, J.-C. Duplessy, F. Joos, V. Masson-Delmotte, D. Olago, B. Otto-Bliesner, W.R. Peltier, S. Rahmstorf, R. Ramesh, D. Raynaud, D. Rind, O. Solomina, R. Villalba, and D. Zhang. 2007. Palaeoclimate. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (Editors). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. p. 435

[18] Hansen, J. et al, 2007 Dangerous human-made interference with climate: a GISS modelE study. Atmospheric Chemistry, and Physics, 7, 2286-2312 available at http://www.atmos-chem-phys.net/7/2287/2007

[19] Jansen et al. Op. cit.

[20] Dansgaard-Oechger events are very rapid climate changes – up to 7 degrees C in some fifty years – during the Quaternary geologic time period, and especially during the most recent glacial cycle. (A Dictionary of Geography. Oxford University Press, 1992, 1997, 2004).

[21] Jansen et al. Op. cit.

A more recent study[22] using high-resolution Greenland ice core data provides more detail about the resulting change, indicating that there was a sharp warming over one to three years (i.e., "abrupt climate change happens in [a] few years") that was followed by [or that transitioned into] a more gradual warming (over fifty years). Based on the IPCC's estimates of temperature increases of approximately 2–4º C in the next 100 years, MacCracken[23] notes that paleoclimatic research indicates that corresponding equilibrium sea-level rise would more appropriately be 10–20 m or more, once melting of the West Antarctic and Greenland ice sheets (especially those parts grounded below sea level) had occurred. The time required to melt the ice sheets is uncertain, and could range from decades to centuries or longer. MacCracken suggests that "significant sea level rise [meaning a rise of over 1 m] could happen relatively quickly," meaning over less than a century, considerably faster than estimated by the IPCC. For example, the average rate of rise from 20 kiloannum[24] (ka) to 8ka was about 1 m/century, so there have, in the past, been periods with high rates of rise, although the North American ice sheet that was melting then was an order of magnitude larger than Greenland is today. For the future, Hansen et al. (2007) make clear that the predominance of positive feedback mechanisms in the climate system has the potential to cause large and rapid shifts in climate and factors like glacial melt and sea-level rise that are closely dependent on the climate; and Ramstorf et al. (2007) present a projected sea-level rise in 2100 of 0.5 to 1.4 m above the 1990 level.

In the report "Dangerous human-made interference with climate: a GISS modelE study", NASA scientist James Hansen, et al. conclude that "…a CO_2 level exceeding about 450 ppm is 'dangerous,'"[25] where "dangerous" is defined by the authors to be global warming of more than 1º C above the level in 2000, potentially leading to effects that may be highly disruptive. The authors compare the corresponding GHG concentrations and associated temperature increases alongside paleoclimatology research to demonstrate that abrupt changes have occurred in Earth's past[26] resulting from a similar range in increased

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[22] JP Steffensen, Andersen, KK, Bigler, M, Clausen, HB, Dahl-Jensen, D, Fischer, H, Goto-Azuma, K, Hansson, M, Johnsen, SJ, Jouzel, J, Masson-Delmotte, V, Popp, T, Rasmussen, SO, Röthlisberger, R, Ruth, U, Stauffer, B, Siggaard-Andersen, M-L, Sveinbjörnsdóttir, AE, Svensson, A, White, JWC. 2008. High-Resolution Greenland Ice Core Data Show Abrupt Climate Change Happens in Few Years. *Science* 321(5889):680–684.

[23] Michael MacCracken "Prospects for Future Climate Change and the Reasons for Early Action" published by Air & Waste Manage. Assoc. 58:735–786, June 2008.

[24] Kiloannum means "one thousand years ago"

[25] Hansen, J. et al, 2007 Dangerous human-made interference with climate: a GISS modelE study. Atmospheric Chemistry, and Physics, 7, 2286-2312 available at http://www.atmos-chem-phys.net/7/2287/2007

[26] Ice core samples and the geologic and fossil record point to a number of instances in Earth's history where abrupt climate changes occurred. More recently (within the last several thousand years), localized impacts to the Atlantic Ocean circulation produced abrupt regional climate changes. For more information, the IPCC summarizes paleoclimatology research in Chapter 6 of the Working Group 1 report "The Physical Science Basis." Jansen, E., J. Overpeck, K.R. Briffa, J.-C. Duplessy, F. Joos, V. Masson-Delmotte, D. Olago, B. Otto-Bliesner, W.R. Peltier, S. Rahmstorf, R. Ramesh, D. Raynaud, D. Rind, O. Solomina, R. Villalba and D. Zhang, 2007: Palaeoclimate. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

temperature as those being predicted, and to argue the existence of a CO_2 concentration equivalent level (in atmospheric GHG concentration) at which the probability of abrupt, irreversible changes in climate-affected systems might occur. While Hansen's 450 ppm estimate is based on modeling that has limitations and uncertainties, Hansen actually considers this estimate of 'dangerous' CO_2 concentration to be an upper limit because it is dependent on a number of simplifying assumptions. He warns that the limit might be lower[27] and that a "safe" level of CO_2 may be 350 ppm—lower than the CO_2-equivalent concentration, including the offsetting effects of aerosols, is today.[28]

Perspectives on Tipping Points from a Critical Review of the Literature and an Expert Elicitation as Presented by Lenton et al. (2008)

Building on the IPCC and CCSP research, leading experts identified a number of climate systems that have tipping points during a workshop titled "Tipping Points in the Earth System" and conducted an expert elicitation involving 52 members of the international scientific community, many of whom participated in the IPCC. This study identified nine systems facing separate tipping points due to increased CO_2 and temperature levels that met four scientifically-based criteria to be considered "policy-relevant potential future tipping elements in the climate system."[29] Additional systems were identified, but insufficient information precluded these systems from meeting the definition of "policy relevant." The systems at risk identified by the researchers are:

- Arctic Sea-Ice;
- Greenland Ice Sheet;
- West Antarctic Ice Sheet;
- Atlantic Thermohaline Circulation (a component of the Atlantic MOC);
- El-Niño-Southern Oscillation;
- Indian Summer Monsoon;
- Sahara/Sahel and West African Monsoon;
- Amazon Rainforest; and
- Boreal Forest

The discussion that follows is drawn mainly from the Lenton et al. (2008) study including the citations therein.

Arctic Sea-Ice. The Arctic sea-ice surface has a higher reflectivity—albedo—than the darker ocean surface. As sea-ice melts from higher air and ocean temperatures, more of the ocean is exposed, which allows more radiation to be absorbed—amplifying the sea-ice melt. Higher temperatures limit the winter extent and thickness of Arctic sea ice. In

[27] Hansen, 2008-2009 State of the Wild "Tipping Point: Perspective of a Climatologist" published by Wildlife Conservation Society
[28] Hansen, 6/23/2008 on-line editorial "Twenty Years Later: Tipping Points Near on Global Warming" available at http://www.huffingtonpost.com/dr-james-hansen/twenty-years-later-tippin_b_108766.html last accessed 8/21/08
[29] Lenton, et al 2008 "Tipping elements in the Earth's climate system" published by the National Academy of Sciences of the USA. Available at http://www.pnas.org/cgi/doi/10.1073/pnas.0705414105

summer, Arctic sea-ice loss could lead to the ice cap melting beyond a certain size/thickness, at which point Arctic sea-ice cover is likely to become unstable, ultimately leading to an ice-free Arctic. Recent record ice losses and modeling studies have led some researchers to suggest that the summer Arctic will be ice-free within a decade or less, that a critical threshold for summer Arctic sea-ice loss exists[30], and that this threshold has already been crossed.

Greenland Ice Sheet. The Greenland ice sheet is also susceptible to positive feedbacks. Melting at the glacial margins lowers the edge of the ice sheet to elevations that are warmer and where more melting will occur. The IPCC estimated the Greenland ice sheet threshold for negative surface mass flux at 1.9–4.6º C above pre-industrial temperature, well within their predicted temperature range for this century. Dynamic ice melting processes, regional temperatures, and warming surrounding oceans—as well as recent observations indicating that even at current temperatures both Greenland and Antarctica are losing mass—has led researchers to conclude that the timescale for Greenland ice-shelf collapse is conceivably on a scale of hundreds rather than thousands of years.

West Antarctic Ice Sheet. The West Antarctic ice sheet is grounded below sea level and positive feedbacks could result from the loss of buttressing sea-ice shelves and the ingress of warmer ocean water. Again, century to millennial timescales are predicted to pass before any collapse. However, the thresholds for ocean warming and surface atmospheric temperature are likely to be crossed this century. A recent study by Schneider and Steig (2008) interpreting ice-core records has postulated strong links between past West Antarctic climate—and potentially its ice sheet—to large-scale changes in global climate variability, particularly major El Niño events.[31]

It should be noted that ice-sheet loss, even over centennial and millennial time scales, could cause sea level to rise at a rate greater than one m/century, which would be more than five times the rate of rise during the 20th century, and the level reached would be higher than has been the case during at least the past few thousand years when coastal cities around the world were established.

Atlantic Thermohaline Circulation. The term thermohaline circulation (THC) refers to the physical driving mechanism of the ocean circulation—resulting from fluxes of heat and freshwater across the sea surface, subsequent interior mixing of heat and salt, and geothermal heat sources; whereas the MOC, discussed above in relation to the IPCC and CCSP reports, is the observed response in an ocean basin to this type of ocean circulation coupled with wind-driven currents. The Lenton et al. (2008) paper refers to risk to the Atlantic Thermohaline Circulation in preference to the AMOC since they are discussing

[30] Senior scientist Mark Serreze at the data center in Boulder, Colo is quoted by the Associated Press (http://hosted.ap.org/dynamic/stories/S/SCI_ARCTIC_ICE?SITE=MAHYC&SECTION=HOME&TEMPLATE=DEFAULT) saying "It's tipping now. We're seeing it happen now." in relation to arctic sea ice declines.

[31] Schneider, D.P., and E.J. Steig. 2008. Ice cores record significant 1940s Antarctic warmth related to tropical climate variability. *PNAS* 105(34):12154–12158. August 26.

the influence of climate changes on the underlying cooling or freshwater forcing of the Atlantic Ocean circulation even though this in turn dramatically impacts the AMOC.

If enough freshwater enters the North Atlantic (e.g., from melting sea ice, the Greenland Ice Sheet, Canadian and Eurasian rivers, and ocean precipitation), the density-driven sinking of North Atlantic waters may be reduced or even stopped, as evidence indicated occurred during the last glacial cycle. If this were to occur, it would likely mean a reduced northward flow of energy in the Gulf Stream and less heat transport to the North Atlantic. At the same time, reduced formation of very cold water would likely slow the global ocean overturning circulation (or thermohaline circulation), leading to impacts on the climate and ocean currents around the world. The IPCC's review of the results of model simulations suggests that an abrupt transition of the Atlantic Ocean's component of the global thermohaline circulation is *very unlikely* this century. More recent modeling with the inclusion of increased freshwater inputs does suggest initial changes could occur this century, with larger and more intense reductions in the overturning circulation persisting for many centuries.

El-Niño-Southern Oscillation (ENSO). The changes that might lead to crossing of a threshold and a shift to increasingly persistent (and frequent) El Niño (or La Niña) conditions are particularly uncertain. Increases in ocean heat content could have an effect on ENSO conditions, but predictive and paleoclimatic modeling studies do not agree on the magnitude, frequency, and direction of these effects. However, ENSO has significant and large-scale effects on the global climate system.

Indian Summer Monsoon. The Indian summer monsoon is the result of feedbacks relating to land-to-ocean pressure gradients and advection of moisture from ocean to land. By warming the land more than the ocean, climate change due to the rising concentrations of greenhouse gases generally strengthens the monsoon; on the other hand, reductions in the amount of solar radiation that is absorbed by the land surface, for example as a result of aerosol forcing or land-use change increasing the planetary albedo in that region, generally weaken it. It takes an albedo greater than roughly 50% to simulate the collapse of the Indian summer monsoon in a simple model.[32] IPCC projections do not show a threshold this century, although paleoclimatic reconstructions do indicate that the monsoon has changed significantly in the past.

West African Monsoon. Sahara/Sahel rainfall is dependent on the West Africa monsoon circulation, which in turn is affected by sea surface temperature. By warming the land more than the ocean and therefore causing greater upward movement of the air, GHG forcing is expected to draw more moist oceanic air inland and thereby increase rainfall in the region, and this is shown in some models. Other models, however, project a less productive monsoon. The reasons for this are not clear; some model results suggest greater drying (e.g., due to increased evaporation due to higher temperatures) while others suggest a greater number of anomalously dry years, presumably due to larger-scale changes in ocean-land weather patterns.

[32] Zickfeld, K, B. Knopf, V. Petoukhov, and H.J. Schellnhuber. 2005. *Geophys. Res. Lett.* 32:L15707.

Amazon Rainforest. The recycling of precipitation in the Amazon rainforest means that deforestation, reductions in precipitation, a longer dry season, and increased summer temperature could cause forest dieback. These conditions are thought to be linked to a more persistent El Niño and an increase of global average temperature by 3–4 degrees Celsius. Important additional stressors that are also present include forest fires and human activity (i.e., land clearing). A critical threshold may exist in canopy cover which could be reached through land-use change alone, or its interplay with regional precipitation, ENSO variability, and global forcing.

Boreal Forest. The dieback of boreal forest could result from a combination of increased heat stress and water stress, leading to decreased reproduction rates, increased disease vulnerability, and subsequent fire. Although highly uncertain, studies suggest a 3 degree Celsius global warming may be the threshold for loss of the boreal forest.

Comparative Evaluation

The Lenton et al. (2008) list differs slightly from that of the IPCC and the CCSP SAPs 3.4 and 4.2 because of differences in definition and criteria, its attempt to be more explicit than the IPCC, and the inclusion of more recent studies. The scientists defined these tipping points as "tipping elements" and attempted to place estimated time frames for when the tipping element of the various systems might be reached, ranging from about 1 year (rapid) to over 300 years (slow). As with the conclusions from the IPCC and CCSP, this group also arrived at the conclusion that the loss of the Greenland Ice Sheet, the collapse of the West Antarctic Ice Sheet, and the disruption of the Atlantic Themohaline Circulation systems are not expected to cross their estimated tipping elements in this century; that is not to say that actions this century will not create sufficient momentum in the climate system to cross the threshold in subsequent centuries. However, this group determined that several of the other systems could potentially reach a tipping threshold within the century: loss of Arctic sea ice, Indian summer monsoon disruption, Sahara/Sahel and West African monsoon changes, drying of the Amazon rainforest, and warming of the Boreal forest. The CCSP, in SAP 3.4, examine changes in precipitation patterns, but focused on North America and did not delve into detail on global system tipping points.

The research into additional systems by Lenton et al. indicates that some of these systems may reach their tipping point within decades or sooner, which differs from the CCSP and IPCC findings. However, the CCSP report, the Lenton et al. research, and the IPCC generally agree on the time frames for glacial melting and impacts to the AMOC of a century or more. Each of the reports had various conditions and nuances on how and when, and to what impact, these systems would contain if and when they reached a tipping point.

Generally, abrupt changes in these systems produce severe negative consequences for humans and other species. However, it is interesting to note that in the case of the Sahara/Sahel and West African Monsoon system looked at by Lenton, et al. shows a possible regional benefit. The prediction for a tipping point leading to increased rainfall and subsequent vegetation would possibly be “a rare example of a beneficial potential tipping element.”[33] While the immediate responses are on a regional level, the impacts of changes in these systems could affect other regional or even global climate systems, thus what might appear as a benefit in one region could actually produce a negative impact in another region.

There is also the potential for warming to thaw frozen Arctic soils (permafrost), causing the wet soils to emit more methane. There is evidence that this is already taking place (Walter et al. 2007). Therefore, a widespread change in soils, from a sink to a source of carbon, could further exacerbate the pace of climate change. The CCSP Assessment Product 3.4 explores the issue of methane releases in detail, more than either the IPCC or Lenton et al. Specifically, the CCSP examines the release of methane from permafrost and near-shore hydrates and concludes that neither of these two sources is expected to deviate from a steady increase over the coming century. However, northern high latitude wetlands could experience a dramatic change in natural methane emissions.

Another area that is being investigated in current research, which was explored only in the CCSP SAP 4.2 in relation to specific ecosystems, that may accelerate climate change at rates faster than those currently observed is the possible shift of sign of soil and vegetation-carbon feedbacks, causing the soil to become a carbon source rather than a carbon sink. Currently, soil and vegetation act as a sink, absorbing carbon from the atmosphere and incorporating this additional carbon in accelerated plant growth and soil carbon storage. However, by mid-century (so roughly at the time the global average temperature increase relative to preindustrial times reaches 2ºC), increasing temperatures and precipitation could cause increased rates of transpiration, resulting in soil and vegetation becoming a potential source of carbon emissions (Cox et al. 2000 as cited in Meehl et al. 2007). This is noted because there is potential for non-climate effects, such as this and ocean acidification that could produce tremendous environmental shifts in non-climate systems.

All of the authors generally agree that understanding how tipping points affect global climate requires examining a number of mechanisms through which climate changes could be initiated as tipping points are reached. These mechanisms range from the appearance or unusual strengthening of positive feedbacks—self-reinforcing cycles—to irreversible phase transitions—where a threshold has been crossed that could lead to either abrupt or perhaps unexpected changes in the rate or direction of change in climate-affected systems. The difficulty in defining exactly where tipping points occur is due, in part, to the difficulty in determining at what points they exist. While climate models incorporate treatments for many positive (and negative, i.e., dampening) feedback mechanisms, the magnitude of their effect and the threshold at which the feedback-related tipping points are reached are only roughly known, especially as to how global conditions may be affected. However, the models used to project the various responses of the climate-affected system to forcing do not have all feedback processes in them. And although significant progress has been made in understanding the qualitative

[33] Lenton et al. 2008

processes that are associated with tipping points, there are limits to the quantitative understanding of many of these systems, which all of the authors point out.

Only found in the CCSP SAP 4.2 are recommendations to decision-makers for management and research, but these were focused on an ecosystems level instead of the larger scale systems discussed in the other reports examined here. However, it is important to note that some discussion of how to manage these changes in a policy arena were discussed in this report which was not discussed in the other studies.

In summary, the main points of comparison are:

- The authors all agree on the likely existence of tipping points.
- There is not a universal definition of tipping points among the authors.
- Tipping points are being studied and the science is evolving with later studies bringing greater definition to the term abrupt climate change by focusing on specific subsystems.
- There is not universal agreement on the specific rates of change that constitute tipping points and the timing of tipping points.
- The precise magnitude of the impacts after tipping points for all systems has not been fully identified.
- Not all systems that could be affected have been examined or possibly even identified.

Policy Analysis and Relevance to Decision Makers

How does the issue of tipping points affect policy analysis and the availability and quality of information for decision makers in the context of global climate change? Do we understand the science behind tipping points and the timing and magnitude of their associated impacts such that we can and should explicitly consider them today in transportation decision making? The answers to these questions are key in determining how to approach tipping points in policy-relevant documents such as documents produced in accordance with NEPA.

This paper does not propose or set any policy for addressing tipping points but only shares discussion topics on the issue and shares current and past practices. However, tipping points could affect decision making if adequate knowledge on timing, occurrence, and impacts were available, and there is utility in informing decision makers that tipping points in the climate system exist, even if their specifics are still not clear Also, at the time of the drafting of this document, there is a lack of Federal guidance for approaching the specific issue of tipping points in decision-making documents such as NEPA analysis. Modes within the Department of Transportation have thus addressed the issue of tipping points in individual ways. In the most visible case, NHTSA developed a climate change-related Final Environmental Impact Statement that addressed tipping points. Some of the challenges associated with tipping points are discussed below.

The impacts of reaching a tipping point in a major climate or ecological system would produce changes at a rate much faster, and far greater, than exists in current planning for climate change adaptation. Subsequently, the reaction, and costs, of responding to a system that has reached a tipping point, would be much different than what had been planned for under a more constant rate of change scenario and would either require a transfer of resources or confronting a potentially enormous response with inadequate resources. Knowledge of tipping points and their timing and impacts would allow transportation planners to determine how to design systems for abrupt or severe changes. Due to the time horizons of some system tipping points which could be within the range of transportation infrastructure life spans developed today, this information would be relevant for planning today's projects as it would affect timing, planning, and especially costs of a project. With the issue of climate change altering transportation planning[34] and the timeframes of transportation planning (often in the 20 – 50 year range or longer, per the life of infrastructure and urban development), it is possible that tipping points could drastically impact this planning process, which is already accounting for the impacts of climate change.

In natural resource management economics, normative criteria for decision-making require understanding how to price the externalities of impacts to natural resources.[35] In the case of climate change, each additional unit of GHG emissions increases impacts (and, usually, costs) and would be valued at a rate to offset the increase in impacts. Determining a "social cost of carbon" (SCC)[36] is an attempt to determine this value. A tipping point, if accurately known, could potentially shift the cost curve dramatically and require the cost of adapting to the effects of that tipping point to be included in the unit of GHG prior to reaching the tipping point. Therefore, the SCC would need to be greater in order to include the impacts of reaching a tipping point. However, due to the ambiguity surrounding where and when tipping points may occur, accurately determining these cost points is difficult, if not impossible at this time. At the time of the writing of this document, the Federal government had not set a standard cost for carbon.

Various transportation modes may approach the issue of climate change tipping points differently depending on the characteristics of those modes. For example, the total impact of aviation emissions on climate change is the subject of ongoing research, and any applicability of the tipping point issue with regard to the aviation sector is premature. FHWA relies on current national and international scientific synthesis and consensus to influence regional planning and decision-making on GHG reduction strategies. Project level scoping, emissions analysis, and stewardship activities can address climate change by supporting local and regional initiatives, by reflecting the best available science and accepted methodologies, and by supporting stakeholder awareness

[34] A number of reports have been developed on the impacts of climate change on transportation. See Potential Impacts of Climate Change on U.S. Transportation, Transportation Research Board Special Report 290 published by the National Research Council of the National Academies, 2008

[35] See Tietenberg's Environmental and Natural Resource Economics, (5th ed, 2000) Chapter Two for understanding how to value resource economics for decision-makers.

[36] A social cost of carbon estimate attempts to set a specific price per unit of carbon released to offset the damages created by the release of carbon into the atmosphere. Many authors have attempted to pinpoint this price producing a range of estimates. It should be noted that at the time of publication, there is no official price set for the SCC to be used by agencies within the Federal Government or even a policy of whether to use a global cost or a U.S. cost, which is also discussed in the NHTSA FEIS.

and dialog. The Federal Motor Carrier Safety Administration calculates the amount of CO2 avoided behind large truck and bus crashes, but does not address impact issues such as tipping points in its NEPA documents.

In a recent past experience, NHTSA had to examine the issue of tipping points in the FEIS for NHTSA's 2008 Corporate Average Fuel Economy (CAFE) rulemaking (NHTSA 2008). The context of analysis for that document was a national standard for automobile fuel economy. NHTSA determined from the review of available literature that exactly where tipping points exist, and at what levels they occur, is still a matter of scientific investigation; NHTSA correctly was unable to quantify the differences in alternatives in their impacts to offset or delay potential tipping points given the state of science at the time of the development of the FEIS (the release of the CCSP Synthesis 3.4 report occurred after the publication of the NHTSA FEIS). Where information in the analysis included in the FEIS is incomplete or unavailable, the agency relied on CEQ's regulations regarding incomplete or unavailable information (40 CFR § 1502.22(b)).

The FEIS addressed the requirements of 40 CFR § 1502.22 appropriately. The FEIS' survey of the current state of climate science tipping points provided a "summary of existing credible scientific evidence which is relevant to evaluating the…adverse impacts of the CAFE standards."(NHTSA 2008) In *Colorado Environmental Coalition v. Dombeck*, the Tenth Circuit found that the ultimate goal of the agency is to ensure that the EIS's "form, content, and preparation foster both informed decision making and informed public participation." 185 F.3d 1162, 1172 (10th Cir. 1999) (quoting *Oregon Envtl. Council v. Kunzman*, 817 F.2d 484, 492 (9th Cir. 1987)). The Tenth Circuit held that 40 CFR § 1502.22 could not be read as imposing a "data gathering requirement under circumstances where no such data exists." *Id.*

In this case, NHTSA acknowledged in the FEIS that information on tipping points or abrupt climate change is incomplete, and the state of the science did not allow for a characterization how the CAFE alternatives influenced these risks. Ultimately, NHTSA determined that this action alone, even as analyzed by the most stringent alternative, would not produce enough of a CO_2 emission reduction to avert levels of abrupt and severe climate change. However, NHTSA concluded that, to the degree the rulemaking reduced the rate of CO_2 emissions, the rule contributed to the general reduction or delay in reaching tipping point thresholds. NHTSA used this argument throughout the EIS for a variety of impacts that are occurring and expected to continue, despite the inability of the agency to quantify the exact reductions in impacts from global warming beyond sea level rise, temperature increases and precipitation changes.

Mirroring the difficulty of incorporating tipping points in the NEPA process, an article (published at about the same time NHTSA published its FEIS) in the American Bar Association's Transportation Committee quarterly, *TQ*,[37] describes the challenges of incorporating climate change in the NEPA process. The author concludes that, with the

[37] *See* Serassio, Helen, Addressing Greenhouse Gas Emissions and Climate Change: NEPA Analysis in Proposed Federal Transportation Actions published in TQ, ABA Transportation Committee Quarterly, Vol. 1, No. 2 Fall 2008

lack of formal policy and guidance by CEQ or the EPA, and in light of legal action on the issue, agencies should take a hard look at the GHG implications from their proposed actions to avoid or withstand potential litigation. In *Center for Biological Diversity v. NHTSA*, the court pointed to tipping points as an area of concern in which NHTSA's NEPA documentation was deficient.[38] As a result, the agency addressed tipping points at length in the FEIS, reflecting the latest research, in order to contribute to a more complete and defensible document. However, given the modeling and scientific limitations to accurately predict what impacts a Federal action may have on mitigating a specific tipping point, no quantifiable conclusion could be reached at the time the FEIS was published.

The issue of tipping points requires greater research and understanding before solid policy recommendations can be drawn. The environmental, human and related economic impacts from tipping points and subsequent responses could be costly and severe, thus accurate predictions are critical. While the current research has alerted scientists to potential large events, continued monitoring, research, and modeling will be required, especially of the systems that have greater potential impacts, in order to produce specific recommendations for policy decisions. In addition, further guidance will be useful in determining how to address the issue in NEPA analysis since the issue of tipping points has not yet been incorporated into the NEPA process, nor many other Federal decision-making processes across the U.S. government.

[38] 538 F.3d 1172 (C.A. 9th Cir, 2008)

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