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Image: Ira Block, NAT GEO, 2011.

Feedback mechanisms in the Paleocene-Eocene Thermal Maximum

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Introduction

On May 9 this year, the daily mean concentration of carbon dioxide (CO_2) surpassed 400 parts per million (ppm) (NOAA Institute, 2013). This represents a milestone in contemporary climate change, caused by the massive emissions of CO_2, mainly due to the global energetic dependence on fossil fuels, and land use change. These CO_2 atmospheric levels have probably never been experienced on Earth for the past 3 million years (IPCC, 2007).

If the emission of greenhouse gases (GHG) continues at this pace, it is very unlikely that global average temperatures will not rise over 2 °Celsius by the end of this century. Our planet is crossing a threshold towards a "dangerous" climate change. Different scenarios are being designed, trying to predict the changes that we might expect to see in a near future. Although a lot of progress has been made in recent years, some drivers of global warming are yet not well understood. One of these processes are the so called "climate feedbacks". These are processes that will either amplify or reduce global warming.

The political climate change discussion tends to focus on human scales. But the Earth's mechanisms forcing the climate act on different ones. Hence, this paper aims to provide a glimpse into the Earths climate from a geological time perspective. As a specie, the human-being has only existed for a short period of time. We evolved inside "an icehouse world", in which CO_2 concentrations are relatively low (180–380 ppm) (Dunn, 2008). As the concentration of CO_2 keep rising, looking to the past might be the best answer to predict our future. 50 million years ago, a sudden release of carbon dioxide is recorded in the sediment layers and teeth of ancient animals. This event is called the Paleocene–Eocene Thermal Maximum (PETM), and it is considered as one of the closest parallels available to contemporary climate to study the changes that can happen when massive volumes of CO_2 are pumped into the Earth's atmosphere (Pagani et Al, 2006).

Under this scenario, the aim of this paper is to gain insight about the key mechanisms of the PETM generation, by reviewing and contrasting the theories that explain this episode. Accordingly, it is considered that they could shade some light regarding the possible implications for the current period of anthropogenic climate change. Specifically, this paper would like to focus on the role that GHG feedback mechanism played during this period. The main research question is: *"What was the role that GHG* *feedback mechanisms played during the PETM and what implications might be drawn to the current climate change scenarios".*

The Paleocene-Eocene Thermal Maximum

Approximately 55 million years ago, the Earth experienced a series of sudden and extreme global warming events, called hyperthermals. The first and largest of these events is the PETM. This event is characterized by a massive input of carbon and intense global warming. These processes happened in the relative short timespan (for geological processes) of approximately less than 10,000 years (Dickens, 1999) to 20,000 years (Cui et al., 2011). Hence, the average rate of heating in this period is one of the fastest ever recorded and therefore it may be the best ancient analogue for contemporary and future increases in atmospheric CO_2 (Pagani et al, 2006).

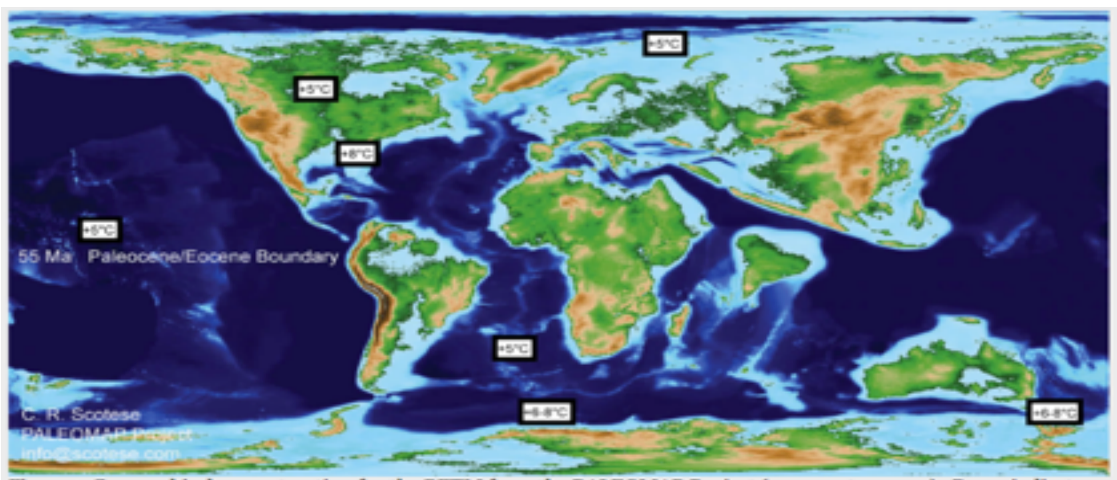

Figure 2. *Geographical reconstruction of the PETM, showing the Temperature changes relative to the Paleocene background (Texas University Climate Research Group, 2013)*

The PETM period lasted for approx. 170,000 to 200,000 years (Pagani, et al. 2006), and it is marked by a large decrease in the $^{13}C/^{12}C$ ratio of marine and terrestrial organic carbon, indicating a large release of methane (CH_4) and/or CO_2 into the atmosphere. These changes in the global carbon cycle are linked to global warming (Pagani et al., 2006). Temperature records indicate that during the onset of the PETM, middle and tropical latitudes experienced a temperature increase of 5°C to 10°C (Wing et al. 2005), while high latitudes experienced an 8°C to 10°C increase in sea surface temperature (Zachos et al. 2003).

The increase in temperature caused a rearrangement in the geographic distributions of most organisms, with tropical forms moving poleward in both marine and terrestrial realms (McInerney & Wing, 2011). During the PETM, the increase in temperature is believed to be the driven force that induced some mammals to decrease their body sizes (Eberlene, 2012). Furthermore, the large release of carbon caused widespread deep ocean acidification and carbon dissolution, related to a major extinction of benthic foraminifera (Thomas, 2003).

Although there is scientific consensus that a large carbon release occurred during the PETM, the source of this carbon is still debated. Five sources are being currently discussed (McInerney & Wing, 2011):

1) **Dissociation of methane hydrates:** Methane clathrates are icy solids consisting of methane surrounded by water molecules. They are stable in deep-sea sediments, but they might have been destabilized by increasing temperature caused by changes in ocean circulation (Dickens et al. 1995, 1997) or by decreasing pressure resulting from slope failure (Katz et al. 1999).

2) **Wildfires**: Burning of extensive peat and coal deposits, caused by increasing atmospheric O_2, dryer climates, and/or uplift of coal basins (Kurtz et al. 2003).

3) **Massive volcanism:** Injection of magma into organic-rich sediments in the Norwegian Sea could have caused the release of methane (Svensen et al. 2004).

4) **Drying epicontinental seas:** Isolation of a shallow seas caused by tectonic movements, leading to desiccation and oxidation of organic matter (Higgins & Schrag 2006).

5) **Permafrost:** During the Paleogene, Antarctica did not support a large ice cap and may have stored vast quantities of carbon in permafrost and peat layers that could have been rapidly thawed and oxidized, releasing carbon (DeConto et al. 2012).

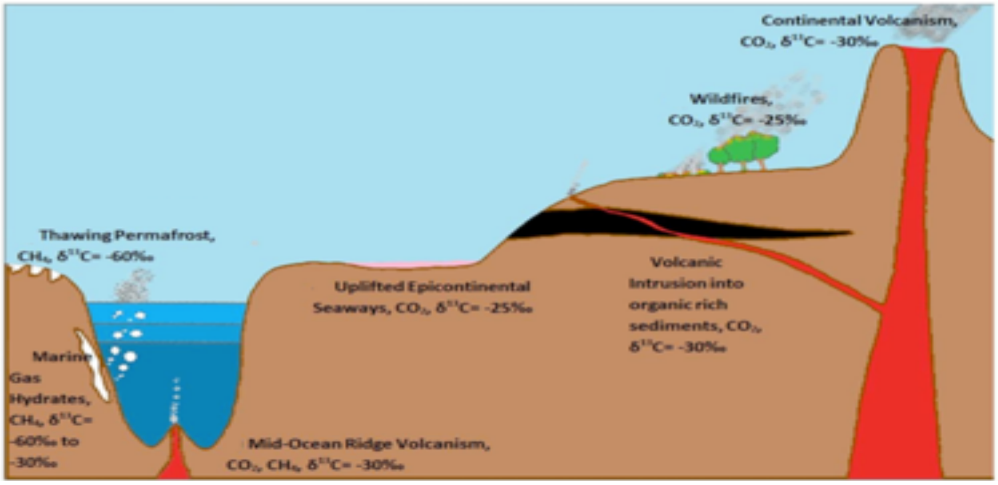

Figure 3. *Diagram showing the possible sources of Carbon triggering the PETM. (Modified from Martin et Al., 2013)*

This paper will discuss theory of methane hydrates dissociation by Dickens et al. (1995) and the theory of permafrost thawing by De Conto et al. (2012), since these have had a major relevance in the discussion of the PETM (McInerney & Wing, 2011), and might provide insight regarding the role of GHG feedback loops for the current climate change.

Dissociation of Methane Hydrates

Methane Hydrates deposits are located within a mid-depth zone around 300–500 m thick, in the sea sediments, a range called the gas hydrate stability zone (GHSZ) where they coexist with methane dissolved in the fresh, not salt, pore-waters. Above this zone methane is only present in its dissolved form at concentrations that decrease towards the sediment surface. Below it, methane is gaseous (Dickens, 1997).

The role of the methane clathrates dissociation has also been identified with temperature changes in major warming geological events, such as the termination of the Snowball Earth (Kennedy, 2008), or during the Permian–Triassic extinction event (Benton, 2003). Methane hydrates dissociation is also involved in theories that regard this mechanism as a possible positive feedback loop for the contemporary climate change, such as the "clathrate gun hypothesis" (Kennett et al., 2002).

In order to explain the dramatic increase of CO_2 in the atmosphere during the PETM, Dickens et al. (1995) proposed the "gas hydrate dissociation" hypothesis. This theory establishes that some earth system threshold was crossed, so that deep ocean temperatures rose rapidly. This warmth propagated into sediment on continental slopes, which shoaled the base of the GHSZ and converted large amounts of gas hydrate to free gas. Since methane has limited solubility in water, and because it is a very light gas (lighter than air), it quickly makes its way up through the water column and into the atmosphere. After a short period of time (10 years) methane is oxidized, forming carbon dioxide and water. This increase in the concentration of GHG led to atmospheric warming. This increased warming can convert even more gas hydrate to free gas, and these consecutive processes can thus constitute a feedback loop.

More evidence sustaining the role of methane hydrates for the PETM warming emerged from the records of sediments columns and seismic activity. In fact, Katz et al. (1999) proposed a theory in which the methane disassociation from the clarathes does not need to rely in a rapid increase in temperature, but rather in mechanical disruptions caused by erosion or seismic activity. In other words, changes in the currents of deep-water circulation accompanied by increased seismic activity in the continental sea floor, stimulated sediments erosion and eventual submarine slope failures. This mechanical disruptions in the sea floor caused the methane release from the gas reservoirs trapped between the frozen hydrate-bearing sediments, starting the feedback mechanism that could explain the warming of the PETM.

However, the amount of carbon released by methane clathrates reservoir was not enough to explain the changes in temperature observed during the TEMP (Zeebe. et al., 2009). Hence, this hypothesis implied that another feedback mechanism that was not taken into account must had been playing a role, or in the worst-case scenario, that the current climate models were underestimating the temperature sensitivity in respect to CO_2 (Zeebe, et Al, 2009).

Thawing of Permafrost

Another possible source of the large carbon release at the PETM, is the thawing of permafrost. Permafrost is defined as subsurface earth materials remaining below 0 °C for two consecutive years (Schuur, 2008). Permafrost occurs mainly in the Artic and boreal regions, but can also be found in mountainous regions. In the continuous zone, permafrost thickness ranges from 350–1450m and in the discontinuous zone, the ranges vary between 1 and 50m (Schuur, 2008). The surface layer of permafrost which thaws for a period of the year is called the active layer. This layer can be between a few centimeters depth to more than 2 meter in the continuous zone, and up to a few meters in the discontinuous zone (Schuur, 2008).

Through the thawing of the active layer, microbial decomposition will take place, releasing carbon from the permafrost. This carbon was frozen into permafrost through aeolian deposition, alluvial sedimentation and vertical peat deposition, which slowly increase soil depth on timescales of decades to millennia (Schuur, 2008). Warming in the permafrost regions will affect carbon release in three ways. Higher temperature will lead to larger areas of permafrost with an active layer, the overall active layer thickness will increase and the period the active layer is present will prolongate.

While permafrost soil carbon (PFSC) stocks were dismissed in the past as too small to cause the PETM (Higgins, 2006), recent studies have shown that Antarctica was mostly subaerial and ice free during the Palaeogene, potentially storing massive amounts of PFSC (Wilson, 2009). Noticing that the sequence of multiple, progressively smaller hyperthermals that occurred following the PETM could correspond to similar orbital geometries (Lourens et al., 2005), DeConto et al. proposed that the hyperthermals are linked to high-latitude orbital forcing through carbon-cycle feedbacks involving permafrost soil carbon.

Their hypothesis was tested using a Global Climate Model (GCM) with coupled terrestrial biosphere and soil components. First a simulation was run, to calculate pre-PETM conditions. This simulation showed conditions well suited to sequestering PFSC (Tarnocai et al., 2009). At 900 eppmv (equivalent ppm in volume) of CO_2, global-mean surface temperature is 6 °C warmer than today. The Antarctic is ice free but 22.4 x 106 km2 of permafrost still remains in the high latitudes of both hemispheres, it's stability is however highly sensitive to orbital forcing. Simulations with different orbital geometry inputs reveal a reduction of the global permafrost region by up to a third. The amount of carbon that is released is than calculated from the areas that undergo thawing. Because not all the details of Palaeocene-Eocene PFCS reservoirs are known, they are modeled after present permafrost conditions, and are estimated at 3,728±1,033 Pg C, nearly half of which is in Antarctica. A loss of a third of the global permafrost region releases more than 1,200 Pg carbon to the atmosphere. This carbon input at rates up to ~1.5 Pg C/yr can raise the atmospheric CO_2 by more than 550 ppm. This can result in more global warming and further increase permafrost thawing. Simulating the model with this additional carbon input, shows that almost all the permafrost will melt, releasing 3,434±951 Pg carbon and at the same time raising the global temperature by 6 °C within the timeframe associated with the PETM. This result shows that high-latitude climate forcing can trigger massive PFCS carbon release and can account for the sudden and extreme warming in the PETM.

Discussion

There exist evidence that support both Dickens and DeConto theory. However, the most likely scenario is that both feedback loops were interacting when explaining the unusual amount of CO_2 released to atmosphere and hydrosphere during the PETM (Cui, 2011).

The evidence extracted from the $^{13}C/^{12}C$ ratio proxies remains a strong evidence for the dissociation of sea floor gas hydrates. This is due to the extremely negative δ13C value of marine gas hydrates (Dickens et al., 1995). However, as previously mentioned, the relatively low amount of carbon contained in the GHSZ, and the initial heating that triggered its dissociation remained debated. In other words, clathrates alone indeed could not explain the initial triggering of the increase in CO_2, but rather act as positive feedback mechanism that increased temperature.

DeConto et al. (2012) hence provided a feasible theory to explain the triggering of the PETM and the possible feedback loops implied. The evidence provided by the orbital geometries and a recent reconstruction of Antarctic palaeogeography, demonstrated the favorable conditions for permafrost. Hence, the PETM can be linked to high-latitude orbital forcing through carbon-cycle feedbacks involving permafrost soil carbon. His models showed that massive PFCS carbon release can indeed account for the sudden and extreme warming in the PETM.

Examinations of the PETM shows that the quantity of GHG released into the atmosphere and hydrosphere during the event are so large, that it is very likely that both methane hydrates dissociation and permafrost thawing, plus another sources of carbon played a role (Cui, 2011).

Hence, whatever the cause of the PETM, it is unlikely that a single source of carbon release could have initiated the PETM. Pagani et al. (2006) argued that marine gas hydrates could only give rise to a CIE of around –6% if the climate sensitivity to CO_2 in the Paleocene was much greater than it is currently assumed to be.

Despite PETM beings a pertinent geological analogue for future global change (Jones et Al., 2010, Dunn, 2008; Zeebe et Al, 2009), there are differences between PETM and contemporary Earth's conditions. These have to be taken into account when trying to apply the feedback mechanism studied in this paper to contemporary climate change. Firstly, the background climate state of the early Paleocene is different from the Earth's present conditions. The Earth was a lot warmer before the PETM started, sea levels were higher, and both atmospheric and deep oceans temperatures were higher (Jones et al, 2010). Moreover the polar ice sheets were absent (Zachos et Al, 2008) and oceans and the biosphere had a different chemistry (Kump, et Al, 2009).

However, there are still conditions that might raise a question regarding the potential strength's of the feedbackloops. For instance, the carbon stored in the GHSZ during the Paleocene was believed to be 43% of the contemporary amount (Dickens, 1997). In other words, there exist today a major carbon reservoir, that could imply a larger quantity of CO_2 flux to the atmosphere if destabilized.

Secondly, the release rates of carbon into the atmosphere and hydrosphere during the PETM was at least an order of magnitude slower than contemporary release rates, achieved through the combustion of fossil fuels and deforestation (Zeebe et al. 2009). During PETM carbon was added at peak rates of ~1.7 Pg C yr-1. (Cui, 2011) while current levels of anthropogenic GHG release, including consumption of fossil fuels and land use change, are calculated at ~8.8 Pg C yr-1 (IPCC 2007). Moreover, during PETM global temperatures rose by 5–10°C at middle and tropical latitudes, while high latitudes experienced an 8–10°C increase in sea surface temperature. Considering that these temperature rises were achieved over an period of 10,000-20,000 years, the mean annual temperature rise during the PETM (0.0010-0.00025 °C yr^{-1}) is once again dwarfed by current temperature rise which the IPCC has predicted at about 0.2°C for the next two decades.

	PETM	Present Climate Change
Tons of $C0_2$ per year	5 billion	33 billion in 2010
Temperature changes	6°C-9°C in 20000 years	1°C -4°C in 100 years
Change per year	.00045 °C	.03 °C
Total tons of CO2	100,000 billions	329 billions since 1751

Table 1. *Comparison between the release rate of $C0_2$ and temperature rise. Based on Cui, 2011;* Friedlingstein (2010) and IPCC (2007)

If the current rates of atmospheric CO_2 emissions remain constants at 1.9 ppm per year, we could reach PETM levels of atmospheric CO_2 [approximately 1600 ppm (McInerney & Wing, 2011)] within 850 years. This estimate is potentially conservative given the current and anticipated acceleration of CO_2 emissions (Dunn, 2008) and the unknown magnitude of the feedback loops.

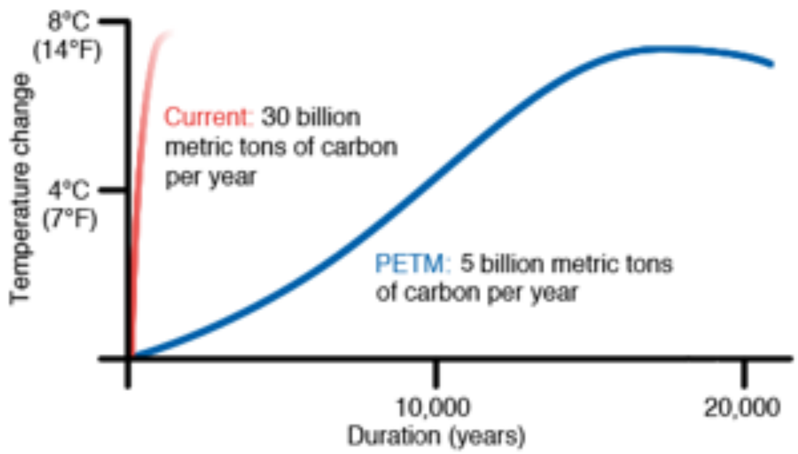

Figure 4. *Rate of temperature change between current global warming (red) and PETM (blue). Modified from the Weather underground (2013)*

Despite this figures, it is currently not believed that anthropogenic climate change can cause a sudden destabilization of marine gas hydrates or initiate a permafrost thawing feedback loop, at least not for decades or even centuries (Archer, 2007).

There exist already evidence that hydrates are currently releasing methane to the atmosphere in response to anthropogenic warming, for example along the Arctic coastline of Siberia (Archer, 2007). Still, most of the hydrates are located at depths in soils and ocean sediments where anthropogenic warming and possible resulting methane release will take place over time scales of millennia (Archer, 2007). Individual catastrophic releases like landslides and pockmark explosions are too small to reach a sizable fraction of the hydrates (Archer, 2007). And although increased permafrost degradation is already observed (Torre Jorgenson, 2006), risk assessments, based on expert opinion, estimated that up to 100 Pg C could be released from thawing permafrost by 2100 (Gruber et al. 2004) a number many times smaller than the release of CO_2 during PETM as calculated by DeConto.

Conclusion

The evidence obtained from the analysis of the feedback mechanism operating at the PETM occurred under very different time scales and conditions from today, which implies that drawing conclusions about catastrophic climate change events happening in a human life time spam would be biased. Probably, most effects will happen at a rate that will represent a glimpse in geological terms, but "generational" in human terms.

However, it is very likely that our current climate change episode will have a colossal impact on life on Earth, both in geological and evolutionary terms. Although there exist no record of massive extinctions during the PETM, except for the foramifera, there is evidence for threatened massive pole ward species migration and biological adaptations in all the other species. For instance, archaic mammals were replaced by modern groups, including the first primates (Clyde and Gingerich, 1998; Smith et al., 2006), and floras underwent important changes including increased diversity, leaf size, and shape (Wing , 2005; Jaramillo, 2006).

All of the changes to life occurred in a climate that changed much slower than our current one does. Already ecosystems have been responding sensitively to warming (IPCC, 2007). Species extinctions are on the rise, of the 44,838 species assessed by the IUCN, 16,928 are listed as threatened with extinction (IPCC, 2007). Furthermore, millions of species are of yet not assessed, so the number of threatened species could be definitely much higher. However, unlike during the PETM, ecosystems today are fragmentized, and most large animals are already threatened in their natural habitats, with no possibility to move to new latitudes. Given all these current conditions, extinctions could happen at unprecedented rates, changing biodiversity forever.

Research into the large carbon release that occurred during the PETM proposes methane clathrates dissociation and permafrost thawing or a combinations of these feedback loops as plausible explanations. Once certain thresholds are reached, both mechanisms are capable of releasing massive amount of carbon into the atmosphere and hydrosphere. Although the resulting release of carbon happened at a very fast pace on geological timescales, these processes are still slow on human times scales. However, when these mechanisms are triggered, the additional release of carbon, combined with the anthropogenic releases will speed up the current rate of global warmer even further.

The PETM period should thus serve as a warning. The feedback loops that propelled the fast warming of this era should be used in the political climate change discussion. And since there still exist a high degree of uncertainty regarding the size of the carbon stocks of both methane clathrates and permafrost, and their thresholds and precise mechanisms, further research becomes extremely urgent in this area, in order generate scenarios of possible climatic drastic shifts.

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