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The effects of tropical cyclones on the carbon cycle

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Abstract

Tropical cyclones influence processes within the carbon cycle on different time-scales. Forested ecosystems suffer windfall and long-term impacts from tropical cyclones, leading to the release of CO_2 to the atmosphere. The coarse woody debris created by extreme wind speeds and landslides brought on by tropical cyclones can leave a forested ecosystem via riverine channels and end up in the ocean, where it is unclear whether it is buried or slowly decomposed. Particulate organic carbon is flushed out of terrestrial ecosystems along with the coarse woody debris. Furthermore, air-sea fluxes of CO_2 are influenced and local levels can be altered significantly by the passage of a tropical cyclone. Mixing induced in the euphotic zone of the oceans leads to increases in primary production in the wake of tropical cyclones, which could be an important factor in the global carbon balance. Global warming has led and will lead to changes in the frequency and intensity of tropical cyclones, and therefore the importance of these processes will shift in the future.

In this review, the effect of tropical cyclones on tree mortality, terrestrial carbon transport, ocean primary production and air-sea co2 fluxes were singled out and researched. Factors playing into these processes and the speculated impact of the changing climate were analysed. Case studies on each of these processes were examined and their impact and importance was quantified. As tropical cyclones mainly impact the oceans and make landfall between 45° north and 45° south of the equator, these areas were focused on. Both modelled and observed methods of research were considered and reviewed.

Table of contents

Abbreviations

TC – Tropical Cyclone

Gg – Gigagram

Tg – Teragram

Pg – Petagram

CWD – Coarse Woody Debris

NPP – Net Primary Productivity

POC – Particulate Organic Carbon

SST – Sea Surface Temperature

pCO_2 – Partial pressure of CO_2

1. Introduction and background

Tropical cyclones originate mainly between 5° and 30° north and south of the equator, and are fuelled by heat flux from the ocean to the atmosphere (a schematic diagram of the formation of tropical cyclones is shown in Figure 1). The storm systems range in size from a couple of hundred to thousands of kilometres in diameter. A storm is classified as a tropical cyclone once its maximum sustained wind speeds reach 33 ms^{-1}. At higher wind speeds, the Saffir-Simpson scale indicates the intensity of the storm. In addition to high wind speeds, tropical cyclones often contain several thunderstorms that carry extremely high levels of precipitation which can cause flooding events. These are frequently exacerbated by swells brought on by the gale force winds and low atmospheric pressure found in tropical cyclones (TC), which means that coastal communities and ecosystems are particularly vulnerable to their effects.

Apart from their devastating effect on coastal communities in the form of loss of life and economic damage, TCs affect the carbon cycle. Terrestrial effects are limited mainly to eastern coastal areas of landmasses, as trade-winds and poleward movement generally lead to a west north-west trajectory for TCs. High levels of tree mortality are caused by the high wind speeds of tropical cyclones that make landfall by uprooting trees and damaging the canopy of forests. As the photosynthesizing capability of the trees is reduced, growth and carbon dioxide uptake are stunted. The windfall created by the TC is turned into a source of carbon dioxide to the atmosphere as it decomposes, and leads to higher risk of forest fire due to the massive accumulation of coarse woody debris (CWD) (McNulty 2002; Zeng et al. 2009). Additionally, dead and damaged trees are more vulnerable to insect infestation, which have the potential to lead to significant tree mortality (Ravn 1985; Fredericksen et al. 1995). Extensive rainfall and flooding brought on by a TC lead to increased incidence of landslides and large scale erosion, which further damages forest habitats and increases tree mortality (West et al. 2010). Nutrients are returned to the soil by the decomposition of the windfall and post-TC tree growth is enhanced, however, on average TCs lead to permanently impaired tree growth in areas with high return frequencies and therefore a net negative impact on a forested ecosystem (Ruffner 1978; Conner 1998; Tanner et al. 2014).

As riverbanks and forested areas are flooded, substantial amounts of roots, dead branches and whole trees can be transported to the oceans through river systems (West et al. 2010). This CWD and POC changes nutrient availability and physical conditions in estuarine and marine ecosystems significantly, while it is oxidizing and decomposing slowly in low oxygen conditions (Maser and Sedell 1994; Wohl et al. 2009). Depending on the turbidity of the flow and concentrations of POC and CWD, these fluxes of carbon can be submerged into the deep ocean giving rise to a carbon sink (Mulder and Syvitski 1995; Hilton et al. 2008).

TCs influence the ocean dynamics. The density of ocean water is determined mostly by its temperature and salinity. The temperature of the ocean decreases steadily with depth in the mixed layer up until the thermocline. Beyond the thermocline, the water temperature and density only varies marginally. Tropical cyclones can induce mixing below the thermocline due to extreme wind stress, leading to upper ocean water being cooler in the wake of a tropical cyclone. As nutrient density and dissolved inorganic carbon levels increase with depth, the cold water that wells up during a TC leads to increased nutrient availability in the euphotic zone (Eppley and Renger 1988; Marra et al. 1990). This can cause a substantial increase in primary production in the aftermath of TCs (Dickey et al. 1998). Lin et al. (2003) estimate that 20-30% of the total primary production in the South China Sea in the year 2000 was brought on by tropical cyclones (Lin et al. 2003). During the storm, high wind speeds lead to heightened fluxes between the ocean and the atmosphere. Carbon dioxide is transported out of the ocean by the TC, but as CO_2 readily dissolves in water it is mixed back in the aftermath of the storm (Bates et al. 1998; Lévy et al. 2012).

1.1 Aim

In this work, the available literature on tropical cyclones and their connection to the carbon cycle in the described forms is analysed. As this review is limited in time, its focus will lie on the effect of tropical cyclones on the carbon balance of forested ecosystems and the oceans euphotic zone. Particular attention is paid to the implications of recent findings and gaps in research still to be filled. The feedback mechanisms between the climate and tropical cyclones and the role of climate change is discussed in detail. The primary aim is to establish what the influence of tropical cyclones on the carbon cycle is. In order to fulfil the aim, the following questions will be researched:

- How do tropical cyclones affect the carbon balance?
- In how far do tropical cyclones affect terrestrial carbon transport, and what happens to the carbon once it reaches the oceans?
- How do tropical cyclones affect forested ecosystems?
- How do tropical cyclones affect ocean dynamics and air-sea fluxes?
- Are there any feedback mechanisms between these processes and tropical cyclones?
- How are tropical cyclones influenced by climate change already, and how will they be affected in the future?

2. Methodology

2.1 Methods of literature review

This study is a literature review. The literature was chosen based on its relevance to the subject and its recentness, to ensure that the research is not outdated and possibly obsolete. Priority was given to research published in renowned journals, based on their Impact Factor. Both observational and modelled studies were used and reviewed.

The initial work of the thesis consisted of reading and compiling literature, and reviewing articles of import. After preliminary work was presented, the focus of this thesis was narrowed down from the impacts of tropical cyclones on the entire climate to the impacts on processes within the carbon cycle. The references were compiled and configured using ENDNOTE.

2.2 Methods of past published studies

Observational studies

Observational studies were of great import to this literature review. These can be separated into two categories: on site observational studies, and studies conducted using remote sensing.

A typical long-term plot study was conducted by Burslem et al. (2000), consisting of an on-site evaluation of the short-term effects of tropical cyclones and the long-term recovery of tropical rain forests on Kolombangara, one of the Solomon Islands. The climatic conditions, geology and geography of the island were reviewed and described in detail. A census of the tree species was conducted and the forest was divided into forest types to simplify classification. The distribution of these forest types over the island was ascertained. Plots were established in 1964, and they were chosen in accordance with the forest types to establish full coverage of the islands tree species. Each plot was 1.5 acres (0.6 ha) in size and located on flat land. Trees of each species that were larger than 15 cm in diameter were tagged and measured as well as relocated frequently over the coming decades, depending on their state. Crown exposure and maturity of the trees was measured or estimated to determine the impact of extreme wind speeds.

The datasets were then statistically analysed to obtain information about average and plot-level tree mortality and recovery in relation to the frequency and intensity of TCs that struck the Solomon Islands (Burslem et al. 2000).

A representative study, which uses aspects of observational and modelling studies, was conducted on Taiwan by West et al. (2010). Its focus lay on the mobilization and transport of coarse woody debris to the oceans triggered by an extreme tropical storm. High spatial-resolution FORMOSAT-2 satellite imagery was used to determine landslide areas across Taiwan. A supervised classification of bare areas was performed using the Normalized Difference Vegetation Index (NDVI). The slope was used to distinguish bare areas in landslide areas from bare areas not brought on by landslides. Lastly, the landslide areas were individually reviewed and corrected if necessary (West et al. 2010).

Modelling studies

Data about the impact of TCs are often difficult to acquire due to extreme conditions inside the storm and cloud cover obstructing light hindering the attainment of remotely sensed data. Modelling the conditions inside the storm provides a way around these difficulties.

Huang and Imberger (2010) performed a modelling study on variation of partial pressure of CO_2 in ocean surface water in response to the passage of a hurricane. They used previously validated models. The main model used was a hydrodynamic model called the ELCOM model to study mixing and turbidity in the upper ocean. Incorporated in this model was a carbon model which used factors and parameters known to influence the partial pressure of CO_2 in water, such as dissolved inorganic carbon, alkalinity, temperature and salinity. Various equations from previously published literature were used. The model was set up based on data obtained from measurements taken during Hurricane Frances and aimed to imitate the conditions assumed to be prevalent during the passage of a tropical cyclone (Huang and Imberger 2010).

3. Results of literature review

3.1 Impact from Tropical Cyclones on the Terrestrial Carbon Cycle

3.1.1 Forested Ecosystems

3.1.1.1 Tree Mortality

Forested ecosystems recovering from land use and other processes around the globe produce a net carbon sink of 1 to 2 Pg C yr^{-1} (Bousquet et al. 2000). Strong TCs impact carbon release of forested ecosystems over many decades. The carbon balance is affected by the initial damage, the recovery time of the forests, and delayed mortality (McNulty 2002).

3.1.1.1.1 Immediate effects

Initial damage of TCs on forested ecosystems due to extreme wind speeds and strong precipitation consists of uprooting of trees, defoliation of canopies and breaking of branches and stems (Zimmerman et al. 1994). The severity of forest damage can be expressed as a function of wind speed, in which damage increases exponentially at higher wind speeds (Xi 2015). Trees with a large diameter are more likely to be uprooted and cause a domino effect when they collapse onto adjacent trees, whereas smaller trees are more likely to bend and snap but are seldom uprooted (Gresham et al. 1991). Pre-TC conditions play a significant role in determining the vulnerability of a forested ecosystem. If the soil moisture levels pre-TC are high, uprooting effects were more likely to occur (Xi et al. 2008). Storm surges brought on by a TC may also lead to widespread forest damage (Juárez et al. 2008).

TCs lead to a substantial increase in the amount of dead tree biomass and a decrease of the amount of carbon that is absorbed by forests, and might be detrimental to total storage capabilities of forests (McNulty 2002). Increased decomposition may weaken the CO_2 sink function of a forest (Juárez et al. 2008). The immediate tree mortality caused by a single TC is largely dependent on the forest density of the landfall location (Zeng et al. 2009). Hurtt et al. (2000) note a long-term trend of lower tree mortality caused by TCs in recent decades relating to a decrease in the forested area and the average age of forests, and thus decreased tree exposure and carbon density (Hurtt et al. 2006).

Short-term tree mortality rate may vary widely across all forests. Everham and Nicholas (1996) report an initial tree mortality rate between 1-25% for tropical forests struck by TCs (Edwin M. Everham and Nicholas 1996).

3.1.1.1.2 Long-term effects

The catastrophic mortality associated with the immediate effect of tropical cyclones on forested ecosystems may alter regeneration patterns, and provides an ideal environment for colonizing vegetation (Lugo and Scatena 1996; Gagnon and Platt 2008). Forested areas frequently affected by TCs will often not be filled with mature trees, but rather with young trees that form a successional forest, depending on local environmental conditions. This reduces the average density of trees, i.e. proximity of one tree to the next, compared to mature forests, whereas the basal area is increased (Twilley et al. 1992). Sanford et al. (1991) report that soil nitrogen is increased with frequent TC activity and that lasting forest productivity is improved (Sanford et al. 1991). However, McNulty (2002) criticizes that this result is uncertain as the study was never validated (McNulty 2002).

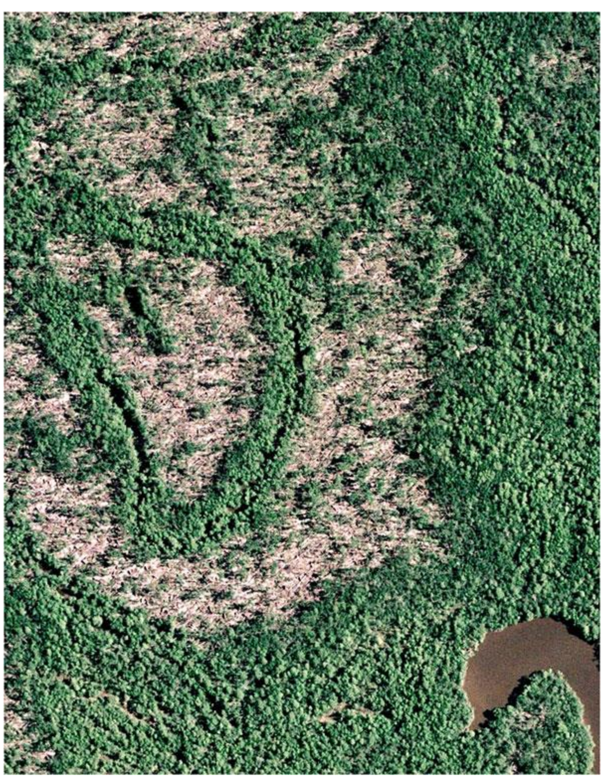

Figure 2: Forest damage caused by Hurricane Katrina (2005). NASA Satellite Image, open source.

The removal of large swaths of the canopy of a forest can lead to increased soil exposure to incoming radiation, decreasing moisture availability and changing the surface albedo and thus altering the regional climate (Carlton and Bazzaz 1998; Juárez et al. 2008).

Windfall increases the risk of forest fires (Myers and van Lear 1998). This risk is increased depending on the amount of woody debris left in the wake of a TC. In the wake of Hurricane Hugo, a category 5 hurricane that formed in the Atlantic Ocean in 1989 and caused extensive damage in Puerto Rico and the United States. It left between 1.5 and 3-meter-deep woody debris in its wake. In the following fire season 8500 hectares of forest burned, a maximum in the previous 6 years (Miranda 1996). Furthermore, trees damaged by a TC event are more vulnerable to the effects of insect outbreaks, for which the likelihood increases after a TC due to a reduction in the photosynthetic capability of the remaining trees (Ravn 1985; Fredericksen et al. 1995).

Timber is salvaged in the wake of a TC to decrease the amount of carbon lost from the sequestration pool to the atmosphere, and reduce the risk of forest-fire and insect outbreaks. The share of non-salvaged wood compared with the share of salvaged wood regulates the total release of carbon from the woody debris left behind by a TC. This share is determined by the site of TC induced damage, its accessibility, and the state of the debris (McNulty 2002). Miranda estimates that 9% of the woody debris following Hurricane Hugo was salvaged in an extensive and well-coordinated operation (Miranda 1996).

Forest recovery

Tree recovery from TC damage is estimated to last at least 15 years, but plots may require much longer regrowth periods (Merrens and Peart 1992; Conner 1998). Frangi and Lugo suggest that a four-hour hurricane event caused change that lasted up to 60 years in a tropical forest ecosystem (Frangi and Lugo 1991). High rates of mortality have been observed up to 42 months after a tropical cyclone struck a forested ecosystem, suggesting that continued observation and monitoring of affected forests is necessary for a comprehensive account of the carbon balance (Wolfgang 1985). These prolonged periods of recovery lead to a long-term loss in carbon sequestration capacity. Trees can be directly destroyed by TCs and their carbon released through decomposition over the following years, or the trees survive the initial storm exfoliated and with loss of branches, or in some cases loss of larger parts of the canopy. Hurricanes affect mature vegetation more significantly than young vegetation, and young vegetation replaces the mature vegetation. As young vegetation has higher rates of net primary production (NPP), this has a compensating effect on the loss of carbon. This effect is enhanced by the increased availability of nutrients after a TC, due to the decomposition of windfall (McNulty 2002).

The most significant mechanisms of regrowth are re-sprouting of damaged stems or crowns, and new individuals growing from seeds or saplings that benefit from the release of nutrients from the CWD (Burslem et al. 2000). Boucher et al. (1994) find that because the most likely form of regeneration after a strong disturbance like a TC is re-sprouting from stems and branches, the species dominant before the TC will be the most dominant in the first years after the TC (Boucher et al. 1994). Therefore, determining the species composition after TC disturbance is not vital to recording the carbon balance of a forest, although Burslem et al. report otherwise. According to Burslem et al. (2000), knowledge about the species composition after the damage has occurred is required to estimate the post-TC carbon balance of a forest, and cannot be inferred to be similar to the composition before (Burslem et al. 2000). If the species composition before the TC struck is known to be shade intolerant, regrowth will be slowed down, as the windfall will shade the soil (Tanner et al. 1991). Nicholas and Walker (1991) report that forests regrow rapidly after hurricane damage (Nicholas and Walker 1991). The stem-diameter growth rate of surviving trees over a period of 21 years following a TC was found to be elevated, where undamaged trees grew more rapidly than damaged ones. The growth rates were found to be especially high in the years directly following the TC (Tanner et al. 2014).

3.1.1.1.3 Case Studies

Tree mortality and carbon release

On Kolombangara, an island of the Solomon Islands, four TCs struck between 1967 and 1970. The mortality rate depended largely on the species, but was found to range from 6.5 to 10.9% during these four years. The steady state mortality in the years before was estimated to be between 0-2.61% (Burslem et al. 2000).

Hurricane Katrina struck the southern coast of the U.S. in 2005 and caused an estimated 320 million trees to be severely damaged or destroyed by initial wind damage. The carbon released by this event was found to be around 105 Tg, which corresponds to between 50-140% of the total net annual U.S. carbon sink into forested ecosystems (Pacala et al. 2001; Chambers et al. 2007). The TC led to the release of up to 77.6 Mg C ha^{-1} (Chapman et al. 2008). As a category 4 on the Saffir-Simpson scale, a storm such as Hurricane Katrina is unlikely to make landfall on U.S. soil more than once every 100 years (Elsner et al. 2006). Compared with the 1-2 Pg C annually taken up by recovering forests, a release of 105 Tg constitutes a loss of around 5-10% of carbon (Bousquet et al. 2000; Chambers et al. 2007).

Averaged over New England, tropical cyclones lead to the release of 1 Mg C ha^{-1} yr^{-1}. According to Brown and Schroeder aboveground production of woody biomass in this area between 1970 and 1980 was 1-4 Mg C ha^{-1} yr^{-1} (Brown and Schroeder 1999).

The carbon released over the period 1980-1990 by TCs over the U.S. potentially offset the U.S. forest carbon sink by about 9-18% (Zeng et al. 2009). Averaged over the 150 years between 1851 to 2000, an estimated 97 million trees in the entire U.S. were lost to the direct impact of tropical cyclones annually, corresponding to a carbon loss of 53 Tg, and a source of 25 Tg to the atmosphere. A peak in hurricane activity, both in frequency and intensity, between the year 1870 and 1900 caused a pronounced spike in tree mortality in the U.S. (Landsea et al. 2004). As more old forests existed in the 19th century and the early 20th century and there was more tree cover, TCs damaged a higher number of trees (Zeng et al. 2009).

The strongest windfall was directly related to the highest wind speeds (Uriarte and Papaik 2007). McNulty finds a range between 2.9 and 20 Tg of carbon detritus created by four TCs of varying intensity (McNulty 2002). Large annual variations in mortality occur due to differences in tropical cyclone activity.

Forest recovery

Twilley et al. (1992) report that biomass in mangroves is constrained in areas with frequent TCs (Twilley et al. 1992). Mangrove trees located on the west coast of the Yucatan were found to have significantly higher biomass than those on the east coast, where storms are more frequent (Ruffner 1978). Forest productivity was found to be decreased for periods between 14 and 19 years in forests in South Carolina after Hurricane Hugo (Conner 1998).

Tanner et al. (2014) monitored a forest plots' tree mortality in Jamaica following Hurricane Gilbert in 1988 (Figure 3). Damaged stem mortality was significantly higher following the TC, and required up to 21 years to return to pre-hurricane rates. Undamaged stem mortality was reduced markedly in the years following the TC. The annual probability of stem mortality of damaged trees increases by up to four percentiles in the year following the TC, and then decreases near linearly over 21 years to the level of the undamaged trees, which hover around 1% stem mortality. The annual probability of stem mortality of the undamaged trees is reduced from 1% to around 0.5% in the years following the TC (Tanner et al. 2014).

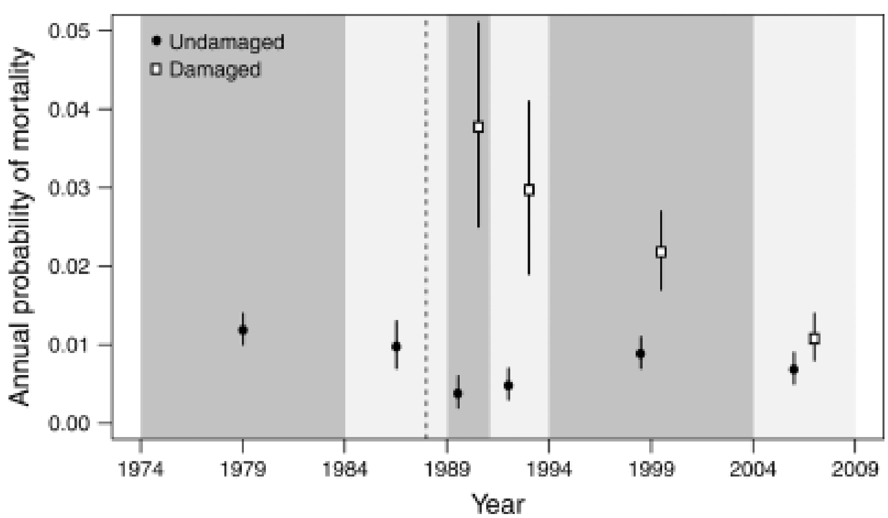

Figure 3: Long-term effects of Hurricane Gilbert on stem mortality in a plot in Jamaica. The year of the hurricane is marked by the dashed line (1988). The shaded background marks the periods of the censuses (Tanner et al. 2014).

3.1.1.2 Terrestrial carbon transport to the oceans

A key component of the carbon cycle is terrestrial carbon transport from rivers to the ocean (e.g. (Ittekkot 1988)). Small mountainous rivers are an especially large source of sediment and particulate organic carbon to the ocean (Milliman and Syvitski 1992; Kao and Liu 1996; Lyons et al. 2002; Carey et al. 2005; Syvitski and Milliman 2007). In tropical latitudes, rivers will be affected by TCs which strongly determine their shape and therefore their future discharge levels (Filippelli 1997; Gomez et al. 2004). TCs mostly flush out previously weakened sediment. This weakening can occur due to seismic effects, continuous erosion or a previous TCs' effects (Dadson et al. 2003; Dadson et al. 2004). Many riverine floods brought on by TCs create hyperpycnal flows and bury terrestrial sediment offshore, which puts it out of reach of the carbon cycle. Offshore mud sampling confirms that the carbon to nitrogen ratio of sediment buried off the coast of TC affected landmasses is the same as the ratio of terrestrial organic matter, suggesting that long-term burial and preservation of terrestrial carbon occurs via this pathway (Dadson et al. 2005; West et al. 2010). The sudden influx of dissolved particles to coastal and marine ecosystems can trigger an increase in primary production in the form of phytoplankton blooms (Mallin et al. 1993; Yuan et al. 2004).

3.1.1.2.1 Transport of Coarse Woody Debris

TCs can mobilise large amounts of CWD as they flood riverbanks and carry photosynthetic carbon such as branches and dead trees. The effects of this CWD transport is underreported and not well quantified, due to the transport of large debris (often given at >10cm in diameter) only occurring in large flooding events which make monitoring and taking measurements significantly more problematic (West et al. 2010).

CWD has properties that are important to terrestrial ecosystems and marine ecosystems alike. The debris delivers vital nutrients to the euphotic zone of the oceans, and regulates the cycling of carbon (Maser and Sedell 1994; Wohl et al. 2009; West et al. 2010). The large efflux of CWD changes the conditions in the open oceans. The temperature and light incidence in the open sea might be reduced significantly by drifting CWD. Another area that would be impacted are benthic ecosystems. However, the effects of large tropical cyclone effluxes of CWD on marine ecosystems has not been quantified accurately (West et al. 2010). CWD was found to oxidize slowly and to be transported for very long distances (Spanhoff and Meyer 2004). If the vegetation affected by landslides regenerates more quickly, this process could constitute a carbon sink (Hilton et al. 2008; Restrepo et al. 2009).

Figure 4: A water reservoir transporting substantial amounts of coarse woody debris in Taiwan after the passage of a tropical cyclone.

Taken from: Mobilization and transport of coarse woody debris to the oceans triggered by an extreme tropical storm (West et al. 2010). Photo by Po-Lin Chi.

3.1.1.2.2 Transport of Particulate Organic Carbon

Exports of particulate organic carbon are highest during storm events (Hood et al. 2006; Jeong et al. 2012). More than a third of the organic carbon transport from the terrestrial biosphere to the oceans comes from western Pacific mountainous rivers (Wollast 1993; Schlünz and Schneider 2000). Most of this transport is TC induced (Hilton et al. 2008). Whether this transport and subsequent burial constitutes a carbon sink or not depends on the nature of the particulate organic carbon (POC). If it is photosynthetically derived carbon (non-fossil) it is a sink, if it is carbon that is not actively cycled as it is stored in deep soils (fossil), it is not (Stallard 1998; Hayes et al. 1999; Blair et al. 2003). High levels of non-fossil POC during rainfall events can be induced by overland flow (Larsen et al. 1999).

After entering the ocean downstream, 90% of the photosynthetically derived POC is estimated to be remineralised (Hedges et al. 1997). Hyperpycnal flow, however, can lead to turbidity currents that deposit non-fossil POC to deep ocean basins (Mulder and Syvitski 1995; Hilton et al. 2008). Hyperpycnal flow during flooding periods induced by TCs have been observed to last long enough to transport as much as 90% of non-fossil POC. The burial of this POC in areas such as Taiwan mainly ensues when tropical cyclones occur. Within the Intertropical Convergence Zone (ITCZ), a combination of swift erosion, frequent tropical cyclones and tectonic activity leads to floods that reach hyperpycnal density due to high levels of POC and CWD, which leads to high potential of burial of non-fossil POC. Hilton et al. (2008) conclude that without the frequent occurrence of TCs photosynthetically derived carbon will only be delivered to the ocean partially, and stress the significance of this mechanism and its susceptibility to a changing climate (Hilton et al. 2008).

3.1.1.2.3 Case Studies

Coarse Woody Debris transport

West et al. (2010) monitored the effects of TC Morakot on landsliding and mass wasting in Taiwan. The yield to the oceans was estimated to be between 9.3-19.1 Gg km^{-2} of CWD for one of the catchment areas monitored. Extrapolated over the entirety of Taiwan, 3.8-8.4 Tg of CWD were expelled to the oceans during the TC Morakot event, which translates to 1.8-4.0 Tg C (West et al. 2010). This flow was estimated to be around 200-400 times as much as the annual CWD yield from Japanese rivers to the ocean, even though the landsliding and mass wasting densities were observed to be within the norm (Seo et al. 2008; West et al. 2010). Additionally, the CWD delivered by TC Morakot is equivalent to 10-26% of the annual POC efflux from the Amazon River to the oceans in terms of carbon (Schlünz and Schneider 2000; West et al. 2010). The return time of TCs such as Morakot to Taiwan was not estimated. Due to interplay between TCs and the monsoon, West et al. (2010) suggests that Morakot was a storm with anomalously high precipitation (West et al. 2010).

Particulate Organic Carbon transport

TC Mindulle and Aere struck Taiwan in 2004. Measurements taken during these TCs found elevated levels (up to 43%) of non-fossil POC suspended in the LiWu River (Hilton et al. 2008). Landslides occurring during the TC event contributed significantly to the carbon transport in the form of POC and CWD, by delivering smaller vegetation and whole tree trunks along with roots to the river channel. The flood in the LiWu River brought on by TC Mindulle is estimated to have transported around 5,5 Gg of non-fossil carbon in the form of POC. The catchment of the LiWu river is about 10% of the surface area of Taiwan. A transport of 16 to 202 Gg of photosynthetically derived carbon km^{-2} y^{-1} was estimated for the LiWu river by extrapolation of measurements performed during TC Mindulle and Aere, at a yield rate of 13 Mg C km^{-2} for TC Mindulle (Hilton et al. 2008). TCs such as Mindulle have a low return period of around half a year in Taiwan (West et al. 2010).

This rate of transport is among the highest in riverine systems when compared globally (Ludwig et al. 1996; Stallard 1998; Hilton et al. 2008). When compared to the CWD yield of Typhoon Morakot the POC value expelled by Mindulle is a small fraction, which is consistent with lower precipitation values observed during TC Mindulle (West et al. 2010). Landmasses within the ITCZ have higher rates of riverine carbon transport in general, however, rivers in New Zealand that are not within the ITCZ but affected by TCs have non-fossil POC levels comparable to those of the river LiWu (Leithold et al. 2006; Hilton et al. 2008). Dadson et al. (2005) concludes that TCs are responsible for the majority of dissolved solute weathering fluxes to the ocean (Dadson et al. 2005).

During a flooding induced by Hurricane Nicole in 2010, 9 kg of C ha-1 were flushed into riverine systems in Maryland from a 12-hectare large forested catchment. In 2011, Hurricane Irene caused floods that led to POC levels of 21.2 kg of C ha-1. The latter contributed 56% of the annual POC efflux from the forested catchment, whereas the contribution of Hurricane Irene to the annual precipitation in this catchment was 155 mm of the total 1462 mm in 2011, which equates to a relative share of 10.6%. Stormflow POC levels amounted to 76% of POC export in 2011, compared to baseflow comprising 24% (Dhillon and Inamdar 2013).

3.2 Impact from Tropical Cyclones on Ocean Processes

3.2.1 Dynamical mechanisms for Ocean-Atmosphere coupling

3.2.1.1 Oceanic entrainment across the thermocline

In undisturbed ocean waters, the stratification is determined by the density of the water, and the density is in turn determined by the temperature and salinity of the water. An upper mixed layer equilibrium is established over time, separated from the deep ocean by the thermocline below. Below the thermocline, the water is cool and nutrient rich. Above the thermocline, the water is warm and nutrient-poor but rich in light.

A tropical cyclones' strong winds mix the water column directly and reach beneath the upper layer of the ocean subject to permanent mixing causing entrainment, therefore propagating heat beneath the thermocline and pumping cool water to the surface (Jansen et al. 2010). This cold, nutrient rich water is brought to the euphotic zone and is used by phytoplankton to enhance primary production (Eppley and Renger 1988; Marra et al. 1990; Dickey et al. 1998). The strongest upwelling during the passage of a TC can be found in and around the centre of the storm, where the strongest wind speeds occur. However, massive entrainment has been observed in TCs with slow translation speeds (Lin et al. 2003; Shi and Wang 2007).

3.2.2 Enhancement of Primary Production by disturbance of dynamic mechanisms

Phytoplankton consume carbon dioxide and play an important role in the air-sea exchange of CO_2. Tropical cyclones enhance primary production, and the enhancement is dependent on the strength of the storm (Lin et al. 2003; Hanshaw et al. 2008; Lin 2012; Foltz et al. 2015). Primary production affects the uptake of carbon dioxide, and therefore the climate (Eppley and Peterson, 1979). The effects of TCs on primary production are most strongly found in areas such as the subtropics, which have a very distinct thermocline close to the surface. The vertical distribution of nutrients was found to be the most important factor determining the response of primary production to TCs, while pre-existing conditions in the areas affected, such as inertial currents and strong stratification played a smaller role. Phytoplankton are mixed upwards by TCs. Along with increased nutrient availability, this further enhances the primary production in the upper ocean layer in the wake of TCs (Babin et al. 2004). Stronger, fast moving TCs were found to produce lower chlorophyll A concentrations but affect a larger area (Zhao et al. 2008; Wang et al. 2014).

Historically, there was a disconnect between the amount of primary production observed and the amount that should theoretically be there, and some phenomena including Rossby waves, internal waves, and TCs were suspected as being the cause (Eppley and Renger 1988; Marra et al. 1990; McGillicuddy and Robinson 1997; Dickey et al. 1998; Uz et al. 2001).

Lin et al. suggest that primary production induced by tropical cyclones has not been accurately measured, and reasons that quantifying the enhancement of primary production by TCs is a difficult process that has previously not been possible due to inadequate technology. Additionally, the type of sensor required to observe biochemical ocean responses (visible and specific infrared frequencies) is obscured by cloud cover, which is prominent during TC events (Lin et al. 2003). Foltz et al. find a substantial increase in primary production in every TC that passed through the subtropical North Atlantic between 1998 and 2001 (Foltz et al. 2015). Hanshaw et al. (2008), however, suggest that TCs are not frequent and large enough to significantly alter primary production in the oceans and propose that other events produce anomalies that are larger than those produced by TCs. Additionally, the integrated effect of TCs on primary production may have been lower than previously estimated. In the North Atlantic the integrated effect of TCs on the primary production is in the lower percentiles (Hanshaw et al. 2008).

3.2.3 Air-Sea exchange of CO_2

Tropical cyclones can cause substantial fluxes of CO_2 between the ocean and the atmosphere (Bates et al. 1998; Bates 2007). The partial pressure of CO_2 (pCO_2) is largely determined by the water temperature, the alkalinity and salinity, and dissolved inorganic carbon levels. Of these, the sea surface temperature (SST) is the dominant factor (Takahashi et al. 1993; Mahadevan et al. 2011). Temperature change leads to a decrease of pCO_2 given at 4.23% per degree Celsius (Takahashi et al. 1993). Vertical mixing induced by the TC leads to an increase in dissolved inorganic carbon upwelling to the surface waters (Koch et al. 2009; Huang and Imberger 2010). The partial pressure of CO_2 in the oceans is directly related to the efflux of CO_2 from the oceans to the atmosphere. It is reduced as a result of the upwelling of nutrients induced by a TC, which leads to higher primary production and therefore consumption of CO_2 by phytoplankton (Lévy et al. 2012). Additionally, the increased piston velocity during TCs plays an important role in regulating the efflux (D'Asaro and McNeil 2007; McNeil and D'Asaro 2007). The lack of pCO_2 data during the passage of TCs due to extreme conditions has led to inaccuracies and uncertainty in the estimation of the effect of TCs on the CO_2 efflux from the oceans (Bates 2007). A moored buoy in the South China Sea obtained measurements with a three-hour frequency during a TC. From these measurements, it was inferred that pCO_2 of surface waters is mainly determined by vertical mixing induced by extreme winds (Nemoto et al. 2009).

Entrainment persists after the storm passes, which leads to the SST and pCO_2 being reduced up to a month after the passage of the TC. This leads to carbon dioxide being taken up by the ocean, which can balance the efflux effect of the TC (Lévy et al. 2012).

Huang and Imberger (2010) showed that both the atmospheric partial pressure and the ocean water partial pressure of CO_2 decrease during the passage of a tropical cyclone using a coupled hydrodynamic carbon model. The efflux of CO_2 to the atmosphere is maximal during the highest wind speeds. The minima of pCO_2 in the lower atmosphere coincide with the passage of the eyewall and the eye of the TC, whereas the pCO_2 of the upper ocean decreases during the whole passage period of the TC. These effects were found to be less pronounced further away from the centre of the TC, and the CO_2 flux drops substantially during the passage of the eye itself (Huang and Imberger 2010).

3.2.4 Case Studies

Enhancement of Primary Production by disturbance of dynamic mechanisms

Lin et al. (2003) quantified the impact of Typhoon Kai-Tak on primary production in the South China Sea (Lin et al. 2003). Typhoon Kai-Tak, a category 2 storm on the Saffir-Simpson scale, persisted for four days on the South China Sea before moving northwards. As Typhoon Kai-Tak was a slow-moving TC, wind speeds were increased over the same area for a longer period and the upwelling and entrainment effects were enhanced. The sea surface temperature was reduced by between 6-9 degrees Celsius in the wake of the TC (Price 1981; Price et al. 1986; Lin et al. 2003).

The response of the phytoplankton matched the radius of the Typhoon, and the cold-water body left behind, accurately. Chlorophyll A concentrations on the surface of the wake were found to have increased from ≤0.1 mg/m³ to 3.2 ± 4.4 mg/m³ a few days after the passage of the TC. The highest numbers of chlorophyll A concentrations recorded were 30 mg/m³, which constitutes an at least 300-fold increase from pre-TC conditions. The deep mixing and increased pumping velocity may explain the heightened nutrient availability required to induce the amplified primary production (Lin et al. 2003).

Carbon fixation in this single event was estimated at 0.8 Tg. Lin et al. (2003) states that this is a minimum estimate, as several days of primary production were not included due to lack of cloud-free data. The 0.8 Tg estimate constitutes around 2-4% of the South China Sea annual primary production. For all TCs, the impact on the South China Sea is given as a 20-30% contribution to total annual primary production. (Lin et al. 2003). The South China Sea is one of the areas most frequented by TCs and an area of significant TC genesis (Wang et al. 2007).

The strength of the TC does not determine the biological response in the form of a phytoplankton bloom. Typhoon Hagibis, a category 1 storm on the Saffir-Simpsons scale, and therefore a relative weak TC, had a very large impact on the chlorophyll A concentrations in the South China Sea. A long upwelling time and high upwelling velocity induced strong and deep mixing of the upper ocean, leading to a phytoplankton bloom that produced around 30% of the total yearly chlorophyll a generation of the South China Sea. However, Sun et al. (2010) suggest that only Typhoon Hagibis had a significant impact on primary production in the South China Sea between 1997 and 2007 (Sun et al. 2010).

Zhao et al. (2008) and Sun et al. (2010) find low impacts on primary production by TCs. According to Zhao et al. (2008) only 3.5% of the annual primary production in the South China Sea is induced by TCs, whereas Sun et al. (2010) states that only Typhoon Hagibis had a significant impact on the primary production in the South China Sea between 1997 and 2007 (Zhao et al. 2008; Sun et al. 2010).

A phytoplankton bloom was observed in the wake of hurricane Katrina. Pre-hurricane concentrations of chlorophyll A were around 0.1 mg/m3. The chlorophyll A concentrations reached 1.5 mg/m³ at its highest point after hurricane Katrina passed, and the maximum reduction in SST was 6-7 degrees Celsius.

Both the increase in primary production and the lowered SST coincide with where the strongest upwelling occurred, which is where the center of the TC passed. One week after the maximum concentrations of chlorophyll A were observed, the levels returned back to near pre-storm levels (Shi and Wang 2007).

Babin et al. (2004) examined 13 TCs which occurred between the years 1998 and 2001 in the Sargasso Sea area in the North Atlantic Ocean. A decrease of SST and an increase in chlorophyll A concentrations in the surface waters was found in the wake of every TC, and the parameters were found to be correlated. The increase in primary production ranged between 5 and 91%, however, the absolute magnitudes found were relatively low and the contribution to total annual primary production was found to be around 1% per TC. The chlorophyll A values ranged from 0.0551 to 0.1513 mg/m3 (Babin et al. 2004). The Sargasso Sea is considered an ocean desert due to its low primary production (McGillicuddy and Robinson 1997; Babin et al. 2004).

Air-Sea exchange of CO_2

Hurricane Frances formed in 2004 and at maximum intensity was a category 4 TC (Beven 2004). During Hurricane Frances, the atmospheric levels of CO_2 dropped by about 20-30 μatm near the centre of the storm. This value rebounded to pre-storm levels after around one day. The levels of CO_2 in the upper ocean decreased more slowly but did not rebound until much later. A large fraction of this drop in CO_2 concentrations can be explained by lower SSTs caused by entrainment, with an increase in alkalinity leading to further reduction of CO_2 levels. Increased levels of dissolved inorganic carbon partially negated the decrease. In total, Hurricane Frances released between 3.5-10.4 Tg C (Huang and Imberger 2010).

The total annual uptake of carbon by the oceans was estimated to be around 2.0 ± 1.0 Pg by Takahashi, whereas Gruber et al. (2009) suggested a value of 1.9 (+0.6 and -0.7) (Gruber et al. 2009; Takahashi et al. 2009). Bates et al. (1998) estimates that the total annual efflux of CO_2 from the oceans is around 1.34 Pg C (Bates et al. 1998). Huang and Imberger (2010) estimate a total annual global CO_2 efflux of 0.047 – 0.141 Pg C caused by TCs, whereas Bates et al. (1998) estimate an efflux of between 0.042-0.509 Pg C. In a later paper this is revised to 0.04 to 0.08 Pg (Bates et al. 1998; Bates 2007; Huang and Imberger 2010). A more recent estimate finds that previous approximations were overestimated, and that a value of 0.007 Pg C of total annual influx of CO_2 induced by TCs is more accurate. Lévy et al. (2012) criticise that post-storm mixing effects in supersaturated regions were not considered previously (by e.g. (Bates et al. 1998; Bates 2007; Huang and Imberger 2010)), and the differing impact of TCs over undersaturated regions were not studied appropriately. Additionally, earlier results extrapolated from results obtained considering very few TCs to global oceanic efflux. According to Lévy et al. (2012), wind efflux effects and post-storm mixing are nearly balanced out on a global average (Lévy et al. 2012).

Figure 5 shows the modelled variability of CO_2 fluxes induced by TCs. Image (a) shows that the annual total effect of TCs leads to a significant uptake of up to -0.5 mg CO_2/m^2 by the North Pacific Ocean off the coast of Mexico, and an annual uptake of -0.1 to -0.2 mg CO_2/m^2 in the Gulf of Mexico. A very large region in the North Pacific Ocean off the coast of China, Japan and the Philippines shows annual effluxes from the ocean to the atmosphere on the order of 0.1 to 0.3 mg CO_2/m^2. Lastly, a region between Australia and the east coast of Africa releases between 0.1 to 0.3 mg CO_2/m^2 annually (Lévy et al. 2012).

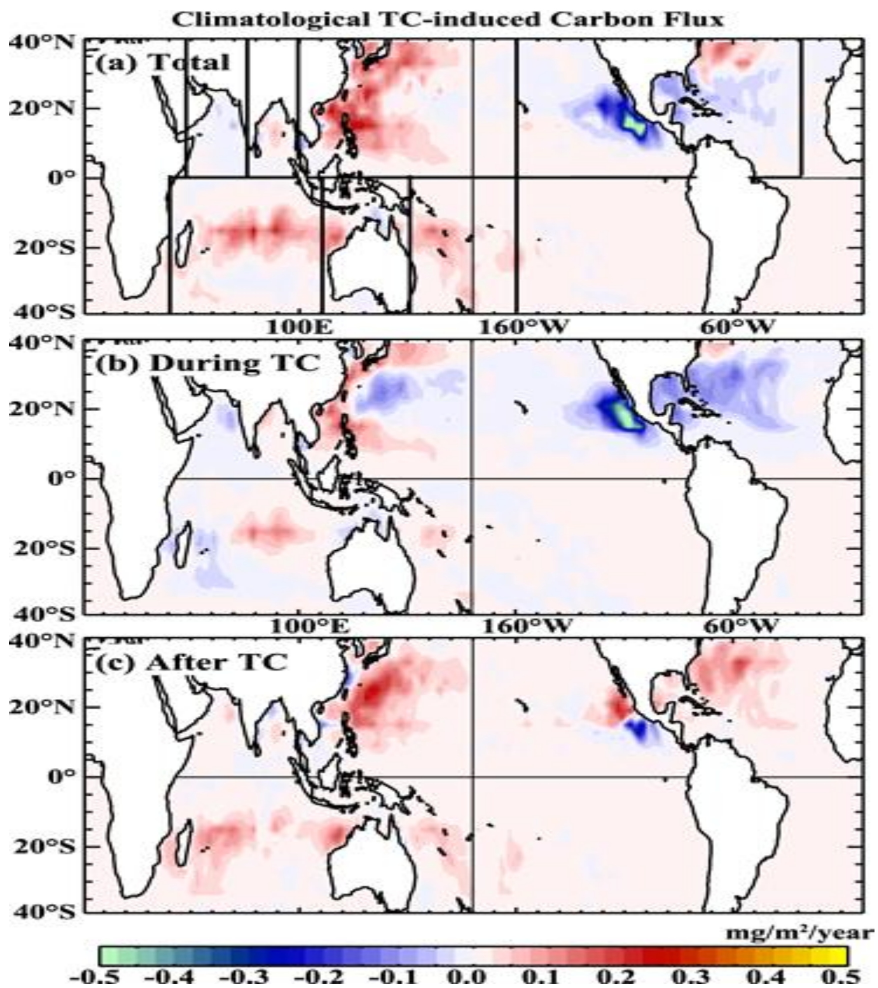

Figure 5: Cumulative average seasonal Air-Sea flux of CO_2 induced by TCs. Blue areas show a flux of CO_2 from the atmosphere to the ocean, and red areas show a flux of CO_2 from the ocean to the atmosphere. Image (a) shows the flux from 1.5 days before the TC to 30 days after the TC. Image (b) shows the flux from 1.5 days before to 1.5 days after the TC. Image (c) shows the flux from 1.5 days after the TC to 30 days after the TC. The lines divide the figure into ocean or sea basins. (Lévy et al. 2012).

3.3 Projected changes in tropical cyclones during climate change

The total global number and intensity of TCs is constrained by meridional heat transport, which in turn is limited by the imbalance in incoming radiation on earth. As climate change is projected to heat up higher latitudes more effectively, the energy imbalance will be reduced and so will the available energy for meridional heat transport. However, warmer oceans will lead to increased heat availability and potentially more intense TCs. Properties of individual TCs are determined by the energetics of latent and sensible heat release from oceanic fluxes.

Global historical measures of tropical cyclones are used to identify trends in hurricane activity, however, it is controversial whether the records are suitable for this task (Landsea et al. 2006). The records for global tropical cyclone frequency over the past century showed no clear observed trends (Knutson et al. 2010). Additionally, considering past observing capabilities, long-term trends in frequency that were observed are highly uncertain (Hartmann et al. 2013). An increase in frequency of TCs has been identified in the North Atlantic (Kossin et al. 2007).

The clear majority of models suggest that the frequency of TCs will decrease in the future. Knutson et al. (2010) suggest a reduction by between -6 to -34% globally, and substantial variation, both positive and negative, in individual storm basins. The predictions in the in the individual storm basins were made with very low confidence. In contrast to the frequency, tropical cyclones are set to increase their intensity by between 2 to 11% globally over the coming century due to an increased amount of energy available. Furthermore, rainfall values near the centre of the tropical cyclones are set to increase by up to 20% (Knutson et al. 2010).

Consistent with this review, Kim et al. (2014) found a reduction in the frequency of TCs by 19% globally with doubled CO_2 levels. Each of the TC generating basins around the world were found to have reduced TC formation. Additionally, a minor increase in intensities of TCs was observed (Kim et al. 2014). Elsner et al. (2008) and Knutson et al. (2013) suggest an increase in the amount of TCs that reach category 4 and 5, using a modelling approach (Elsner et al. 2008; Knutson et al. 2013).

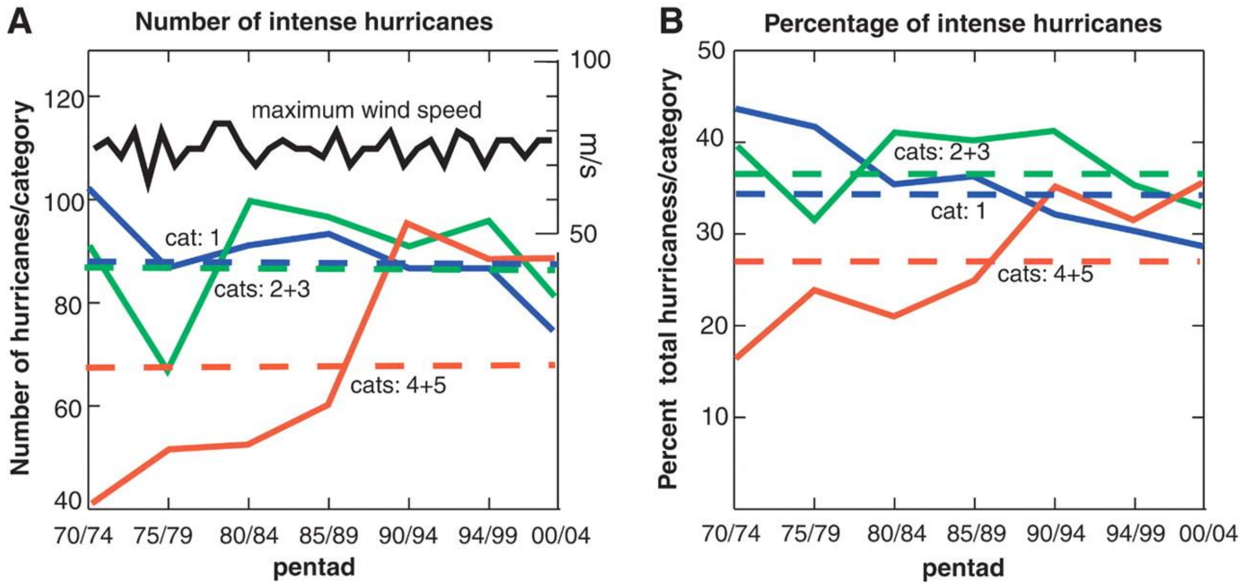

Figure 6: The observed intensities of tropical cyclones from 1970 to 2004 in the Saffir-Simpson scale. Image A shows the sum of intense hurricanes in all categories with the global maximum wind speed in black at the top. The dashed lines depict the average number in each of the categories. Image B shows the percentage of total hurricanes in each category, with the dashed lines displaying the average value. (Webster et al. 2005).

Figure 6 shows the changes in the absolute and relative number of intense TCs across the globe between 1970 and 2004. Category 1 storms used to be the most frequent type of TC. The frequency of category 1 storms decreased by around 20% in this period, whereas the incidence of category 2 and 3 storms decreased by around 10%. The relative change of category 4 and 5 storms is an increase of around 100%. The maximum wind speeds reached by TCs stayed at around the same level (Webster et al. 2005).

4. Discussion

4.1 Tree Mortality

Most researchers agree that long-term loss of carbon sequestration capacity is induced by major TCs. The damage caused leads to a reduction in a forests carbon uptake capabilities, and the decomposition of windfall releases CO2, which affects the global climate negatively. Mature and tall trees are most affected by the extreme wind speeds brought on by a TC. As mature trees have a long history of sequestering carbon, the loss of such trees is especially detrimental. However, the higher growth rate of young trees could compensate this loss somewhat. A substantial share of lost carbon could be reclaimed when the forest regenerates. With increased nutrient availability post-TC, and colonizing vegetations' rapid growth rates, regrowth periods could be short in some cases. Post-TC forest productivity has been shown to be increased in many affected forests, though mainly of the least affected trees (Figure 3).

Whether these trees can compensate for the substantial loss of carbon induced by a TC is unlikely. The mortality of the affected trees stays high for up to 42 months, which shows that immediate damage and long-term damage to a forest needs to be monitored. Connor et al. (1998) showed that the productivity of the affected forested ecosystem does not return to pre-TC levels for 15 years, which is a significant period for the effects of one TC. Depending on the damage that occurred during the TC, this period could be shorter or longer. However, as the average intensity of TCs is increasing (see Figure 6) damage to forests could be greater in the future and regrowth periods of affected forests could lengthen. As the research that was reviewed regarding the recovery periods of forested ecosystems affected by TCs came to vastly different conclusions, more research is required in this field *(Section 3.1.1.1.1 and 3.1.1.1.2).*

The salvaging of timber is a double-edged sword. Removing the coarse woody debris leads to a reduction in the risk of forest-fires and insect outbreaks, however, it would also be a removal of the nutrients captured within the trees from the forested ecosystem. This could have a negative impact on the regeneration period of the affected forest. As exposed soil tends to dry out and have insufficient moisture levels, removing the cover of debris could be detrimental to regrowth as well. If the debris is salvaged however, it could be put to good use as fuel or lumber, a somewhat sustainable resource. So far salvaging levels after the passage of TCs are very low. With knowledge about the pre-TC conditions in the forest and its soils, and about the intensity of an incoming TC, one can set up sustainable post-storm recovery and salvage plans. Prediction of the damage that will be caused by a TC is hampered by the fact that the range of observed damage is so wide (1-25% mortality given for tropical forests). However, it is clear that damage increases exponentially at higher wind speeds and is insignificant at low wind speeds. If the mortality is around 1%, it will be similar to background mortality and therefore insignificant. However, if the mortality is around 25%, this will be catastrophic for a forested ecosystem and recovery periods will be correspondingly long. Further research is required to establish what share of trees can be salvaged without affecting long-term regrowth and therefore the carbon sequestration capacity *(Section 3.1.1.1.1 and 3.1.1.1.2).*

Many forested ecosystems affected by TCs have low return periods. These form a successional forest, one with generally lower levels of carbon sequestration due to smaller tree size. If forests that are frequently affected form a permanent state of successional forests, only areas infrequently struck by TCs would constitute a long-term loss of carbon to the atmosphere. The equilibrium reached by these successional forests might however be interrupted by an exceptionally strong TC at any given time *(Section 3.1.1.1.1 and 3.1.1.1.2).*

The fact that one TC can cause a loss of carbon equivalent to the total annual uptake of carbon of a very large region such as the U.S. shows the significance of the effect of TCs on forested ecosystems. The carbon loss per hectare caused by Hurricane Katrina was on average 77 times as high as the average annual loss by forests per hectare in New England, which shows the large impact TCs of high intensity can have on forested ecosystems. While the return period for TCs such as Hurricane Katrina to the south coast of the U.S. are currently estimated to be high, this might change with increasing intensity of TCs. When compared to the 1 to 2 Pg C found to be taken up by recovering forests annually, the 105 Tg released by this single event constitutes a significant loss. Furthermore, as this value only concerns the impact of a single TCs that made landfall in 2005, the global impact could be higher. Average carbon loss induced by TCs in the U.S. compared to uptake was around 9-18% annually between 1980-1990, which is little compared to the impact of Hurricane Katrina. It can be speculated that the intensity of TCs in this period was lower, and the impact correspondingly so, but it is more likely that Hurricane Katrina was an exceptionally impactful tropical cyclone *(Section 3.1.1.1.3).*

Afforestation is often used as a means to reduce atmospheric levels of CO_2. Creating and protecting more forests, and especially mature forests, leads to an increase in trees that will be significantly impacted by TCs. McNulty (2002) and Tanner et al. (2014) suggest that long-term impact and recovery of forests affected by TCs is not well researched, and with increasing intensity of TCs the lack of information could prove significant.

4.2 Terrestrial Carbon Transport

The example of Taiwan was mainly used for CWD and POC outflushing induced by TCs. Taiwan is regularly struck by TCs and has an ecosystem with many mountainous rivers. As more than a third of terrestrial carbon transport to the ocean comes from mountainous rivers and most of this transport is induced by TCs, Taiwan is a very important region of research. However, caution must be exerted when extrapolating these findings, as Taiwan might be more prone to terrestrial carbon transport than other regions. The area is subject to intense precipitation and tectonic activity, and the erosion rates are therefore very high. This leads to both rapid mass wasting and quick regeneration of plant life, which results in a substantial yearly delivery of biomass to rivers, and ultimately to the ocean. Nonetheless, rivers in New Zealand that are not in the ITCZ were found to have similar levels of POC due to floods created by TCs *(Section 3.1.1.2).*

The 1.8-4.0 Tg C expelled from Taiwan in the form of CWD are a significant loss of carbon. This is not on the order of the 105 Tg C lost due to Hurricane Katrina and the resulting tree mortality, yet the return period for TCs in Taiwan is much shorter than in southern United States. Moreover, the loss of carbon per square kilometre was on the same order in these two events, indicating that tree mortality and CWD expulsion are effects induced by TCs that are of similar importance. Compared to the annual expulsion of CWD from the entire area of Japan, the single event that was TC Morakot exported 200-400 times more CWD from the affected areas in Taiwan to the oceans. This reinforces the importance of quantifying and assessing the impact of TCs on CWD accurately *(Section 3.1.1.2.1 and 3.1.1.2.3).*

Relative to the scale of CWD carbon transport the POC transport induced by TCs was found to be minor. However, when compared to riverine systems worldwide, the POC levels attained during TC Mindulle were among the highest, indicating that TCs play a major role in the transport of POC. Even in catchments with much lower POC values, TCs can contribute most of the annual POC transport *(Section 3.1.1.2.2 and 3.1.1.2.3).*

Whether terrestrial carbon transport induced by TCs is a source or sink is heavily debated. Floods brought on by TCs transport a substantial portion of the carbon flux from terrestrial ecosystems to the oceans, but what happens when the carbon reaches the oceans is not very well known. Hedges et al. (1997) states that 90% of the non-fossil POC that enters the ocean is remineralised, though this includes non-storm sources of terrestrial carbon. Hilton et al. (2008) find that most of the flow entering the oceans during TCs downstream is at hyperpycnal concentrations, which has been documented to lead to burial. Whether the burial by hyperpycnal flows be considered a long-term sink is controversial. CWD flushed out during TC events is especially difficult to track. The CWD could float on the surface of the ocean for very long periods and decompose and oxidize slowly, it could be transported back to shore, or it could be buried *(Section 3.1.1.2).*

West et al. (2010) emphasizes that the expulsion of CWD by TCs is not very well documented, mainly because monitoring CWD during TCs is challenging. Additionally, the effect these massive fluxes of CWD have on marine ecosystems has not been researched sufficiently. A similarly comprehensive source other than West et al. (2010) on the topic of CWD was not found. The effect of TCs might constitute a significant negative carbon-feedback if the CWD that reaches the oceans is buried, or not readily decomposed. This effect is enhanced if the forested areas from which the CWD was expelled regenerate quickly *(Section 3.1.1.2).*

Since large rainfall events and floods create anomalously high spike in POC and CWD concentrations, the rise in intensity and rainfall in TCs should increase the significance of TC induced carbon transport to the oceans (See Figure 6). Therefore, the importance of establishing whether this process comprises a negative or positive feedback on the climate increases correspondingly *(Section 3.3).*

4.3 Enhancement of Primary Production by disturbance of dynamic mechanisms

The observation of enhanced primary production induced by TCs is relatively new. This is mainly because observation of this phenomenon is obstructed by the extreme conditions and cloud cover that come with a TC. Lin et al. (2003) were one of the first to quantify the process and to show its significance. Since then it has become clear that TCs affect primary production positively around the globe, but that areas such as the South China Sea can't be extrapolated from, due to their elevated level of primary production and high incidence of TCs, and that initial findings were likely exaggerated *(Section 3.2.2 and 3.2.4).*

Both Lin et al. (2003) and Sun et al. (2010) find high contributions of TCs to the primary production in the South China Sea. However, Sun et al. (2010) find that only few anomalous TCs with exceptionally strong entrainment contribute to primary production significantly. Both in the Sargasso Sea and in the North Atlantic the effect of TCs was found to be negligible when integrated or extrapolated over longer time periods. It can be speculated from these findings that areas such as the North Atlantic and the Sargasso Sea that have low annual primary production are not as affected by the effects of TCs. On the other hand, it could also be that results found by Lin et al. (2003) were anomalous and extrapolated without precaution and therefore the contribution of TCs to primary production is overstated. Hurricane Katrina was found to increase chlorophyll a concentration fifteen-fold. However, contribution to annual primary production was not provided and the significance of this value is therefore uncertain *(Section 3.2.4).*

A speculated reason for the large differences observed in primary production could be that a shallow thermocline together with low nutrient conditions at the surface of the ocean lead to high relative change, but high absolute change occurs mostly in areas with year-round high values of primary production such as the South China Sea. In areas that are known as ocean deserts, the relative change of primary production can be high, but the absolute chlorophyll concentrations will remain low after the passage of a TC.

As long-term datasets on the contribution of TCs to primary production are not available yet, and the results found primarily in the last decade or so are not conclusive, the process of primary production induced by TCs needs to be researched further.

4.4 Air-Sea exchange of CO_2

As was the case with measurements regarding primary production, establishing good datasets and accurate measurements in the case of CO_2 fluxes induced by TCs is obstructed by difficult conditions and cloud cover. In this case, some of the best data comes from the chance event that a moored buoy was located along the path of a TC.

Several studies show that the partial pressure of CO_2 in the oceans decreases during the passage of a TC, and conclude that this loss of partial pressure is equivalent to a permanent loss of CO_2 from the oceans to the atmosphere. The loss of partial pressure is explainable with the reduction of SSTs related to the effects of entrainment. However, many studies show only the reduction during the passage of the TC, which is significant, but not the normalization effect induced by mixing observed afterwards. Additionally, when observed as a global phenomenon, Lévy et al. (2012) suggest that previous research did not consider that some regions are undersaturated, which means that an influx effect of CO_2 into undersaturated regions brought on by TCs was overlooked. Figure 5 shows areas of efflux from the ocean induced by TCs and areas of influx into the ocean induced by TCs. Lévy et al. (2012) suggests that these effects balance out globally and that a slight, but negligible, influx of CO_2 into the oceans might be the case. Therefore, the air-sea exchange of CO_2 could be important locally, but not on a global scale. This conclusion is only based on one modelling approach of global conditions, which means that further validation is required *(Section 3.2.3 and 3.2.4).*

5. Conclusions

Tropical cyclones have a pronounced effect on many processes within the carbon cycle. Especially forested ecosystems around the globe are shaped by the passage of major storm systems. The uncertainty in the effects on terrestrial carbon transport and ocean processes is larger, as the research of these processes is faced with more difficulties.

[1] In the present-day climate, TCs have a major negative effect on forested ecosystems up to 45° N and 45° S of the equator and likely lead to increased carbon effluxes into the atmosphere. This negative effect is comprised of immediate damage in the form of windfall and long-term effects, such as delayed mortality, and secondary factors like increased risk of fire and insect infestation. The immediate effects of TCs on forested ecosystems are most likely to increase with intensifying TCs over the coming

century, especially seeing as windfall increases exponentially at higher wind speeds. Secondary risk factors such forest fires and insect infestations could be reduced with coordinated salvaging efforts.

[2] POC and CWD expulsion to the oceans and the resulting effects of these processes are not extensively documented and quantified. It is especially unclear what happens to the massive delivery of CWD from forested ecosystems to riverine systems and finally to the oceans, although various effects have been observed and theorized. It is speculated that this POC and CWD could be buried in the oceans or decomposed very slowly, which would either lead to a permanent sink or a temporary one. The duration of the latter would depend on whether regrowth rates in areas in which the CWD originated exceed decomposition rates. As this process is not fully quantified in the current climate, extrapolating to a warmer future climate scenario would bear great uncertainty.

[3] The enhancement of primary production by TCs is well recognised. However, the magnitude of this effect remains unclear, mainly due to large uncertainties in modelling and the lack of data. A probable conclusion is that initial findings were overstated, but that individual TCs may nevertheless contribute significantly to enhanced primary production. As the depth and degree of mixing increases with a TCs intensity, this effect might be heightened as the average intensity of TCs increases with climate change.

[4] Air-Sea CO_2 fluxes brought on by TCs could be an important local effect in the present climate. Ocean effluxes found from case studies on specific TCs were remarkably high, however, the saturation imbalance of various seas around the globe and the resulting dissimilar effect of TCs may have been overlooked. Thus, the total global effect of TCs on Air-Sea CO_2 fluxes might be negligible. As recent research has produced contradictory results, further research into this phenomenon is necessary.

The effects of TCs discussed in this thesis are often not very well quantified. This may be due to one of many reasons, e.g. the difficulties in obtaining high quality data and the lack of long data series, or a general lack of research. Modelling approaches attempt to bridge the gap, however, these come with their own set of uncertainties. Further research, especially into effluxes of terrestrial carbon into the oceans, is required.

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