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Hurricane threats to military infrastructure in a warming world and possible adaption and mitigation strategies

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Abstract

With respect to global warming the armed forces differentiate between the impacts on infrastructure, facilities and operations and the implications for peacekeeping and conflicts. The climate related stresses for military installations are well documented for e.g. the United States Forces. This includes threats from flooding, droughts, wildfires and desertification. The most imminent threats are due to the rise in sea level and the frequency of major storms, both consequences of global warming. Heavy damage to mainly coastal military and civil infrastructure is expected as a result of more powerful hurricanes reaching further north than currently experienced. In this paper, the changing characteristics of hurricanes in the North Atlantic and Caribbean between 1967 and 2018 are shown and new storm patterns due to the predicted rising in sea surface temperature are explained. Climate models show that future hurricanes exhibit stronger winds and massive precipitation as well as a slower decay and movement after landfall resulting in severe damages and longer lasting flooding. The vulnerability of the Norfolk Naval Shipyard (USA) to such hurricanes is highlighted. Examples

of short and long term, high and low cost, biological and technical adaptation and mitigation measures for protecting coastal installations are described.

Security implications of global warming

The military and intelligence communities tend to cluster the national security implications of global warming induced climate change into two overlapping areas. The first is how climate change will affect installations and military operations. This includes how the response to climate induced disasters will stress military operations and potentially detract from other military missions. The second area is, how climate change poses political and national security threats in peace and open conflict scenarios.

With respect to effects on military installations, the research on upcoming threats and already experienced stresses due to climate change has been done and published for several decades (Crawford 2019; Reinhardt and Toffel 2017; Office of the Assistant Secretary of Defense 2014). In 2019 the US Department of Defence reported that the US military is already experiencing the effects of global warming at dozens of installations (Figure 1). These include recurrent flooding (53 installations), droughts (43 installations), wildfires (36 installations) and desertification (6 installations) as well as the impairment of the physical stability of US military facilities in the Arctic (Crawford 2019). The most urgent threats to e.g. US military infrastructure is that rising sea levels and major storms will inundate coastal infrastructure (Crawford 2019). Recurrent flooding is already experienced at the Keesler Air Force Base Mississippi (USA) as well as the US Naval Base at Norfolk Virginia (USA). Tyndall Air Force Base in Florida (USA) suffered severe damage in October 2018 by Hurricane Michael. (Crawford 2019)

In this article we will discuss the negative effects of the increasing number and severity of tropical storms on military installations. We will focus on existing and future damaging effects of hurricanes on military bases along the Caribbean and Atlantic coastlines of the US (Figure 1). Special attention is given to the situation at the U. S. Naval Base in Norfolk Virginia, which is the biggest naval base worldwide, and to the associated Naval Ship Yard (Reinhardt and Toffel 2017; Reidmiller et al. 2018).

Figure 1: Map of US military assets with multiple climate-related vulnerabilities (Reidmiller et al. 2018).

The National Climate Assessment released in late 2018 highlighted the special vulnerability of the Norfolk Naval base to flooding (Reidmiller et al. 2018). It was exposed to hurricane induced inundations in the past, as shown in Figure 2. Simulations of the possible vulnerability to f sea level induced inundations caused by hurricanes of the categories 1 – 4 making landfall at or near Norfolk Virginia (USA) are performed by NOAA (Horn 2018). With respect to the Norfolk Naval Shipyard a category 1 storm will lead to minor inundations of less than 3 feet (91 cm) and affect 5 – 10 % of the area. In contrast, a category 4 storm will flood the complete Naval Shipyard and inundate most of the area with least 6 feet (182 cm) of sea water(Figure 10, (Horn 2018)).

Figure 2: “USS Kearsarge” at the Naval Base in Norfolk during the 2003 Hurricane Isabel, which causes nearly 130 * 10^6 US$ worth of damage on US marine bases. Modified after (Reinhardt and Toffel 2017).

Characteristic of tropical storms with focus on hurricanes

Warm tropical ocean surfaces are the cause of strong tropical (sub-) storms. These often violent storms are called “hurricanes” in the northern Atlantic and the north eastern Pacific Ocean, “typhoons” in the north western Pacific and “cyclones” in the southern Pacific and the Indian Ocean (DWD 2021).

Several preconditions are required for a tropical storm to build up and move into subtropical areas: a) a sea surface temperature (SST) of at least 26 °C in the uppermost 50 m of the water column, b) unstable climatic stratification in terms of ongoing mixture of air masses, c) high air humidity in the mid troposphere (5 km height), d) existing disturbance in the lower atmosphere with organized rotation, e) low winds (< 37 km/h) and f) a starting point of at least 500 km North or South of the equator. Closer to the equator tropical storms do not form, because the Coriolis-force is too weak to establish a rotating storm (DWD 2021).

The driver of tropical storms is the thermal energy release during the condensation of water vapour in the air over warm tropical oceans.(Emanuel 1986). At sea surface temperatures above 26 C sea water evaporation from the ocean surface gets intense and warm moist air masses move upward until they condensate and precipitate as rain. During this condensation process large quantities of thermal energy are released and lead to further warming of the air. This forces air masses even further up until they release the remaining moisture. The strong uplift of air masses creates a large low pressure zone at sea level which forces moist air masses to move with great speed into this low pressure area, i.e. into the „eye“ of the hurricane. As long as further warm and moist air masses are moving into the low pressure system, the rotating hurricane is increasing its wind speed. Figure 3 shows the global sea surface temperature in October 2018 at the peak of the of the hurricane season in the North Atlantic and the Caribbean Sea. The Coriolis force causes the winds to form a cyclic pattern around the low pressure eye of the hurricane and the hurricane system itself moves slowly westward and towards higher latitudes.

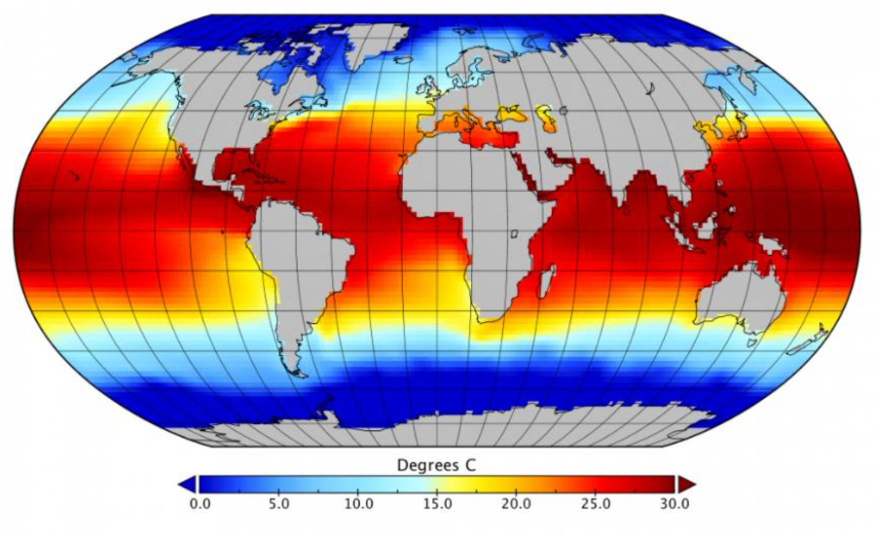

Figure 3: Global sea surface temperatures (SST) in October 2018 (Hausfather and National Center for Atmospheric Research Staff 2019) during the peak of the hurricane season in the North Atlantic and the Caribbean Sea.

The driver of tropical storms is the moisture of very warm tropical oceans (Emanuel 1986). With the SST rising in a warming world, the moisture supply is enhanced. This effect is shown in the phase diagram for water (Clausius-Clapeyron relation) where a rising SST directly leads to higher atmospheric humidity (Wallace and Hobbs 2006) and consequently, to higher hurricane intensities (Knutson et al. 2019). As early as 2008 Elsner et al. found that the most pronounced intensification of tropical storms occurs in the North Atlantic (Elsner et al. 2008). Lower SST and land masses cut off tropical storms from warm and moist air masses at the surface and thus from the thermal energy supply (Tuleya 1994). As an immediate consequence their intensity decays rapidly after reaching the coastline. Therefore the largest damage to humans and infrastructures is inflicted during the first 24 h after landfall (Li and Chakraborty 2020). The areas of origin and the pathways of tropical storms in the period from 2004 to 2014 are shown in Figure 4. The zones of origin do correspond nicely with the areas of the highest SST (Figure 3) while the areas of storm decay correspond to cooler SST-regions or land surfaces.

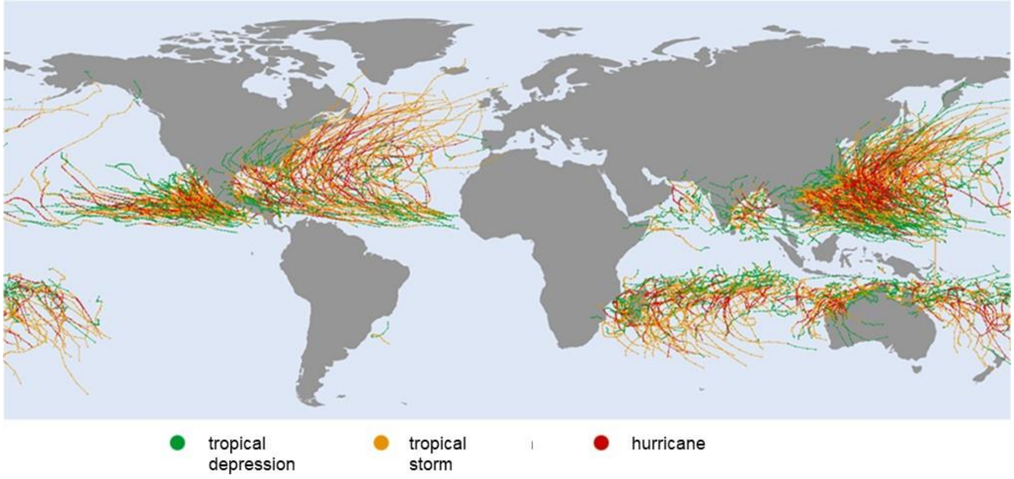

Figure 4: Tracks of tropical storms from 2004 to 2014 (DWD 2021).

The intensity of hurricanes is classified by the Saffir - Simpson scale as shown in Table 1 (DWD 2021; DWD 2020). The defining criteria are wind speed (often termed intensity) and air pressure with wind speed as the most destructive aspect of a hurricane. Other parameters such as storm surge or precipitations are not included in the classification.

Table 1: Classification of hurricanes according to the Saffir- Simpson scale (DWD 2020).

Hurricane Category	**Wind speed**		**Storm surge**	
	[km/h]	**[m/s]**	**[cm]**	**[feet]**
Tropical Storm	63 – 118	18 – 32		
Category 1	119 – 153	33 – 42	120 – 160	3.9 – 5.2
Category 2	154 – 177	43 – 49	170 – 250	5.3 – 8.2
Category 3	178 – 208	50 – 58	260 – 370	8.3 – 12.1
Category 4	209 – 251	59 – 70	380 – 540	12.2 – 17.7
Category 5	> 251	> 70	> 540	> 17.7

The hurricane season in the North Atlantic officially lasts from June to November. In 2020 the North Atlantic experienced a record breaking season when the World Meteorological Organization (WMO) registered 30 tropical storms (World Meteorological Organization 2021; Razzell et al. 06.12.2020). By the end of the year, 30 tropical storms had been named, nine with Greek names. The only other year which needed Greek names was Also the year 2005 brought several deadly storms such as Katrina with more than1 800 lives lost (Kernn 2018) and vast flooding in Louisiana and Mississippi (Knabb et al. 2005). Li and Chakraborty (2020) found for the time period from 1967 – 1992 a total of 26 hurricanes in the North Atlantic which reached the coastline and lasted more than 24h after making landfall. The number nearly doubled to 45 hurricanes of this type in the 25 years from 1993 – 2018.

The emergence and fall of the destructive power of Hurricanes

The rise and fall of the destructive wind speed in dependence of the supply of warm moist air is shown on the evolution of Hurricane Katrina in 2005 (Figure 5). On 23rd of August a tropical depression formed which strengthened over the Gulf of Mexico and reached hurricane status on the 25th. After the first landfall in Florida it was a Category 1 hurricane and moved westward for 6 hours over land while it weakened to a tropical storm. It moved into the Gulf of Mexico on 26th of August where the storm underwent two rapid intensifications becoming a Category 5 hurricane. Katrina reached its peak intensity on 28th of August over the Caribbean Sea and made its second landfall in Louisiana as a Category 3 storm on the 29th. Katrina weakened rapidly after moving inland, becoming a Category 1 hurricane on 29th and a tropical storm about 6 h later. (Knabb et al. 2005)

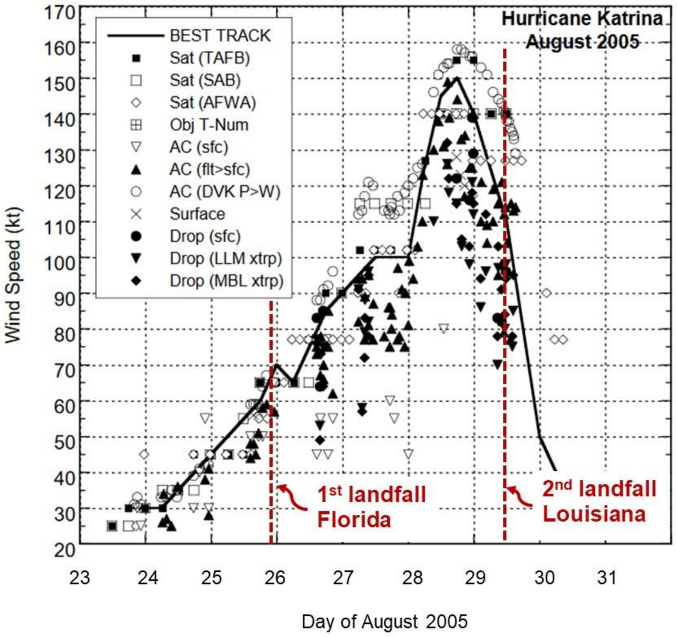

Figure 5: Selected wind observations and best track maximum sustained surface wind speed curve for Hurricane Katrina from 23rd to 30th of August 2005. Katrina made landfall on25th of August at 23:00 UTC in Florida (USA) and on 29th of August at 11:10 UTC in Louisiana (USA). (Marked with red dotted lines) Wind speed in kt = knots. 1 knot = 1.852 km/h = 0,51 m/s. Modified after (Knabb et al. 2005).

Hurricanes inflict their most severe damages within the first 24 hours after landfall. The storms velocity (V) decays exponentially in this period of time (Formula (1)).

$$V_{(t)} = V_{(0)}\, e^{-t/\tau} \qquad (1)$$

Where t is the time past landfall and τ, the decay timescale. τ is a single parameter that characterizes the rate of decay. After the first 24 hours $V_{(t)}$ can no longer be characterized by a single parameter as it is influenced by other parameters such as the land surface properties and the local weather conditions. The larger τ, the slower the decay, and therefore the stronger the hurricane. Li and Chakraborty found that τ has increased in the period from 1993 – 2018 compared to the period from 1967 – 1992 confirming the recent trend to more extreme weather events (Figure 6). (Li and Chakraborty 2020)

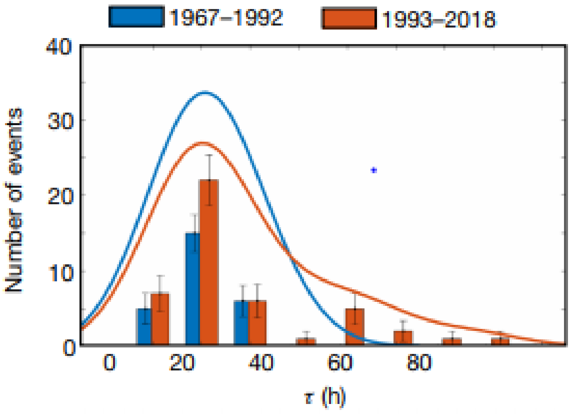

Figure 6: Histogram of τ (decay timescale) for 26 hurricane landfall events between 1967 and 1992 and 45 hurricane landfalls in the period from 1993 to 2018. Error bars are ± 1 standard deviation. Modified after (Li and Chakraborty 2020).

On a global scale most tropical storms never make a landfall. This is also true for hurricanes in the North Atlantic (Figure 4). However, coastal regions may well be affected by nearby passing storms due to the resulting coastal storm surge. A hurricane reaching a coastline inflicts damage due to a combination of extremely strong winds, coastal storm surges and additional flooding due to extensive coastal and inland rainfall. The storm surge and its effects are limited to coastal regions up to 20 km from the coast, whereas strong winds and flooding due to heavy rainfalls may affect regions hundreds of km inland from the coast.

Future behaviour of hurricanes after landfall

The rising global sea surface temperatures will increase the occurrence and intensity of hurricanes. There are already observations of slower hurricane decay after landfall, higher amounts of rainfall and a lower mobility of the storm itself. Also more hurricanes are now making landfall on the US East Coast as shown in Figure 7. (Li and Chakraborty 2020)

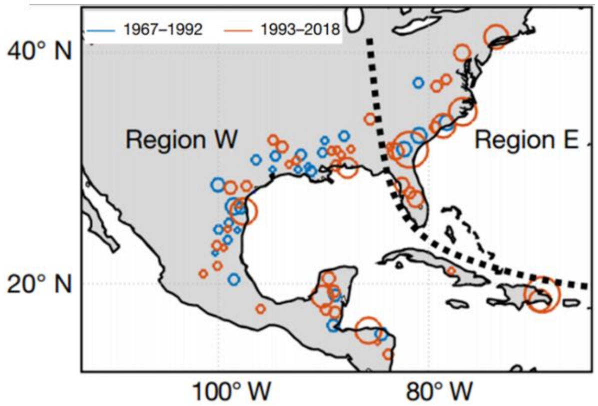

Figure 7: Selected hurricanes from 1967 – 2018 which lasted at least 24 h after landfall. Each circle marks the centroid of the positions of each hurricane during landfall and after 6, 12 and 18 hours over land. The size of the circle marks the decay time scale. Blue circles: hurricanes from 1967 – 1992. Red circles: hurricanes from 1993 – 2018. Region E = US East Coast. Region W = Gulf of Mexico and Caribbean. (Li and Chakraborty 2020)

Li and Chakraborty (2020) simulated hurricane formation using a SST between 300 °K (27 °C) to 303 °K (30 °C) in intervals of 1 °K. The warmer the ocean SST, the greater the moisture supply and, consequently, the faster the intensification of the storm (Figure 8 a). When the hurricane intensities reached about 60 m/s (i.e. a Category 4 hurricane on the Saffir – Simpson scale) a complete landfall of the hurricane was simulated. In modelling terms this means, that the moisture influx to the hurricane was stopped instantaneously and further intensity increases are no longer possible (V). From this time onwards, only decreasing intensities (V) are possible and the decay of the hurricanes was modelled with identical parameters thereafter. (Li and Chakraborty 2020)

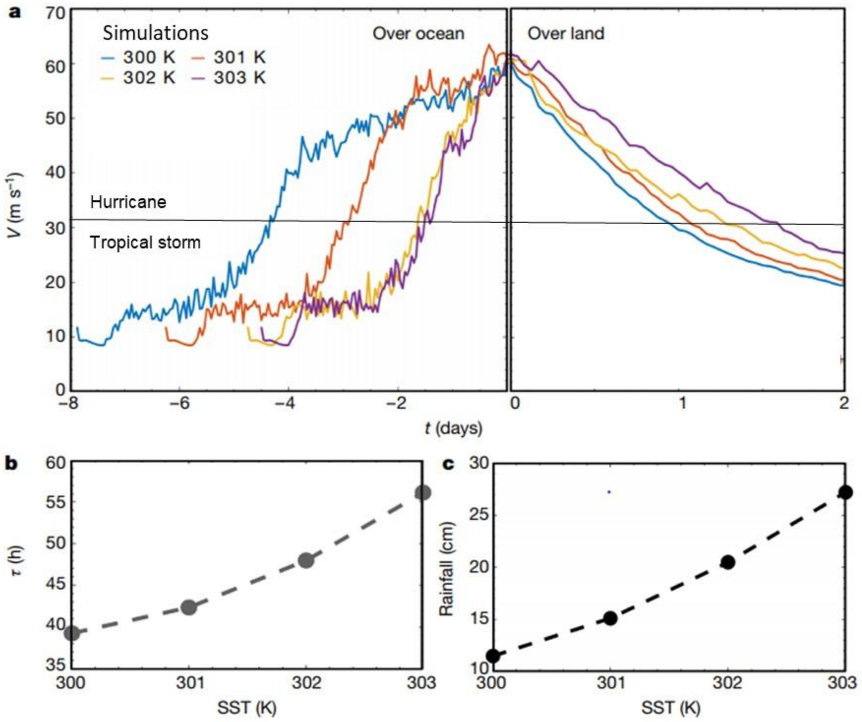

Figure 8: Effect of sea surface temperature (SST) on the decay of simulated landfalling hurricanes. A) Velocity = Intensity (V) versus time (t). t < 0, the hurricanes develop over warm oceans. Different colours represent different SST. At t = 0, the hurricanes make landfall with $V \approx 60$ m/s. B) Decay time (τ) versus SST. C) Rainfall versus SST. This is the total rainfall accumulated inside a radius of 100 km and over the first two days past landfall. Modified after (Li and Chakraborty 2020).

Hurricane formation at 300 °K and 301 °K SST (27 and 28 °C respectively) is much slower than at higher temperatures. It took the tropical storm at least 4 days to reach the Category 4 class. SST equal or higher than 302 °K (29 °K) results in the build-up of a Category 4 storm in less than 2 days, leaving little time for e.g. evacuation measures. Although the intensity at landfall is the same for all four hurricanes of the model, their decay past landfall carries a clear signature of the development over the ocean before the landfall (Figure 8 a). The intensities of the hurricanes that developed over warmer oceans decay at a slower rate (τ) – due to the higher moisture content which serves as energy source. That echoes the field observations (Figure 8 b) but in contrast to these, in the model the increase in τ is solely dependent of the SST. As the enhanced storm moisture eventually precipitates as rain, the rainfall from hurricanes increases approximately 2.5 fold when the SST increases by 4 °C (Figure 8 c). (Li and Chakraborty 2020)

The effect of precipitation is not included as a parameter in the Saffir – Simpson scale. In the past inland rainfall was often heavy, but not as devastating as it is now and will be in the future. This development was demonstrated by Hurricane Harvey which hit the Caribbean and the U.S. states of Texas and Louisiana in August 2017. This Category 4 storm brought to up to 125 cm rain (1250 l/m^2) during its lifetime. The resulting floods caused power outages for 300.000 households in Texas with cascading and devastating effects on critical infrastructure. Eleven percent of the U.S. oil refining capacity and a quarter of the oil production from the U.S. Gulf of Mexico were shut down. Actual and anticipated gasoline shortage caused regional and national price spikes. (Reidmiller et al. 2018)

Figure 9: Flooding caused by hurricane Harvey in Port Arthur Texas (USA), on 31st of August in 2017, six days after Hurricane Harvey made landfall along the Gulf Coast. (Reidmiller et al. 2018).

The future of naval bases

In risk assessment studies, inundations are dealt with as an entity, regardless of the cause. Hurricanes are only one of many contributors. Others are spring tides or extreme rainfall floods. Globally the US-Navy maintains 111 000 buildings and facilities on 890 000 hectares of land. A total new construction of all facilities would cost at least 220 * 10^9 US$. A sea water rise of 90 cm would take 55 Navy bases (worth 100 * 10^9 US$) at risk.

Some bases may have to be abandoned. Most prone are the US-Navy bases in Yokosuka (Bay of Tokyo, Japan) which serves as the headquarter of the Seventh fleet and the base on Diego Garcia, an atoll in the Indian Ocean, an important logistic hub for missions in the Middle East and the Mediterranean Sea.

Bases to be operated in the future, has to be adapted to the coming challenges. For example, the Norfolk Naval base (USA) is currently inundated at least once a month during spring tides and heavy rainfall events. When it was built in 1917, the sea level was 46 cm lower than today. The landing bridges are often affected, impeding the maintenance schedules and the supply of power, water and steam to the ships. Currently the landing bridges are renewed for US$ 100 x 10^6 each. These efforts are severely impeded by the ongoing inundations. The new supply lines are installed above the water line. (Reinhardt and Toffel 2017)

Adaption to and mitigation of stronger hurricanes

Adaption means the introduction of measures to cope with new environmental conditions. In 2014 the U.S. Department of Defence issued a roadmap for the most pressing goals and lines of works with general descriptions of the expected tasks. (Office of the Assistant Secretary of Defense 2014). The implementation of adaption measures is normally done on a short- and/or mid-term time frame compared with mitigation strategies which normally are long-term and which aim to reduce the negative effects of new environmental conditions. Sometimes measures show characteristics of both adaptation and mitigation.

The current infrastructure of coastal protections and buildings is generally not well adapted to cope with the increasing threats of stronger hurricanes. Upgrading is very difficult and costly and in many cases impossible. This is due of a) the sheer size of the involved natural forces, b) the vast areas affected, c) the population density in these areas, d) the millions of buildings and installations in these areas and e) the lack of appropriate funding. Therefore, measures to protect people and infrastructure only seem feasible in a limited number of cases.

For example, the Indonesian capital city of Jakarta suffers from regular and severe floods caused by a combination of rainstorms, subsiding grounds and rising sea level. Therefore in 2019 the government decided to relocate the capital with its approximately 30 million citizens to the island of Borneo within 10 years at an estimated cost of more than 30 billion US$. (Deutsche Welle 2019; Razzel and Jackson 10.01.2021).

Climate change mitigation strategies are generally centred on the containment of the rising global average temperature. Global warming is influenced by many factors, such as release and fixation of greenhouse gases (GHG), ozone, aerosols, clouds, surface albedo (absorption of heath due to the colour of a surfaces), contrails, volcanic activity and many more (Prentice I. C. et al. 2018). Only a few of these factors can be managed by humans and still fewer can be influenced by large companies, organisations or even individuals. (Pachauri 2008) It seems prudent, that civil societies and also the military figures out, in which field the impact caused by their mitigation efforts will be most pronounced and efficient.

Adaption and mitigation may be achieved by technical solutions or by natural processes. Short-, mid- and long-term measures are available for both measures. Some selected examples – with special focus on the military – are described below.

Technical Adaption

Barrages

Typical adaptation strategies for infrastructure are building codes (Office of the Assistant Secretary of Defense 2014). They can only be applied to new buildings, leaving the existing infrastructure at risk. To abandon this infrastructure is generally no option. Protective installations from storm surges in coastal regions and flooding from rivers or both – as in estuaries - were erected for many centuries, as these regions are historically densely populated because of their resourcefulness and trading possibilities. A selection of the most effective ones is given below.

Stationary dikes and levees to protect coastal regions are established for several hundred years and are aimed to last for several decades. They do prevent flooding of coasts and riverbanks but cannot protect estuaries or bays. The Netherlands are most famous for their dikes as huge parts of its lands lies below sea level.

The building of mobile protective barrages is technically possible. They are operational at rivers, bays and lagoons, some for several decades now (see box below). Mobile barrages protect human settlements, allow shipping and freshwater management. Rising sea levels must be integrated into the planning or otherwise the barrier will soon be overwhelmed.

Operational mobile barrages for rivers, bays and lagoons

The Thames Barrier in East London is 520 m wide and operational since 1984. It was established as a consequence to the so called “North Sea Flood” from 1953 with 307 fatalities in the UK alone. Plans to build a new barrier are in preparation downstream of the existing barrier as a) rising sea level will overwhelm the established barrier in the foreseeable future and b) greater parts of London should be protected from future flooding. (Environmental Agency 2021)

Marina Bay in the City state of Singapore is often flooded by the sea leading to inundation in Singapore itself. In an effort to increase its self-sufficiency, the Singaporean government wants to use the bay as freshwater reservoir. Sea water intrusions thwart theses plans. The Marina Barrage is 350 m wide and include powerful pumps which were able to regulate the water level inside the bay when the barrage is closed. It is operational since 2010. (PUB, Singapore's National Water Agency 2021).

Venice in Italy - which is built on sinking ground and often inundated - has built until 2020 the massive 1 600 m wide barrier MO.S.E., which is now successfully in operation protecting the historical heritage of the city (Ministero delle Infrastrutture e dei Trasporti 2021).

The Norfolk Naval base is located at the estuary of the James River. The Norfolk Naval Ship Yard is located a few miles upstream the river. If no further action will be taken stronger hurricanes will lead to severe flooding of the entire naval base and shipyard A simulation of inundations caused by a Category 1 and a Category 4 hurricane is shown in Figure 10 for the Naval Ship Yard. Damage to military infrastructure would be disastrous and severely hamper the US navy combat readiness. Between the southern coast at Willoughby Bay and the northern coast of Fort Monroe the estuary is approximately 3 km wide and is already spanned by the Route 64 in a combination of bridges and tunnels. (Google LLC 2020) None of the already existing barriers is built to resist a storm surge of a Category 4 hurricane which may result in a coastal (Ministero delle Infrastrutture e dei Trasporti 2021)(Ministero delle Infrastrutture e dei Trasporti 2021)(Ministero delle Infrastrutture e dei Trasporti 2021)(Ministero delle Infrastrutture e dei Trasporti 2021)(Ministero delle Infrastrutture e dei Trasporti 2021)(Ministero delle Infrastrutture e dei Trasporti 2021)(Ministero delle Infrastrutture e dei Trasporti 2021) storm surge as high as 540 cm (17.7 feet).

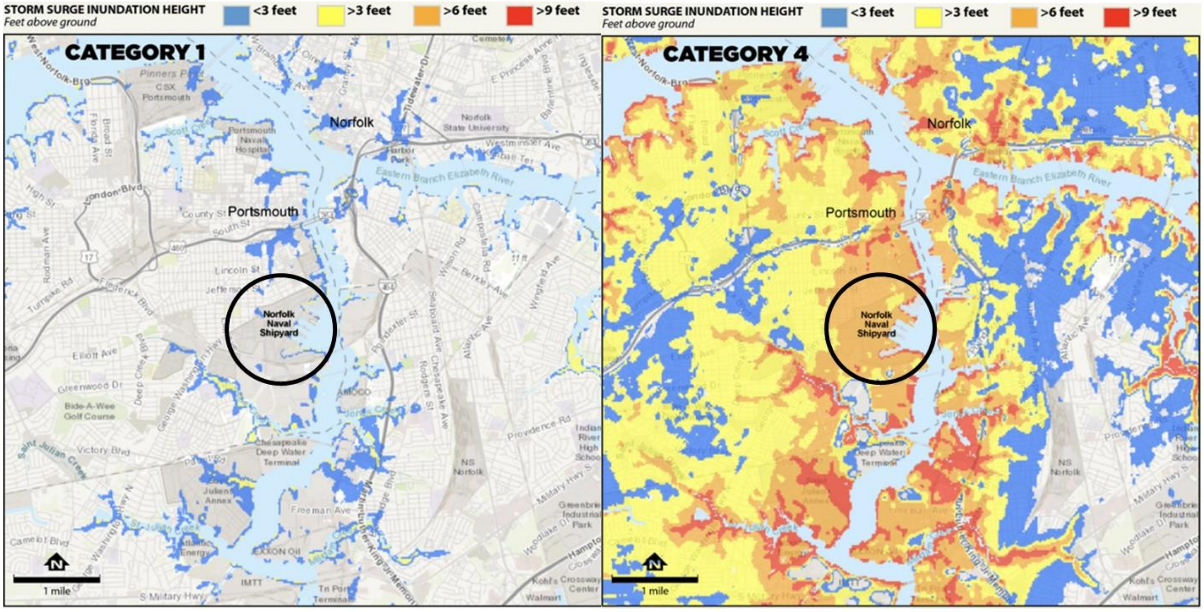

Figure 10: Simulation of inundation effects of a hurricane Category 1 and a hurricane Category 4 making landfall at or near Norfolk (Virginia, USA) on the Naval Ship Yard of the US Navy (indicated by a circle). 3 feet = 91 cm. 6 feet = 182 cm. 9 feet = 273 cm. A animated simulation is available at *https://insideclimatenews.org/infographics/maps-how-hurricane-could-wipe-out-critical-navy-shipyard/* Modified after (Horn 2018).

Technical Adaption and Mitigation

Building Codes

Generally buildings codes may define a) the areas in which building is allowed, b) the technical details of walls, roofs etc. and c) the materials to be used. Points a) and b) are important for adaption to new environmental conditions such as increased danger of inundation. Point c) may play a role in mitigation, when carbon-dioxide poor or neutral materials were compulsory for construction e. g. wood.

The US-Navy requests now a special permission for each building which is to be erected below the future predicted sea level line (2m above present) (Reinhardt and Toffel 2017).

Technical Mitigation

Coolants

The GHG class of halocarbons – also known as Frigene- are used in cooling devices. They work as GHG in the lower parts of the atmosphere and they also deplete ozone in the stratosphere in the polar regions during winter (Baird 1995; Graedel et al. 1994). They are very stable in the environment and generally are released during the life cycle of a cooling device. Non halogenated substitutes are known and in use for many decades but more expensive. The routine replacement of cooling devices or coolants with non-halocarbons could be started immediately with an immediate effect.

Enhancing Albedo

Light coloured surfaces do reflect radiant heat from the sun back into space (albedo) and therefore do not contribute to the heating of the globe. Painting surfaces in light colours would reduce the amount of heat absorbed on earth. Each surface is suitable e.g. walls, roofs, streets, sidewalks, car tyres etc. Each maintenance or replacement can be used to install light coloured versions. Light coloured buildings do also reduce the needed energy for ventilation and cooling of these buildings. (Gill 16.04.2021)

Biological Mitigation

Mangroves

An interesting and ecologically important option to mitigate hurricane storm surges and at the same time improve carbon capture and long term sequestration is the restauration of mangrove forest. They are well known to protect people and property in coastal areas in the tropics from storm surges (Menéndez et al. 2020; Kathiresan 2012; Zhang et al. 2012). They grow in the tropical and subtropical coastal regions of the world with a nice overlap with the tropical storm regions (Figure 4, Figure 11).

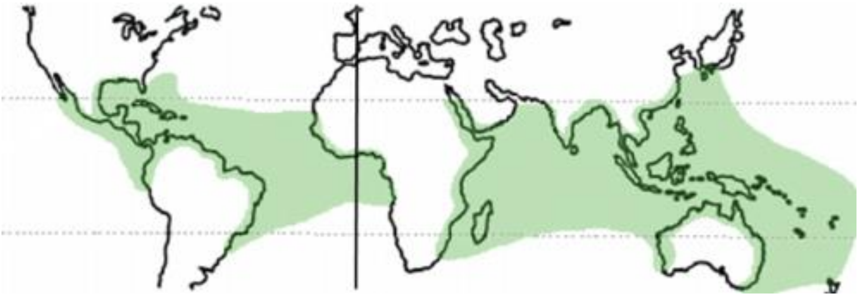

Figure 11: Global distribution of mangroves. Dotted lines = Tropical zone (30 degree north and south of the equator). Solid line = Greenwich meridian. (Quoc Tuan Voa et al. 2012)

Observations and simulations indicate that the 6 to 30 km wide mangrove forest along the Gulf Coast of South Florida effectively attenuate storm surges from a Category 3 hurricane. The surge amplitude decreases at a rate of 40 – 50 cm/km across the mangrove forest and at a rate of 20 cm/km across the areas with a mixture of mangrove islands with open water. In contrast, the amplitudes of storm surges at the front of the mangrove zone increase by about 10 – 30 % because of the blockage of mangroves to surge water. This effect may cause greater impacts on structures at the front of mangroves than the case without mangroves. (Zhang et al. 2012) These effects do apply to all forms of surges. The effects of a tsunami caused surge on mangroves and artificial infrastructures is shown in Figure 12. The human infrastructure is destroyed, while the juvenile mangroves are still intact (Kathiresan 2012).

Figure 12: Boat jetty in the Vellar estuary (south-east cost of India) broken into pieces by a tsunami induced surge on the 26th of December 2004 in the background. The foreground shows an artificially established intact mangrove forest (Kathiresan 2012).

On a global scale the area covered with mangrove forest has profoundly declined in recent years. Globally - and in comparison to other forest ecosystems - its area is small. They are cleared most often for agriculture and shrimp farming (Menéndez et al. 2020). Mangrove forests have one of the highest biomass production (net primary production, NPP) (Larcher 1994) and carbon sequestration – the so called burial rates - of the known forest ecosystems (Mcleod et al. 2011) (Table 2). These processes remove carbon dioxide (CO_2) from the atmosphere and therefore reduce the effects of global warming (Prentice I. C. et al. 2018).

Table 2: Net primary production (NPP) (Larcher 1994) and carbon sequestration (so called burial rates) (Mcleod et al. 2011) for typical ecosystems. The burial rate describes the amount of carbon which is removed from the carbon cycle for many thousand years.

Ecosystem	**NPP [kg dry matter m^{-2} y^{-1}]**	**Carbon sequestration [g C m^{-2} y^{-1}]**
Tropical forests	1.0 – 3.5	4.0 ± 0.5
Boreal forests	0.2 – 1.5	4.6 ± 2.1
Temperate forests	1.0 – 2.5	5.11 ± 1.0
Seagrasses	1.0 – 6.0	138.0 ± 38.0
Salt marches		218.0 ± 24.0
Mangrove forests		226.0 ± 39.0

Afforestation and reforestation of tropical and subtropical coastal regions and estuaries can therefore serve two purposes a) the mitigation of storm surges from tropical storms by reducing the amplitude of the storm surge and b) the mitigation of tropical storms by reducing global warming and therefore reducing SST in the long run. In the U.S. Departments of Defence Adaption Roadmap for Climate Change the need for “partnerships with external, non-federal government land and resource stewardship organizations” is pointed out (Office of the Assistant Secretary of Defense 2014). Mangrove management could be a much valued issue for all involved stakeholders.

The afforestation of small patches of land can have immediate effects on the adjacent surrounding in terms of the microclimate (e.g. cooling, shade etc.), living quality and biodiversity. The movement of “tiny forests” install forests on areas as small as a tennis court. The concept promotes rapid growth of the used local tree species (Nawab 2021).

Long term mitigation

Reduction of carbon dioxide emissions

Carbon dioxide is the most important GHG in terms of the emitted amount and one of the most difficult to reduce, due to lacking alternative fuels and technologies. The military itself emits millions of tonnes of CO_2. The U.S. military for example emits in a typical year without major warfare and conflicts more than 55 million tons of CO_2-equivalents (Figure 13). The relative parts from combat related and non-combat related activities approximately equal each other and the absolute amount was declining considerably during the years between 2000 and 2018 (Crawford 2019).

CO_2-Equivalent

A CO_2-equivalent is the GHG potential of a specific gas with the CO_2 GHG potential used as a reference. CO_2 was selected, as it is the most important GHG with respect to abundancy and production. Potent GHG emitted from military activities are for example nitrogen oxides (289 times 100-year global warming potential of CO_2) from combustion processes and fluorinated hydrocarbons (14 800 times 100-year global warming potential of CO_2) from cooling facilities (Solomon et al. 2007).

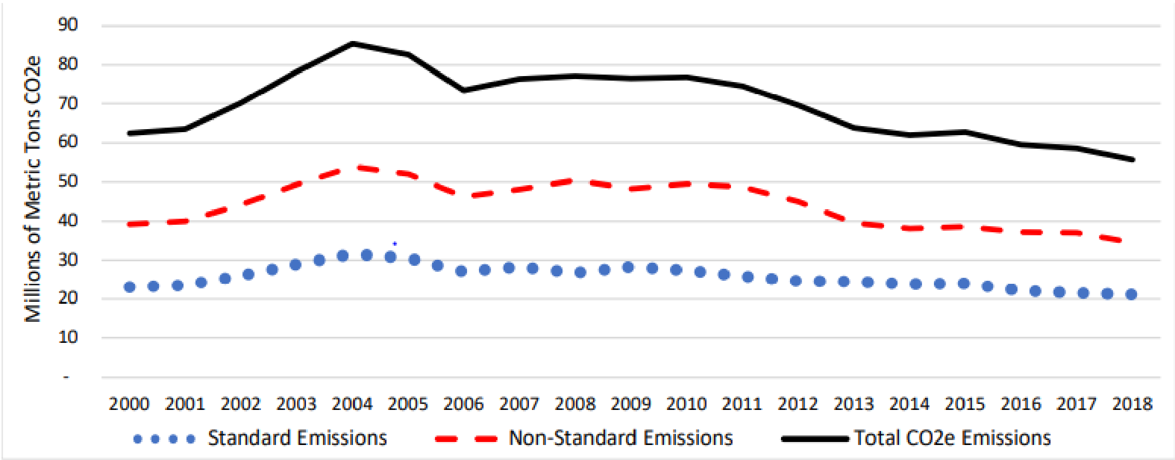

Figure 13: Estimate of the Department of Defence of greenhouse gas emissions (expressed as carbon dioxide equivalents CO_2e) for the fiscal years 2000 -2018. Metric tons = 1 000 kg = 1 ton. Blue dotted line = standard emissions. Red broken line = Non-Standard emissions. Black line = Total Emissions. Non-Standard emissions are defined by the U.S. Department of Energy as “vehicles, vessels, aircraft and other equipment used by Federal Government agencies in combat support, combat service support, tactical or relief operations, training for such operations, law enforcement, emergency response, or spaceflight (including associated ground-support equipment)”. Standard Emissions are defined by the same body as “everything else, that the Department of Defence does to accomplice its functions, roles and missions” (Crawford 2019)

Jet fuel consumption is the largest single position of the U.S. military energy consumption and the largest single expense of the U. S. governmental energy consumption as well (Figure 14) (Fasching et al. 2017) and directly coupled to activities in war zones and foreign countries (Crawford 2019). Diesel and electricity usage were the second and third largest single positions of U.S. military energy consumption, each approximately a quarter of the jet fuel consumption (Fasching et al. 2017). Diesel is used in ships, land-based mobility and mobile installations. Improvements in energy efficiency, alternative CO_2 poor or neutral fuels and in engine technology may have a huge impact on CO_2 emissions. The biggest impact of these improvements would be on airborne activities. Research and development on alternative fuels and engine technologies has intensified during the last years. An overview with respect to the military aspects of fuel cells on military applications is given by several authors (Lauf 2020;

Lauf et al. 2021; Mayor-Hilsem and Zimmermann 2019). Efforts to reduce the weight of aircrafts include e.g. pilotless air fighters and drones.

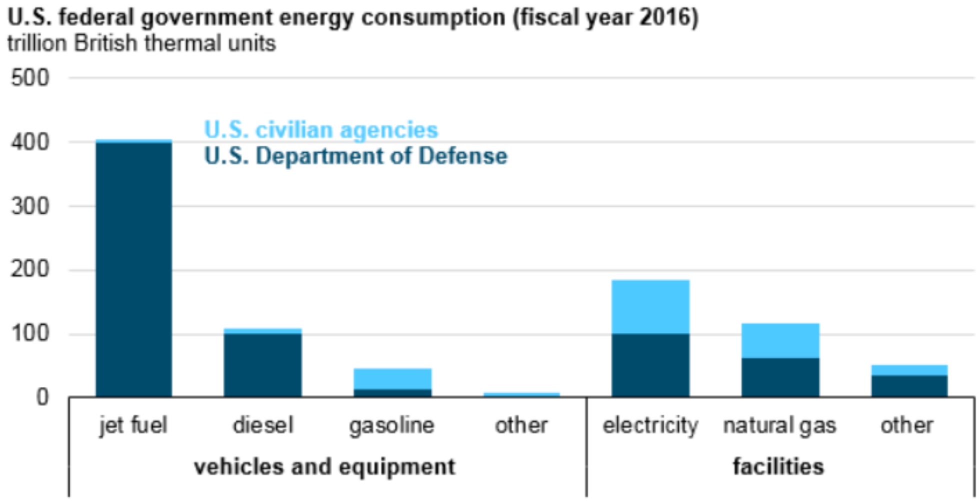

Figure 14: Categories of energy consumed by the U.S. Government and the Department of Defence in 2016. Dark blue = U.S. Department of Defence. Cyan = U.S. civilian agencies.1 * 10^{12} BTU = 296 kWh. (Fasching et al. 2017)

The reduction of the CO_2 emissions would be an important long-term contribution to a net carbon dioxide neutral society and therefore the mitigation of global warming. A profound and immediate effect of reducing fuel transports into war zones would be the steep cut of human losses during fuel transports (Curwood 2017; Crawford 2019).

The transported fuels are currently kerosene and diesel fuels, which are used to operate aircrafts, helicopters, vehicles, heaters and electric generators. The U.S. Marine Corps started solar panel generated electricity supply as early as 2012 for combat outposts in Afghanistan (Figure 15) (Curwood 2017). Electricity for facilities can be produced from renewable sources. It may be procured from respective sources or produced within the compounds of military facilities itself. Field camps of several nations are currently being equipped with large solar panels arrays for reducing the need for liquid fossil fuel supply.

Figure 15: U.S. Marine Corps troops installing solar panels on a combat outpost in Afghanistan (November 2012) to provide power to radios, laptops and computers (Curwood 2017).

Conclusions

The majority of the international community accepts the need to reduce the impacts of global warming and global change. In the “Paris Agreement on climate change mitigation, adaptation and finance” the signing nations – currently 190 UN member states - committed themselves to the goal of keeping the increase in global average temperature well below 2 °C above pre-industrial levels and to pursue efforts to limit the increase to 1.5 °C (United Nations 2015). Achieving this goal would substantially reduce the risks and impacts of climate change but may not be reached without immediate decisive action. The aim is to establish a net carbon free economy as soon as possible. (Prentice I. C. et al. 2018). The 2 °C goal – as it is generally named - can only be reached by active mitigation strategies. Even if it is achieved, which is not certain at the moment, further adaptation strategies are needed to protect existing infrastructure from the consequences of a 2 °C global warming.

What adaption and mitigation strategies may fit the military mission?

Measures to combat global warming and its effects may be a mixture of adaptation and mitigation and may have effects on different time scales. In this publication we define short-term as < 2 years, mid-term as 3 – 5 years and long-term as > 5 years. During these time spans the first effects of mitigation projects will be measurable.

Table *3* shows the time between inception and expected results for adaption and mitigation measures.

So, what can be done within the military environment?

Building codes for fixed installations are technical measures, which can be implemented quickly. When e.g. timber becomes mandatory for regular construction, long-term CO_2 fixation is possible. The construction of dikes, levees and barrages generally took several decades from planning to completion. The Thames Barrier was completed approximately 30 years after the flood, which triggered its construction. The replacement of Frigene coolants with environmentally friendly variants could be started immediately and the positive effect in the lower atmosphere would be immediate while the e effects in the stratosphere have a time lag of several years. Afforestation of mangrove forests in coastal areas develops its protective effects on a mid-term time period. The sequestration of carbon by reforestation or newly afforested areas is a long term process. The development and rollout of alternative fuels will shows its impact at best in a mid-term time scale because the development of engines and technologies as well as the building of infrastructure is a long-lasting effort. The usage of renewable power production technologies can be started immediately, as the technology is mature.

Many opportunities for climate change adaption and mitigation exist for the military. In many cases they are compatible with and in some cases even favourable for the missions of the military. As military forces are a significant part of society its actions have the potential to spearhead social change for the better.

Table 3: Selection of measures for adaption and mitigation of the effects of climate change with emphasis of the military. Measures are categorised a) into technical and biological and b) on their time scale. Short-term < 2 years. Mid-term = 2 – 5 years. Long-term > 5 years.

		Adaption			**Mitigation**		
Measure		**Short-term**	**Mid-term**	**Long-term**	**Short-term**	**Mid-term**	**Long-term**
Building codes	Technical Biological	X					x
Dikes, levees, barrages	Technical			x			
Coolants	Technical				x		X
Light coloured surfaces	Technical				x		
Mangrove forests	Biological		x				X

Tiny forests	Biological		x				X
Alternative fuels	Technical					x	
Renewable power supply	Technical				x		

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