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FINALIZATION OF THE DRAFT INITIAL IMO STRATEGY ON REDUCTION OF GHG EMISSION FROM SHIPS

On the relevance of the 1.5°C goal

Submitted by IMarEST

SUMMARY

Executive summary:	The Paris Agreement declared the goal of holding the global temperature increase to "well below 2°C above pre-industrial levels", and ideally "to 1.5°C". With a view to developing an IMO Strategy, and focussing on the 1.5°C goal, this document discusses how the 1.5°C goal is defined, whether it can be achieved, what impacts may be expected if the limit is exceeded and what this implies for climate change mitigation in the international shipping sector
Strategic Direction, if applicable:	3
Output:	3.2
Action to be taken:	Paragraph 25
Related documents:	None

Introduction

1 The Paris Agreement declared the goal of holding the global temperature increase to "well below 2°C above pre-industrial levels", and ideally "to 1.5°C". This requires rapid reductions in greenhouse gas (GHG) emissions. CO_2 emissions in particular need to be reduced to virtually zero, i.e. all sectors of the economy, including shipping, need to decarbonize.

2 Nationally Determined Contributions (NDC) – countries declaring mitigation targets, to be updated at five year intervals, with updates ideally increasing the level of ambition – are the main mechanism in the Paris Agreement for achieving this goal. Taken together, countries' NDCs at present fall significantly short of putting the world on track for the 2°C goal, let alone 1.5°C.

3 International aviation and shipping are the two major greenhouse gas emitters currently not included in the Paris Agreement, because emissions are not apportioned to any specific parties to the Paris Agreement.

4 International aviation has put in place a measure to control its CO_2 emissions in 2016, through its specialized UN agency, the International Civil Aviation Organization (ICAO). However, even with this measure in place, CO_2 emissions are projected to increase, rather than decrease. In summary, this puts the Paris Agreement's temperature goals in serious doubt.

5 MEPC 70 laid out a *Roadmap for developing a comprehensive IMO strategy on reduction of GHG emissions from ships*.

6 With a view to developing an IMO Strategy, and focussing on the 1.5°C goal, this document addresses the following questions: how is the 1.5°C goal defined?, is it possible?, what are the impacts of exceeding the limit?, what does it mean for the international shipping sector?

The 1.5°C goal and greenhouse gas emissions

7 The definition of the 1.5°C goal depends on the definition of global average surface temperature, on the definition of the "pre-industrial" reference period, on the definition of warming at present, and on the observational record, which is subject to considerable uncertainty.

8 The details of defining the temperature goals are of particular relevance in the debate on 1.5°C because the world has come close to this limit, with an observed global temperature increase of around 1°C since pre-industrial times.

9 The remaining emissions budget consistent with the 1.5°C goal is being exhausted fast so that rapid reductions and, ultimately, decarbonization are needed to stay within budget.

Climate change impacts

10 Impacts range from the more direct, such as increasing temperature or ocean acidification, to the more indirect, such as forced migration due to loss of livelihoods.

11 The more indirect impacts are the consequences of more complex chains of cause and effect, and are therefore generally harder to predict.

12 In general, attribution science – understanding the climate change signature (or otherwise) of particular climate events – has made significant progress in recent years.

13 Nonetheless, prediction is difficult, and it is impossible to define a safe level of climate change. However, higher levels of climate change pose higher levels of risk, and a temperature increase of 2°C poses higher risks than a temperature increase of 1.5°C.

14 There exist thresholds and potential tipping points in the climate system. The 1.5°C is in part informed by the risk of reaching some thresholds, although uncertainty when thresholds are reached is significant.

15 Temperature change has risen substantially from the mid-20th century (this can be seen clearly in figure 1 in the annex) as a result of industrial development globally with the corresponding increase in demand for energy. As energy demand is still on the upward trend, a precautionary approach is appropriate. It therefore means a 1.5°C scenario is clearly preferable to a 2°C scenario.

16 In addition, the evidence suggests that the difference between the former and the latter holds the risk of a more than linear escalation of at least some climate change impacts, such as sea level rise. The goal of holding climate change to the 1.5°C limit is therefore of great significance.

What 1.5°C means for the international shipping sector

17 International shipping is currently the only major emitter that is yet to declare its Strategy with respect to GHG abatement and climate change mitigation.

18 Taken together, declared mitigation commitments from Parties to the Paris Agreement and the international aviation sector fall far short of what is needed to achieve the Agreement's headline temperature goals.

19 This indicates that international shipping is not the only sector under pressure to reconcile the commitment to avoid dangerous climate change with ongoing emissions.

20 It also calls into question any GHG strategy that would rely on other sectors to deliver additional cuts to their emissions that would allow a proportionately higher budget for international shipping.

21 Taking into account the long subsidence times of increases in atmospheric CO_2, limiting the global temperature increase requires decarbonization.

22 In practice, a perceived potential conflict between mitigation action and the prerogative of economic growth, means that the gap between the action required to achieve declared climate change goals, and mitigation commitments by individual parties persists.

23 The importance of the 1.5°C goal, and the severe impacts of climate change beyond this limit, mean that ways to reconcile economic development with mitigation and longer term sustainability need to be found.

24 The international shipping sector is expected to contribute to mitigation action. Minimizing the extent of any negative consequences for business in the sector and for the service it provides to economic development may require cooperation from the relevant parties.

Action requested of ISWG-GHG 3

25 The Group is invited to note the report on the relevance of the 1.5°C goal as set out in the annex to this document and to take action as appropriate.

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ANNEX

ON THE RELEVANCE OF THE 1.5°C GOAL

Michael Traut

1 Introduction

New evidence, in terms of observed climate change and understanding of the Earth system, has led to a reassessment of what constitutes dangerous climate change. In turn, this has led to calls for revising the goal of limiting the global temperature increase downward from 2ºC to 1.5°C [1].

As many countries declared their support, the push for this lower goal grew in momentum, leading to its inclusion alongside the higher 2°C goal, with Article 2 of the Paris Agreement declaring the goal of "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels" [2].

As the 1.5°C goal has previously received comparatively little attention, the Intergovernmental Panel on Climate Change (IPCC) was mandated to dedicate a special report to it, due to be published in 2018. At this point, because global temperature has already increased by about 1°C since pre-industrial times, the limit is fast approaching. This document shines a light on what 1.5°C means. Section 2 defines the goal and analyses how far the world is away from this limit, in terms of greenhouse gas (GHG) emissions that are driving the global temperature increase. Section 3 gives an overview of climate change impacts that are observed or projected, paying attention to the difference between 1.5°C and 2°C. Section 4 concludes by addressing the critical need for identifying meaningful pathways towards achieving the set goal.

2 Defining the 1.5°C goal

It is one of the headline goals of the Paris Agreement "to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels" [2]. As the international shipping sector seeks to define its role "in supporting the goals of the Paris Agreement", as per the roadmap given in MEPC 70/WP.7, it is worth parsing what this goal means, and how it may be defined more precisely. This is of particular relevance to the 1.5°C, as historical warming has brought the world close to this limit already.

First, the term "temperature increase" is shorthand for the increase in the global average surface temperature. Over land area, the surface temperature is the surface air temperature (SAT) close to the land surface (typically at 10 m). Over sea areas, there is an ambiguity. Surface temperature can either be defined in the same way as over land, or as sea surface temperature (SST). Climate models often use the latter definition, and observational datasets the former, which gives slightly lower estimates of the temperature increase to date, as SST lags behind SAT.

Because temperature measurements are taken at discrete locations, and because the increase in surface temperature varies by location – e.g. temperature has increased faster over land than over the oceans – there is significant uncertainty in calculating the change in global average temperature. Because absolute temperature averages are harder to estimate than temperature changes, the temperature anomaly, i.e. the temperature change, since pre-industrial times gets reported rather than figures for absolute temperatures.

Figure 1 shows the temperature anomaly according to two of the most widely used datasets, the Hadley Centre's HadCRUT4 [3], and the NASA's GISTEMP [4].

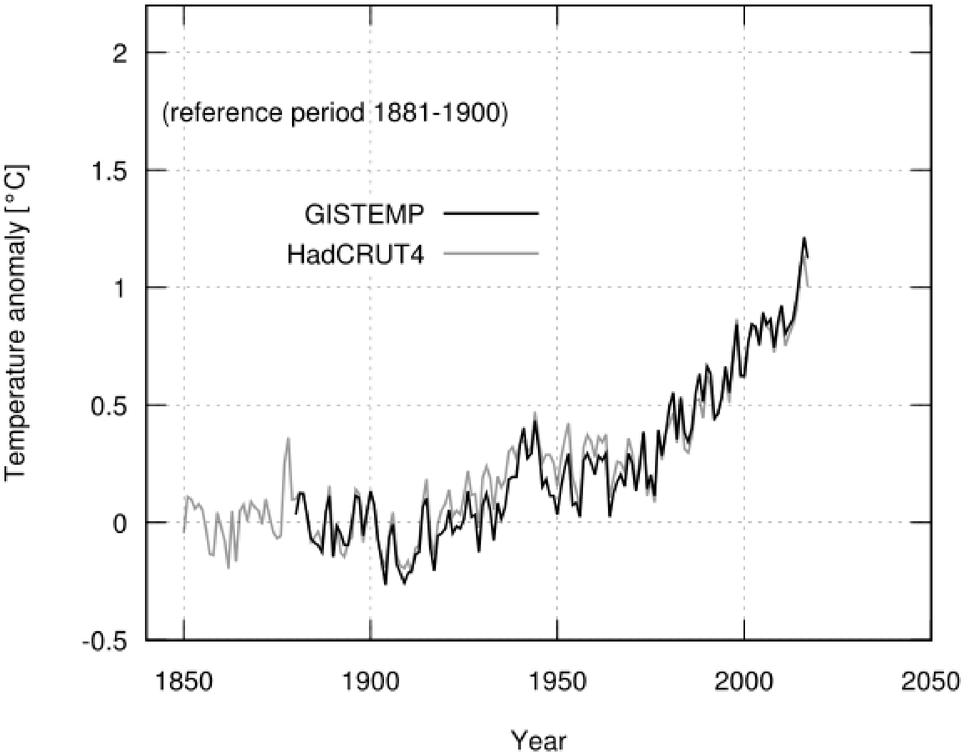

Figure 1: Observed temperature record (data from [3] and [5])

Parsing further the 1.5°C as declared in the Paris Agreement, the temperature increase "above pre-industrial levels" requires defining a reference period. Figure 1 uses the period 1881-1900, a compromise between data availability and reaching back as far as possible. In 2017, the temperature increase was 1.00°C according to the HadCRUT4 record, and 1.12°C according to the GISTEMP record. However, the temperature increase in a given year also varies due to natural internal variability, with e.g. the El Niño Southern Oscillation (ENSO), one of the major contributing factors. ENSO involves a large scale variation of pressure levels over the Pacific and other parameters. With an irregular return period of a few years, the associated warm phase, called El Niño, is associated with warmer years, as in 1998, and 2015-2016 (cf. Figure **1**). Therefore, it is also possible to use trend averages taken over a time period of several years, which would produce a slightly lower estimate in 2017.

In summary, the "temperature increase above pre-industrial levels" depends on the definition of global average surface temperature, on the definition of the "pre-industrial" reference period, on the definition of warming at present, and on the observational record, which is subject to considerable uncertainty.

Finally, many literature sources, explicitly or implicitly, consider alternative interpretations of the term "to limit the temperature increase to" a given temperature difference. While it may appear obvious to interpret the goal to mean that the temperature anomaly does not exceed the limit, considerable attention is given to "overshoot scenarios" in which temperature would actually exceed the limit, but subsequently decrease to bring the temperature anomaly below the given limit.

However, widening the definition of the 1.5°C goal to include overshoot scenarios is problematic for a number of reasons. First, to make the goal meaningful at all, additional parameters would have to be determined: the size of the overshoot and the period until temperature returns below the nominal limit. Simply increasing both parameters would make the 1.5°C goal lose any meaning. Second, most overshoot scenarios rely on unproven technologies to remove CO_2 and/or other GHGs from the atmosphere. Third, even if the 1.5°C limit were exceeded only temporarily, this would commit the world to climate change impacts associated with higher levels of warming, many of which may be irreversible.

A definition of the 1.5°C goal to include overshoot scenarios may thus conflict with "The ultimate objective of" the United Nations Framework Convention on Climate Change (UNFCCC) "to achieve ... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" [6]. The details of defining the temperature goals are of particular relevance to the debate on 1.5°C because the world has come so close to this limit, that, at one end of the range (in terms of defining global temperature and observational uncertainty), GHG emissions to date may already have committed the world to warming beyond 1.5°C.

2.1 Temperature increase and greenhouse gas emissions

The temperature increase observed since pre-industrial times is due to anthropogenic greenhouse gas emissions into the atmosphere, i.e. emissions from human activity, such as the combustion of fossil fuels, industrial processes, and land use change. In fact, the best estimate is that warming due to anthropogenic greenhouse gases is even larger than the observed increase because it is partially masked by the climate impact of aerosols, not least due to sulphur emissions from international shipping.

CO_2 is the largest contributor to anthropogenic warming and increases in atmospheric CO_2 take from centuries to millennia to subside. Therefore, whether a given temperature goal will be achieved, hinges on the success of abating CO_2 emissions. In fact, the IPCC's Fifth Assessment Report (AR5) demonstrated that there is a near linear relationship, in that variables increase at similar rates, over a wide range of future climate change scenarios, between total CO_2 emissions and global temperature increase [7].

Historical CO_2 emissions from fossil fuel burning, industrial processes, and land use change, since pre-industrial times up to and including 2016, amount to about 2,300 $GtCO_2$, with annual emissions of about 41 $GtCO_2$ in 2016 [8]. Looking forward, the IPCC has calculated the remaining cumulative CO_2 emissions budget from 2011 onward. Subtracting historical emissions over the period 2011-2016 [8], the median estimate (across the set of climate models used) of the remaining CO_2 emissions budget before the 1.5°C limit is exceeded is 300 $GtCO_2$, from 2017 onwards. Using a slightly different method, and a lower estimate of warming to date, Millar et al., have estimated the remaining CO_2 emissions budget from 2015 onwards

[9]. Subtracting 2015 and 2016 emissions, their remaining cumulative CO_2 budget from 2017 is 750 $GtCO_2$. Even the latter, more lenient, estimate would equate to less than twenty years at current emission rates. Clearly, rapid decarbonization is necessary to retain any chance of achieving the 1.5°C goal. Before turning to the topic of climate change mitigation, the following section discusses climate change impacts and the motivation for holding the global temperature increase to below 1.5°C.

3 Impacts

Life, including human life, and ecosystems have evolved to fit a climate that has been fairly stable over the Holocene, the epoch of geologic time since the end of the last Ice Age, for about 10,000 years. Consequently, rapid changes of climatic conditions are expected to have severe impacts. Impacts range from the more direct, such as increasing temperature or ocean acidification, to the more indirect, such as forced migration due to loss of livelihoods or loss of land (cf. section 3.9).

The more indirect impacts are the consequences of more complex chains of cause and effect, and are therefore generally harder to predict. However, even some of the more direct impacts are difficult to predict. For example, modelling the global temperature increase in a given emission scenario is associated with significant uncertainty. Furthermore, short term variability of weather conditions means that particular events, such as extreme heat waves, can only be attributed to climate change in a probabilistic manner and attribution is not possible in a deterministic way. That is, it is possible to say that an event has been made much more likely to happen by climate change, compared to a counterfactual scenario without man-made climate change, much like a specific dice roll may be more likely if the dice have been loaded [10].

In general, attribution science –understanding the climate change signature (or lack thereof) of particular climate events– has made significant progress in recent years [11]. Nonetheless, prediction is difficult and it is impossible to define a safe level of climate change. However, higher levels of climate change pose higher levels of risk, and a temperature increase of 2°C poses higher risks than a temperature increase of 1.5°C.

There exist thresholds and potential tipping points in the climate system, i.e. points beyond which non-linear and possibly irreversible effects are triggered, e.g. as positive feedback loops set in. The 1.5°C is in part informed by the risk of reaching some thresholds, although uncertainty when thresholds are reached is large, too. In the following, a – by no means exhaustive – overview of climate change impacts, or climate risks, is given. The overview is structured to proceed from more direct to more indirect impacts.

Where possible, discussion includes impacts already observed, impacts expected in the future, and the difference between a 1.5°C and a 2°C scenario.

3.1 Increased heat

In many regions of the world, increased temperatures are detrimental to human life and how it is organized, especially – but not limited to – extreme events. Asked in an interview whether there was anything besides multicultural tolerance that enabled Singapore's success, Lee Kwan Yew, widely considered as the nation's founding father, once replied "Air conditioning", for "making development possible in the tropics" [12]. This highlights two points about the risk of rising temperatures. First, it will make development more difficult in some places. Second, increased demand for air conditioning means increased demand for energy, exacerbating the difficulty of decarbonizing energy supply [13].

In some places, under RCP8.5, the high end climate change scenario among the four Relative Concentration Pathways (RCP), with an expected temperature rise slightly above 4°C by the end of the century [14], a significant share of the South Asian population is projected to experience episodes of wet bulb temperature[1] exceeding 35°C by 2100, which can be considered an upper limit on human survivability. Under RCP4.5 (with an expected temperature rise slightly above 2°C by the end of the century), 55% of the South Asian population are projected to experience episodes of wet bulb temperature exceeding 31°C, a level that is understood as dangerous to human health, compared to 15% in current climate conditions [15]. For marine systems, rising temperatures will induce changes in ocean circulation, changes in connectivity, and changes in upwelling, as well as decreased ocean productivity, on which humans depend [16].

The global temperature increase from climate change is not evenly distributed – many regions will experience much higher temperature increases than the global average. In terms of impacts, it is worth noting that poor and vulnerable populations will be hit hardest, due to both geography and limited capacity for adaptation.

3.2 Ocean acidification

As the concentration of atmospheric CO_2 increases, oceans take up more carbon, decreasing the pH value of ocean waters – ocean acidification – as shown in Figure 2. Together with increased temperatures, this puts coral reefs under critical stress and could impact the ability of reefs to recover from disturbance, proving detrimental to ecosystem services (cf. section 3.5). It may obstruct the formation of calcium carbonate skeletons in other organisms of vital importance to the oceans' biosphere (i.e. the collective habitats and ecosystems throughout the oceans) [17, 18].

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[1] Wet bulb temperature is the temperature that a parcel of air would have if it were cooled adiabatically by evaporating water until 100% humidity is reached. I.e. it is lower than temperature, and the difference is larger for drier air. If wet bulb temperature gets too high, keeping body temperature stable through perspiration becomes difficult.

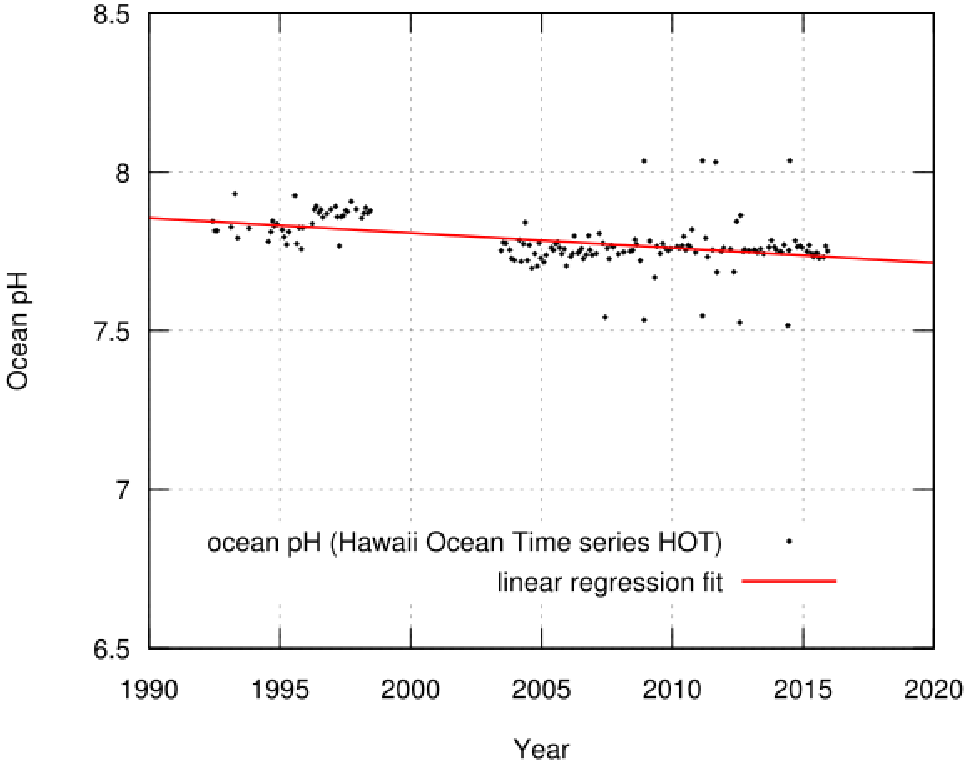

Figure 2: Ocean pH time series (data: Hawaii Ocean Time series, HOT [19])

3.3 Sea level rise

Increasing global temperature causes sea level rise. The main contributions to rising sea levels come from thermal expansion (as the volume of water increases with increasing temperature), and inflow from ice melt. Satellite altimetry provides a record of average sea level rise since the 1990s, at ~3 mm/year, as shown in Figure 3. Because the Earth's vast oceans and cryosphere take a long time to equilibrate with increased atmospheric temperature, climate change to date has already locked in sea level rise for millennia to come. The IPCC's Fifth Assessment Report estimated sea level rise of 2.3 m per°C over the next 2,000 years. This estimate does not include tipping points towards the destabilization of major ice sheets. Beyond the estimate over the next 2,000 years, AR5 estimates that destabilization of the Greenland ice sheet is triggered at some point between 1°C and 2°C warming and would add a further 5 m of sea level rise [20]. More recently, research has indicated that an ice sheet instability, i.e. the onset of a positive feedback loop resulting in ice sheet melting, in West Antarctica may have been triggered already, committing a further sea level rise of about 1 m [21-23]; and that destabilization across the full West Antarctic ice sheet could be triggered eventually [24]. Antarctic and Arctic ice sheet dynamics remain little understood, adding significant uncertainty to sea level rise projections, and posing a severe risk. Evidence for this risk is corroborated by records of past sea levels [25].

Sea level rise threatens hundreds of millions of people living in low lying areas, putting them at risk of losing their land (as in Bangladesh), or their entire countries, as in some Small Island Developing States (SIDS). Where adaptation is possible, this will impose large costs, escalating with the rise of sea levels.

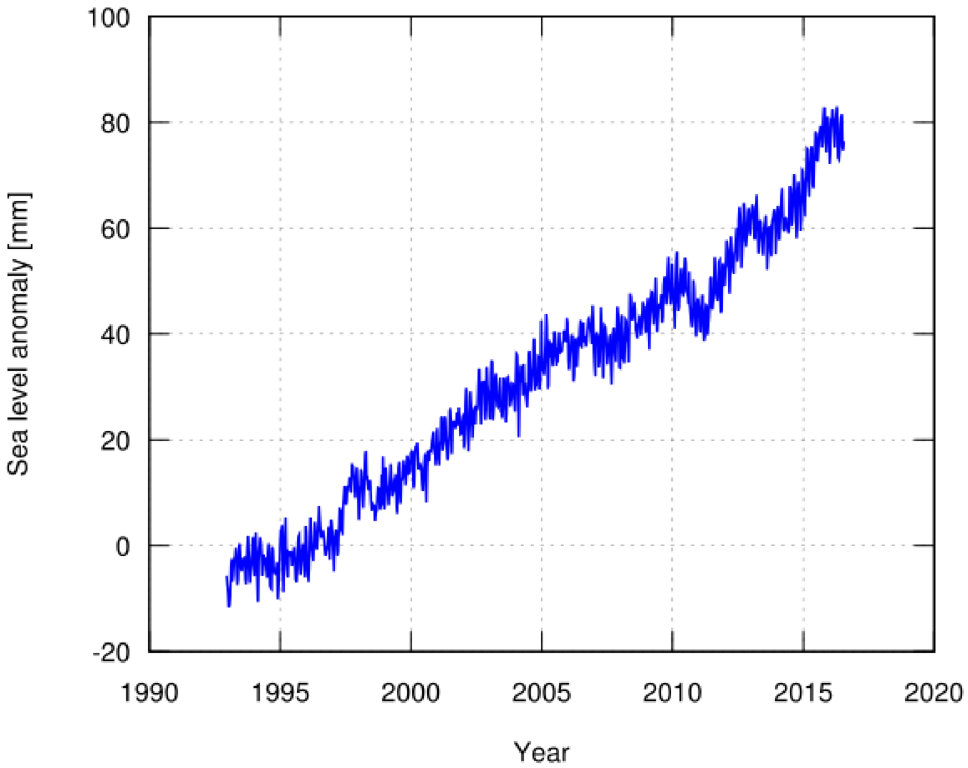

Figure 3: Observed sea level rise (data from [26])

The potential of melting Arctic sea ice to free up Arctic shipping passages has received wide attention in recent years. Arctic sea ice decline also threatens ecosystems in the region and beyond. While the potential of Arctic shipping remains limited until at least the second half of the 21st century, the 1.5°C goal is of outstanding importance to avoiding Arctic sea ice loss. Ice cover is predicted to remain stable from mid-century under RCP2.6, which is the low end climate change scenario from the suite of Representative Concentration Pathways (RCP), with a predicted temperature increase between 1.5°C and 2°C. On the high end, RCP8.5 foresees summer sea ice in accelerating decline by the end of the century, with no remaining winter sea ice [27].

3.4 Precipitation, droughts, and water availability

A warmer atmosphere can hold more water. In addition, warmer temperatures enhance evaporation. These physical principles indicate that climate change may lead to both more extreme precipitation, and more extreme dry spells, depending on regions.

Attributing extreme events to climate change is difficult, however, because of local – and changing – weather patterns and large natural variability[2].

For instance, the Mediterranean region is projected to become drier and experience more droughts in the future [28]. However, extreme dry spells are still driven by natural variability, making it difficult to show a clear fingerprint of anthropogenic climate change [29].

Changing precipitation patterns in themselves pose a challenge to adaptation, for example in agriculture, since human settlements have evolved under a more stable climate.

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[2] Natural variability includes all kinds of naturally occurring — i.e. not due to human influence — fluctuations in climatic conditions, over a wide range of spatial and temporal scales.

Furthermore, there are regions already affected by perennial scarcity of water resources. By increasing the probability of droughts, climate change holds the risk of exacerbating the issue, e.g. in the riparian zones bordering on the Nile [30], or the Jordan [31].

Comparing modelling results for 1.5°C and 2°C, Schleussner et al. find reductions of water availability with increasing levels of climate change, with the impact most pronounced in the Mediterranean [32]. However, the uncertainty associated with the results is large and diminished water availability remains a high risk that is hard to quantify.

A different risk to fresh water supplies comes from seawater intrusion in estuaries, if storm floods become more frequent, and as sea levels rise.

3.5 Coral reefs and other ecosystems

Coral reef ecosystems are highly sensitive to water temperature. In the past, El Niño events that brought warmer water temperatures have caused major coral bleaching events [33]. Following bleaching, where coral polyps lose their symbiotic pigmented algal cells, corals may recover but bleaching can also be a step along the way to coral death, as happened in the Caribbean in 2005 [34]. Following such mass bleaching events, coral reefs take a long time to recover. For instance, it was reported that recovery of coral reefs in the Maldives following mass bleaching associated with the 1998 El Niño event took up to a decade [35].

If such events take place more frequently as temperature increases due to climate change, this will reduce the capacity for recovery and put coral reefs around the world at existential risk. Beside rising temperatures, ocean acidification, rising sea levels, and other human-induced stressors exacerbate this risk.

Veron et al. have made the case for an atmospheric CO_2 concentration of 350 ppm as an upper limit [36]. Atmospheric CO_2 concentration was stable at around 280 ppm for thousands of years in pre-industrial times. Since, it has risen to above 400ppm in 2017. If CO_2 concentration were to reach 450 ppm (roughly corresponding to a 1.5°C scenario), there is a risk that coral reefs will then be in terminal decline globally [36].

The future of coral reefs likely depends on their natural (or even artificial) resilience and capacity to adapt. In a study simulating the behaviour of global reefs under 1.5°C and 2°C climate change scenarios, varying the assumed capacity for adapting to warmer water temperatures as well as the impact of ocean acidification and other stressors, results reflect the uncertainty in predicting outcomes but also reveal major differences between 1.5°C and 2°C, with 1% (in 1.5°C case), and 6% (in 2°C case) of reef cells at risk of long term degradation by the end of the century under optimistic assumption. Under less optimistic assumptions the risk extends to 69% (1.5°C), and 99-100% (2°C) [32].

Coral reefs are ecosystems of extreme biodiversity, of outstanding economic value, and a source of food (including vital protein) for an estimated half billion people [37]. Coral reefs are also just one example of the ecosystems affected by climate change. The IPCC AR5 reports that spring has been advancing by three days per decade in the Northern hemisphere [38]. Species may respond to changing climate conditions through phenotypic and genetic changes. AR5 also notes the risk of species extinction [38]. As these processes are hard to predict, a precautionary approach clearly supports 1.5°C scenario over a 2°C scenario, in order to guard against this risk.

3.6 Storms

Whether climate change increases the intensity of storms –and cyclones in particular– has been one of the most debated topics in climate science. Extreme storm events can cause large damage, both in terms of loss of human life and financial cost. In 2005, hurricane Katrina caused more than one thousand deaths, and damages in excess of $100 billion in the US [39].

The simple physical principle that a warmer atmosphere contains more energy, and therefore the potential for more intense storms, suggest the potential for more intense storms due to climate change. Emanuel presents a more elaborate analysis of storms and the air-sea interface and the definition of potential intensity as a function of sea surface temperature and other parameters, providing a value for the maximum potential wind speed of a storm which would increase with an increase in global temperature [40]. However, observing trends in cyclone intensity is hampered by the lack of reliable data. The Accumulated Cyclone Energy (ACE) is a measure of the intensity of cyclones in a given year. The IPCC's Fourth Assessment Report (AR4) presented time series data of ACE for six ocean regions, but there are no clearly discernible long term trends and the reliability of the underlying data has been questioned [41]. While AR4 considered it "likely" that intense tropical cyclone activity would increase, AR5 revised this to state "low confidence" and that it was "more likely than not in the Western North Pacific" [14, 42], in spite of the argument that many models predict *increased* intensity and *decreased* frequency of tropical cyclones [43].

While there remains significant uncertainty, more intense storm events are clearly a potential risk, relevant to many coastal regions but also to ships at sea and to marine ecosystems [34].

3.7 Food security

Climate change impacts on crop yields, and food production more generally, are extremely complex and difficult both to observe and to project. Clearly, yields are sensitive to growing conditions, including temperatures, water availability, atmospheric CO_2 concentration, and other factors. Most of these factors vary regionally and by crop, making it difficult to assess impacts aggregated at the global level. Other conditions, such as the prevalence of pests and diseases, or extreme weather events, may also shift or exacerbate due to climate change but are more indirect and therefore not considered in most modelling studies.

Furthermore, farmers can adapt to changing growing conditions, e.g. by growing more heat-resistant cultivars. Modelling yield of the four major crops wheat, soy, rice, and maize under a global temperature increase of 1.5°C and 2°C, respectively, Schleussner et al. have found mixed results, with a wide range of uncertainty [32]. In their modelling ensemble (i.e. the set of agricultural model simulation runs from which results are calculated) without CO_2 fertilization (enhanced photosynthetic production from increased atmospheric CO_2 concentration), all crop yields reduced between 1.5°C and 2°C, highlighting a significant though uncertain risk, as the effect of CO_2 fertilization is difficult to quantify. Considering absolute production, rather than yields, also depends on the expansion or otherwise of agricultural land area.

Considering fisheries and livestock, the IPCC AR5 draws no definitive conclusions on global production but projects significant negative climate change impacts on fisheries production for developing countries in the tropics, while countries further north may experience positive effects [44].

While global projections show a complicated picture, considering regions makes clear that poor populations (that have contributed least to the drivers of climate change) face the most severe impacts. For instance, Schleussner et al. report that reductions in wheat yield are especially high in West African countries [32].

It is worth noting that, historically, poor harvests have rarely been the sole or even a main cause of catastrophic famines, while a limited say in political decision-making by those affected has played a crucial role [45]. This indicates the potential for successful adaptation. On the other hand, failure to adapt holds the risk of catastrophic impacts on food security, particularly for the most vulnerable populations, with ramifications in terms of migration and conflict.

3.8 Health impacts

Human health will be affected by climate change in multiple ways. Like climate change impacts more generally, these range from the more direct to more indirect – and harder to foresee – impacts. Many of the impacts detailed in previous sections may impinge on human health. For instance, extreme heat can reach harmful levels in some places (in some others, less extreme cold phases might also bring benefits); droughts and reduced water availability may constitute a risk to public health; and climate change may have a detrimental impact on food security and people's access to adequate nutrition.

In addition, climate change may affect geographical spread of vector-borne (i.e. transmitted through a carrier of the pathogen, such as mosquitoes in the case of malaria) and other infectious diseases. While climate change clearly increases the risk in some regions, aggregate effects at the global level (e.g. in terms of cases by year) are far more difficult to estimate. This is further complicated as the total risk is highly dependent on adaptation, medical coverage, and, more generally, human institutions in place to promote public health. Conversely, this also indicates that poor and vulnerable populations, due to both geographical factors and lack of adequate resources, face the highest risk.

3.9 Migration and conflict

In many regions of the world, climate change puts whole populations' livelihoods at risk. Regions at risk of going underwater as sea levels rise provide a stark example. Migration may be the only possible adaptation measure to this and other impacts. In turn, migration is associated with well-known (though not necessarily well-understood) problems.

There is literature arguing that climate change played a role in both the Arab Spring [46], and in the Syrian civil war [47, 48], not least through drought-caused spiking of food prices. Such historical events are generally not well explained by single causes, and attribution to climate change as one of the causes (in contrast with a counterfactual, or what-if, scenario without anthropogenic climate change) is hardly possible in an unambiguous way. However, the complexity of the causes of conflict, and the difficulty of making any sort of forecast, does not mean that the risk is not real, or not severe.

This is reflected in military risk assessments, often referring to climate change as a "risk multiplier" [49]. The phenomenon of 21st century piracy around the Horn of Africa, of great human and financial cost to international shipping, may be the result of a confluence of many drivers or enabling factors. But it is difficult to overlook the loss of livelihood for parts of the Somalian population and not consider it as an enabling factor [50].

On the other hand, the complexity of the issue, and the role of socio-economic and political processes may also be seen as an indicator of the potential for adaptation.

3.10 Impacts and risk

Sections 3.1 – 3.9 provide an overview of some climate change impacts. It is by no means a complete summary. It is based on the existing literature. Some impacts, such as temperature increase, are based on a sound understanding of the underlying physical principles and can be modelled well, even if quantitative uncertainty is significant. Other, more complex ramifications are virtually impossible to model or even foresee. But a lacking ability to model or predict an impact does not mean it is less severe.

On the whole, human civilization has developed in a comparatively stable climate. Consequently, impacts of disturbing the climate are foreseen to be overwhelmingly negative. A precautionary approach therefore means a 1.5°C scenario is clearly preferable to a 2°C scenario.

In addition, the evidence suggests that the difference between the former and the latter holds the risk of a more than linear escalation of at least some climate change impacts, such as sea level rise. The goal of holding climate change to the 1.5°C limit is therefore of great significance.

4 Mitigation and the need for a viable pathway

The previous section gave an overview of climate change impacts that are observed or expected in the future. They provide the motivation to limit the global temperature increase to 1.5°C, one of the headline goals declared in the Paris Agreement.

This requires rapid reductions in greenhouse gas emissions. CO_2 emissions in particular need to be reduced to virtually zero, i.e. decarbonization, as elaborated in section 2.1. Nationally Determined Contributions (NDC) – countries declaring mitigation targets, to be updated at five year intervals, with updates ideally increasing the level of ambition – are the main mechanism in the Paris Agreement for achieving this goal. Taken together, countries' NDCs at present fall significantly short of putting the world on track to achieve the 2°C goal, let alone the 1.5°C goal [51].

International aviation and shipping are the two major greenhouse gas emitters currently not included in the Paris Agreement, because emissions are not apportioned to any specific parties to the Paris Agreement. International aviation has put in place a measure to control its CO_2 emissions in 2016, through its regulatory body, the International Civil Aviation Organization (ICAO). However, even with this measure in place, CO_2 emissions are projected to increase, rather than decrease [52]. In summary, this puts the Paris Agreement's temperature goals in serious doubt.

In practice, a perceived potential conflict between mitigation action and the prerogative of economic growth means that the gap between the action required to achieve declared climate change goals, and mitigation commitments by individual parties, persists. As a longer term aspiration, most parties have committed to achieving sustainable development, as exemplified by the UN's Sustainable Development Goals (SDG) [53]. Ultimately, climate change mitigation, and decarbonization in particular, are a component of sustainable development and the basis for economies to remain viable in the future.

The importance of the 1.5°C goal, and the severity of exceeding levels of climate change, mean that ways to reconcile economic development with mitigation and longer term sustainability need to be found, and found very urgently.

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