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1 **The human imperative of stabilizing global climate change at 1.5°C.**

2

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4

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49
 50 **Abstract (150 words):**

51
 52 Global mean surface temperature is now 1.0°C higher than the pre-industrial period due to
 53 increasing atmospheric greenhouse gases. Significant changes to natural and human (managed)
 54 systems have already occurred emphasizing serious near-term risks. Here, we expand on the
 55 recent IPCC Special Report on global warming of 1.5°C as well as additional risks associated
 56 with dangerous and irreversible states at higher levels of warming, each having major
 57 implications for multiple geographies, climates and ecosystems. Limiting warming to 1.5°C
 58 rather than 2.0°C is very beneficial, maintaining significant proportions of systems such as Arctic
 59 summer sea ice, forests and coral reefs as well as having clear benefits for human health and
 60 economies. These conclusions are relevant for people everywhere, particularly in low- and
 61 middle-income countries, where climate related risks to livelihoods, health, food, water, and
 62 economic growth are escalating with major implications for the achievement of the United
 63 Nations Sustainable Development Goals.

64 **One Sentence Summary:** Climate change is already driving dangerous impacts that will be
65 progressively less manageable at 1.5°C of global warming or higher.

66 **Main text:**

67 Climate change is one of the greatest challenges for humanity. Global mean surface temperature
68 (GMST) is increasing at the rate of $0.2^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$ per decade, reaching 1.0°C above the pre-
69 industrial period (reference period 1850–1900) in 2017 (1). GMST is projected to reach 1.5°C
70 above the pre-industrial period between 2030 and 2052, depending on the model and
71 assumptions regarding projected changes to atmospheric greenhouse gas (GHG) levels and
72 climate sensitivity (1). At the same time, growing awareness of impacts beyond 1.5°C has
73 focused international attention on the feasibility and implications of stabilizing temperatures at
74 this level (2).

75
76 In broad terms, limiting warming to 1.5°C will require a total investment in the energy sector of
77 1.46-3.51 trillion (US\$2010) in energy supply and 0.64-0.91 trillion (US\$2010) in energy
78 demand measures in order to reach net zero GHG emissions by 2050 (3)(p154). On the other
79 hand, the mean net present value (in 2008) of the avoided damages resulting from this action is
80 estimated as totalling \$496 trillion (US\$2010) by the year 2200 (3–5). This, together with other
81 damages that are difficult to fully cost and include (e.g. disruption and migration of human
82 communities; reductions in ecosystem services associated with biodiversity loss), suggests that
83 potential economic benefits arising from limiting warming to 1.5°C may be four or five
84 times larger than the investments needed to stabilize GMST to 1.5°C (SM1)(3).

85
86 Here, we explore the near-term mostly unmonetized impacts projected for 1.5°C of global
87 warming, and the associated risks and adaptation options for natural and human (managed)
88 systems. In order to understand the implications of reaching 1.5°C , we compare it to recent
89 conditions (i.e. 1.0°C warming above the pre-industrial period, Fig 1), and to those that are
90 projected to emerge as we approach 2.0°C of warming. This comparison helps understand the
91 benefits or not of stabilizing GMST at 1.5°C as compared to 2.0°C or higher, as well as
92 providing a framework for societal responses and consequences.

93

94 [Insert Figure 1 here]

95 **Crossing the 1.0°C threshold has already severely impacted natural and human systems**

96
97 The incidence of extremes has increased sharply as GMST has warmed from 0.5°C to 1.0°C
98 (~1980 – 2018) relative to the Pre-industrial period, with the intensity and/or frequency of
99 extremes projected to change further with another 0.5°C of warming (5). As GMST has
100 increased, for example, the average temperature of cold days and nights (i.e. the coldest 10%)
101 has also increased overall, as has the average temperature of warm days and nights (i.e. the
102 warmest 10%) globally (5). These changes have also been accompanied by increases in the
103 frequency and/or duration of heatwaves for large parts of Europe, North America and Australia.
104 Increases in GMST have been accompanied by increases in the frequency, intensity and/or
105 amount of heavy precipitation in more regions than those with decreases, especially in North-
106 Hemisphere mid-latitude and high-latitude areas (5, 6). There is also evidence of increasing
107 rainfall associated with recent tropical cyclones (6, 7) and increasingly heavy precipitation
108 during storms in the Central Sahel (8, 9). The number of tropical cyclones has decreased, while
109 the number of very intense cyclones has increased, for many areas (5). There is less confidence
110 regarding trends in the length of drought, although a significant increasing trend has been
111 detected in the Mediterranean region (particularly Southern Europe, North Africa and the near-
112 East) (10–12).

113
114 As on land, coastal and marine habitats have also experienced an increased frequency, intensity
115 and duration of underwater heatwaves, with a threefold increase in the number of marine
116 heatwave days globally since 1980 (13). The differential heating of the water column has also led
117 to increased thermal stratification in some coastal and oceanic regions which decreases ocean-
118 atmosphere gas exchange as well the turnover of nutrients between the photic layer and deeper
119 layers of the ocean. The annual mean Arctic sea ice extent decreased by 3.5 - 4.1% per annum
120 from 1979 to 2012 (6). The melting of land-based ice includes potentially unstable regions such
121 as the Western Antarctic Ice Sheet (WAIS, Fig 1B), which contributed 6.9 ± 0.6 mm over 1979-
122 2017 to global mean sea level (GMSL). Together with glacial melt water, thermal expansion of
123 the ocean has accelerated the rate of GMSL increase by up to 0.013 [0.007-0.019] mm yr⁻² since

124 the early 20th Century (14). Changes in ocean temperature have also decreased the oxygen
125 concentration of the bulk ocean, interacting with coastal pollution to increase the number and
126 extent of low oxygen dead zones in many deep-water coastal habitats (15). In addition to
127 increasing GMST, anthropogenic CO₂ also enters the ocean causing a reduction in pH (ocean
128 acidification) which negatively impacts processes such as early development, calcification,
129 photosynthesis, respiration, sensory systems, and gas exchange in organisms from algae to fish
130 (5).

131
132 Changing weather patterns (e.g. temperature, rainfall, dryness, storms) have increased negative
133 impacts on natural and managed systems (Fig 1A-D). Changes to coral reefs (5), forests (e.g.
134 changing drought/fire regimes) (16, 17), low-lying islands and coasts (5), and impacts on
135 agriculture production and yield (18, 19) are threatening resources for dependent human
136 communities. There are also many gradual changes that have occurred as GMST has increased,
137 with many being no less important than the more abrupt changes. Land-based biomes (i.e. major
138 natural and agricultural ecosystem types) have also shifted to higher latitudes and elevation in
139 boreal, temperate and tropical regions (5, 15), with similar shifts reported for marine and
140 freshwater organisms. Marine organisms and some ecosystems have also shifted their
141 biogeographical ranges to higher latitudes at rates up to 40 km yr⁻¹. Rates are highest for pelagic
142 organisms and ecosystems such as plankton, and are lowest for more sedentary benthic
143 organisms and ecosystems such as seaweeds and kelp forests (5, 15). These types of changes
144 (e.g. temperature, storms, circulation) have also affected the structure and function of ocean
145 ecosystems with respect to its biodiversity, food-webs, incidence disease and invasive species
146 (5).

147
148 Other changes to biological systems include changes to the phenology of marine, freshwater and
149 terrestrial organisms (e.g. timing of key events such as reproduction and migration) (5, 15). The
150 phenology of plants and animals in the Northern-Hemisphere, for example, has advanced by 2.8
151 ± 0.35 days per decade due to climate change, with similar changes in the flowering and
152 pollination of plants and crops, and the egg-laying and migration times of birds (5, 20). There are
153 indications that climate change has already contributed to observed declines in insects and
154 arthropods in some regions (21, 22). Variations in these types of changes have also been

155 observed in the phenology of tropical forests, which have been more responsive to changes in
156 moisture stress rather than to the direct changes in temperature (5). While the intention here is
157 not to catalogue all of the changes that have occurring in natural systems, it is important to
158 acknowledge that deep and fundamental changes are underway in biological systems with just
159 1°C of global warming so far (5).

160

161 Changes in GMST of 1.0°C have also directly and indirectly affected human communities, many
162 of which depend on natural and managed systems for food, clean water, coastal defence, safe
163 places to live, and livelihoods among many other ecosystem goods and services (5). Coral reefs
164 clearly illustrate the linkage between climate change, ecosystem services and human well-being.
165 At 1.0°C, large-scale mortality events driven by lengthening marine heatwaves have already
166 reduced coral populations in many places (5), with prominent coral reef ecosystems such as the
167 Great Barrier Reef in Australia losing as much as 50% of their shallow water corals in the last
168 four years alone (5, 23, 24). These changes have potential implications for millions of people
169 given their dependency on coral reefs for food, livelihoods and well-being (5).

170 **Understanding climate change over the next few decades: methods and assumptions**

171

172 There are a range of strategies for quantifying risks for natural and human systems at 1.5°C and
173 2.0°C above the pre-industrial period. This requires calculating the future exposure of systems
174 to changes in climatic hazards. Some methods rely on the fact that an equivalent amount of
175 warming (e.g. 0.5°C) occurred in the recent past (e.g. ca. 1950 to 2000, or ca. 1980 to 2018, Fig
176 2A; (3)) potentially providing insights into how risks might change in the near future. In this
177 case, the associated risks of the next 0.5°C of global warming (Fig 2A) are linearly extrapolated
178 from the impacts associated with the previous 0.5°C increase (ca. 1980-2018). This method of
179 projecting future risk is likely to be conservative given (a) the pace of climate change is
180 increasing (25) and (b) the impacts per unit of temperature are likely to increase as conditions are
181 pushed increasingly beyond the optimal conditions for a particular organism or physiological
182 process (Fig 2B)(26). Responses by natural and human systems are likely to also differ if
183 temperature pathways involve a gradual increase to 1.5°C above the pre-industrial period (no
184 ‘overshoot’) as opposed to pathways that first exceed 1.5°C before later declining to 1.5°C,

185 which is referred to as an ‘overshoot’ (5) (Fig 2A). High levels of overshoot involve exceeding
186 1.5°C by 0.1°C (Figure 2A) (3).

187
188 [Insert Figure 2 here]

189
190 Other approaches for understanding how the world may change at 1.5°C and 2.0°C of global
191 warming draw on laboratory, mesocosm, and field experiments. These approaches simulate
192 projected conditions for different levels of warming and, in the case of marine systems, levels of
193 acidification (e.g. changes in pH, carbonate, pollution levels (5, 26, 27). These experimental
194 approaches also provide calibration as well as insight into future conditions and responses (i.e.
195 1.5°C versus 2.0°C). Some caution is also required given that global increases of 1.5°C or 2.0°C
196 may involve a broad range of regional responses. This arises due to uncertainties in (for
197 example) the likelihood of overshoot, land-atmosphere interactions, biophysical effects of land
198 use changes, and interannual climate variability (28). Several lines of evidence for
199 understanding these complex problems include the analysis of the frequency and intensity of
200 extremes as well as projections based on existing climate simulations and empirical scaling
201 relationships for 1.5°C and 2.0°C of global warming (5). Lines of investigation may also include
202 dedicated experiments prescribing sea surface conditions consistent with these levels of
203 warming, as done in the HAPPI (Half a degree Additional warming, Prognosis and Projected
204 Impacts) project (5). Furthermore, fully-coupled climate model experiments can be achieved
205 using GHG forcing consistent with 1.5°C or 2.0°C scenarios (5). These multiple yet different
206 lines of evidence (above) underpin the development of qualitatively consistent results regarding
207 how temperature means and extremes could change at 1.5°C as compared to 2.0°C of global
208 warming.

209 **Projected changes in climate at 1.5°C versus 2.0°C of global warming**

210
211 Understanding the potential advantages of restraining global warming to 1.5°C requires an
212 understanding of the risks associated with the exposure of natural and human systems to climatic
213 hazards, and how they change at 1.5°C relative to 2.0°C (Fig 3)(29). Increases of GMST to
214 1.5°C will further increase the intensity and frequency of hot days and nights, and decrease the

215 intensity and frequency of cold days and nights (Fig 3 C.D.E). Warming trends are projected to
216 be highest over land, in particular for temperature extremes, with increases of up to 3°C in the
217 mid-latitude warm season and up to 4.5°C in cold seasons at high latitudes. These increases are
218 projected to be greater at 2.0°C of global warming, with increases of up to 4°C in the mid-
219 latitude warm season and up to 6°C in the high-latitude cold season (e.g. Fig 3 A.C.D.E.) (29).
220 Heatwaves on land, which are already increasing pressure on health and agricultural systems, are
221 projected to become more frequent and longer (Fig 3 C.D.).

222
223 There is considerable evidence that dryness will increase in some regions, especially the
224 Mediterranean as well as southern Africa (5, 30–32). Risks of drought, dryness and precipitation
225 deficits are projected to increase at 1.5°C and even further at 2.0°C for some regions relative to
226 the pre-industrial period (Fig 3B,F)(5, 33). Recent studies also suggest similar projections for
227 the western Sahel and southern Africa, as well as the Amazon, north-eastern Brazil, and Central
228 Europe (5, 34). Projected trends in dryness are uncertain in several regions, however, and some
229 regions are projected to become wetter(Fig 3 B,F) (5). Reaching GMST of 1.5°C and 2.0°C, for
230 example, would lead to a successive increase in the frequency, intensity and/or amount of heavy
231 rainfall when averaged over global land area (Fig 3 B,F). Global warming of 2.0°C versus 1.5°C
232 increases exposure to fluvial flood risk particularly at higher latitudes and in mountainous
233 regions, as well as in East Asia, China (35) and eastern North America overall (5). The
234 prevalence of subsequent intense wet and dry spells, in which a prolonged drought is
235 immediately followed by heavy precipitation at the same location (potentially leading to
236 flooding) or vice versa, is projected to be greater at 2.0°C global warming versus 1.5°C (36).
237 These large changes between coupled wet and dry conditions represent a major challenge for
238 adaptation as they will affect water quality and availability as well as increased soil erosion
239 along many coastal areas. Sea level rise can also amplify problems through damage to coastal
240 infrastructure and the salinization of water supplies for drinking and agriculture (5).

241
242 Relatively few studies have directly explored the effect of 1.5°C versus 2.0°C of global warming
243 on tropical cyclones (5). These studies consistently reveal a decrease in the global number of
244 tropical cyclones at 1.5°C vs 1.0°C of global warming, with further decreases under 2.0°C vs
245 1.5°C of global warming. Simultaneously, very intense cyclones are likely to occur more

246 frequently at 2.0°C vs 1.5°C of global warming, with associated increases in heavy rainfall and
247 damage, further emphasizing the advantages of not exceeding 1.5°C (5).

248

249 [Insert Figure 3 here]

250

251 Coastal and oceanic regions are also projected to increase in temperature as GMST increases to
252 1.5°C, and further to 2.0°C, above the pre-industrial period. Absolute rates of warming are only
253 slightly lower in the ocean than on land although the shallower spatial gradient of ocean
254 temperature will mean that the velocity of climate change may be higher in many regions of the
255 ocean (5, 37). Increases in ocean temperature associated with 1.5°C and 2.0°C of global warming
256 will increase the frequency and duration of marine heatwaves, as well as reducing the extent of
257 ocean mixing due to the greater thermal stratification of the water column (13, 15). Sea ice is
258 projected to continue to decrease in the Arctic, although restraining warming to 1.5°C will mean
259 an ice free Arctic summer will only occur every 100 years, while warming to 2.0°C above the
260 pre-industrial period will mean an ice free Arctic summer is likely to occur every 10 years by
261 2100 (5, 38). These and other models indicate that there will be no long-term consequences for
262 sea ice coverage in the Arctic (i.e. no hysteresis) if GMST is stabilised at or below 1.5°C (3).

263

264 **Impacts on ecosystems at 1.5°C versus 2.0°C of global warming**

265

266 Multiple lines of evidence (5) indicate that reaching and exceeding 1.5°C will further transform
267 both natural and human systems, leading to reduced ecosystem goods and services for humanity.
268 Importantly, risks for terrestrial and wetland ecosystems such as increasing coastal inundation,
269 fire intensity and frequency, extreme weather events, and the spread of invasive species and
270 diseases are lower at 1.5°C as compared to 2.0°C of global warming (5). In this regard, the
271 global terrestrial land area that is predicted to be affected by ecosystem transformations at 2.0°C
272 (13%, interquartile range 8-20%) is approximately halved at 1.5°C (4%, interquartile range 2-
273 7%). Risks for natural and managed ecosystems are higher on drylands as compared to humid
274 lands (5). The number of species that are projected to lose at least half of their climatically
275 determined geographic range at 2.0°C of global warming (18% of insects, 16% of plants, 8% of

276 vertebrates) would be significantly reduced at global warming of 1.5°C (i.e. to 6% of insects, 8%
 277 of plants, and 4% of vertebrates)(5). In this regard, species loss and associated risks of
 278 extinction are much lower at 1.5°C than 2°C. Tundra and boreal forests at high latitudes are
 279 particularly at risk, with woody shrubs having already encroached on tundra, which will increase
 280 with further warming (5). Constraining global warming to 1.5°C would reduce risks associated
 281 with the thawing of an estimated 1.5-2.5 million km² of permafrost (over centuries) compared to
 282 the extent of thawing expected at 2.0°C (5).

283
 284 Ecosystems in the ocean are also experiencing large-scale changes, with critical thresholds
 285 projected to be increasingly exceeded at 1.5°C and higher global warming. Increasing water
 286 temperatures are driving the relocation of many species (e.g. fish, plankton) while sedentary
 287 organisms, such as kelp and corals, are relatively less able to move. In these cases, there are
 288 multiple lines of evidence that indicate that 70-90% of warm water tropical corals present today
 289 are at risk of being eliminated even if warming is restrained to 1.5°C. Exceeding 2.0°C of global
 290 warming will drive the loss of 99% of reef-building corals (5). These non-linear changes in
 291 survivorship are a consequence of the increasing impact of changes as they move away from
 292 optimal conditions (Fig 2B) (26). Impacts on oceanic ecosystems are expected to increase at
 293 global warming of 1.5°C relative to today, with losses being far greater at 2.0°C of global
 294 warming. Significant compound or secondary risks exist with respect to declining ocean
 295 productivity, loss of coastal protection, damage to ecosystems, shifts of species to higher
 296 latitudes, and the loss of fisheries productivity (particularly at low latitudes)(15). There is
 297 substantial evidence that these changes to coastal risks will increasingly threaten the lives and
 298 livelihoods of millions of people throughout the world (5).

299 **Increasing risks for human (managed) systems at 1.5°C and 2.0°C of global warming**

300 Many risks for society will increase as environmental conditions change. Water, for example, is
 301 often central to the success or failure of human communities. The projected frequency and scale
 302 of floods and droughts in some regions will be smaller under 1.5°C global warming as opposed
 303 to 2°C, with risks to water scarcity being greater at 2.0°C than at 1.5°C of global warming for
 304 many regions (5). Salinization of freshwater resources on small islands and along low-lying
 305 coastlines is a major risk that will become successively more important as sea levels rise,

306 particularly as they will continue to increase even if temperatures stabilise. (5). Depending on
307 future socio-economic conditions, limiting warming to 1.5°C is projected to reduce the
308 proportion of the world's population exposed to climate induced water stress by up to 50% as
309 compared at 2°C (5), although there is considerable variability among regions as already
310 discussed. Most regions, including the Mediterranean and Caribbean regions, are projected to
311 experience significant benefits from restraining global warming to 1.5°C (39), although socio-
312 economic drivers are expected to play a dominant role relative to climate change for these
313 communities over the next 30-40 years.

314
315 Limiting global warming to 1.5°C is projected to result in smaller reductions in the yield of
316 maize, rice, wheat and potentially other cereal crops than at 2.0°C, particularly in sub-Saharan
317 Africa, Southeast Asia, and Central and South America (40–42). A loss of 7-10% of rangeland
318 stock globally is also projected to occur at an increase of 2.0°C above the pre-industrial period,
319 which will have considerable economic consequences for many communities and regions.
320 Reduced food availability at 2.0°C as compared to 1.5°C of global warming is projected for
321 many regions including the Sahel, Southern Africa, the Mediterranean, Central Europe and the
322 Amazon. Few examples exist where crop yields are increasing and hence food security is at
323 increasing risk in many regions (41). Although food systems in future economic and trade
324 environments may provide important options for mitigating hunger risk and disadvantage (43,
325 44)(5), assuming that solutions are found to the decline in the nutritional quality of major cereal
326 crops from higher CO₂ concentrations (5).

327
328 Food production from marine fisheries and aquaculture is of growing importance to global food
329 security but is facing increasing risks from ocean warming and ocean acidification (5). These
330 risks increase at 1.5°C of global warming and ocean acidification, and are projected to impact
331 key organisms such as finfish, corals, crustaceans and bivalves (e.g. oysters) especially at low
332 latitudes (5). Small-scale fisheries that depend on coastal ecosystems such as coral reefs,
333 seagrass, kelp forests and mangroves, are expected to face growing risks at 1.5°C of warming as
334 a result of the loss of habitat (5). Risks of impacts, and subsequent risks to food security, are
335 projected to become greater as global warming reaches 1.5°C (5, 43, 44) Tropical cyclones have
336 major impacts on natural and human systems, and are projected to increase in intensity in many

337 regions, with the damage exacerbated by rapid sea level rise (14, 45). The tropical cyclones in
338 the North Atlantic basin in 2017 had significant and widespread effects on the small islands of
339 Caribbean as well as the United States, resulting in many deaths, displacement of communities,
340 elevated rates of morbidity and mental health issues, as well as the long-term loss of electricity
341 generation and distribution. These impacts have resulted in significant economic damage, which
342 has exceeded the annual GDP of some small island developing States (46, 47).

343
344 Millions of people are already exposed to coastal flooding due to sea level rise and storms,
345 particularly in cities. Projections of sea level rise remain uncertain (5), and may include
346 significant non-linear responses, in part due to the contribution of land-based ice (48–50). Due to
347 the time lag between increased emissions and higher sea levels, differences in mitigation at 1.5°C
348 and 2.0°C, are relatively small compared with the uncertainty in the projections at 2050 or even
349 2100. Small differences can, however, have big impacts: an increase of 0.1m of sea level rise, for
350 example, will expose an additional 10 million people to flooding (5) particularly those living in
351 low-lying deltas and small islands (5, 51). Even with mitigation, adaptation remains essential,
352 particularly as multi-metre sea level rise remains possible over several centuries for higher levels
353 of temperature rise (5). Estimates of the net present value in 2008 of global aggregate damage
354 costs (which would be incurred by 2200 if global warming is limited to 2.0°C) reach \$69 trillion
355 (5). Damages from sea level rise alone contributes several trillion of dollars per annum (52). The
356 net present value in 2008 of global aggregate damage costs associated with 1.5°C warming
357 which would be incurred by 2200 if global warming is limited to 1.5C are less than those at
358 2.0°C, with comparable estimates around \$54 trillion in total (5).

359
360 Warming of 1°C has increased the frequency and scale of impacts on human health through
361 changes to the intensity and frequency of heatwaves, droughts, floods and storms, as well as
362 impacts on food quantity and nutritional quality (through increasing CO₂ concentrations)
363 resulting in undernutrition or malnutrition in some regions (5, 43, 44). Multiple lines of evidence
364 indicate that any further increases in GMST could have negative consequences for human health,
365 mainly through the intensification of these risks (5, 53). Lower risks are projected at 1.5°C than
366 2.0°C of global warming for heat-related morbidity and mortality, and for ozone-related
367 mortality if ozone precursor emissions remain high. Limiting global warming to 1.5°C would

368 result in 420 million fewer people being frequently exposed to ‘extreme heatwaves’ (defined by
369 duration and intensity (54)) and about 65 million fewer people being exposed to ‘exceptional’
370 heatwaves as compared to conditions at 2.0°C GMST warming (55). Human health will also be
371 affected by changes in the distribution and abundance of vector-borne diseases such as dengue
372 fever and malaria, which are projected to increase with warming of 1.5°C and further at 2.0°C in
373 most regions (5). Risks vary by human vulnerability, development pathways, and adaptation
374 effectiveness (43, 44, 56). In some cases, human activities can lead to local amplification of heat
375 risks from urban heat island effects in large cities (57, 58). More specific impacts of, and
376 solutions to, climate change on cities are provided elsewhere (43, 56)

377
378 Global warming of 1.5°C will also affect human well-being through impacts on agriculture,
379 industry and employment opportunities. For example, increased risks are projected for tourism in
380 many countries, whereby changes in climate have the potential to affect the attractiveness and/or
381 safety of destinations, particularly those dependent on seasonal tourism including sun, beach and
382 snow sport destinations (5, 15). Businesses that have multiple locations or markets may reduce
383 overall risk and vulnerability, although these options are likely to be reduced as stress and
384 impacts increase in frequency and areal extent. Risks and adaptation options may lie in
385 developing alternative business activities that are less dependent on environmental conditions.
386 These risks become greater as warming increases to 2.0°C and pose serious challenges for a large
387 number of countries dependent on tourism and related activities for national income (5).

388
389 Multiple lines of evidence also reveal that poverty and disadvantage are also correlated with
390 warming to 1.0°C above pre-industrial period, with the projection of increasing risks as GMST
391 increases from 1.0°C (today) to 1.5°C and higher (43, 44). In this regard, out-migration from
392 agriculturally-dependent communities is positively correlated with global temperature although
393 our understanding of the links between human migration and further warming of 1.5°C and
394 2.0°C is at an early stage (5). Similarly, risks to global aggregate economic growth due to
395 climate change impacts are projected to be lower at 1.5°C than 2.0°C by the end of the century
396 (5). The largest reduction in economic growth at 2.0°C compared to 1.5°C are projected for low-
397 and middle-income countries and regions (the African continent, Southeast Asia, India, Brazil
398 and Mexico). Countries in the tropics and Southern Hemisphere subtropics, are projected to

399 experience the largest negative impacts on economic growth if global warming increases from
400 1.5°C to 2.0°C above the pre-industrial period (5, 43, 44). The most perceptible impacts of
401 climate change are likely to occur in tropical regions as GMST increases to 1.5 °C and eventually
402 to 2°C above the pre-industrial period (59).

403

404 Table 1 summarizes the emergence of potential climate change ‘hotspots’ (i.e. areas where risks
405 are large and growing rapidly) for a range of geographies and sectors (5). In all cases, these
406 vulnerable regions show increasing risks as warming approaches 1.5°C and higher. Not all
407 regions, however, face the same challenges. In the Arctic, for example, habitat loss is
408 paramount, while changing temperature and precipitation regimes represent primary risks in the
409 Mediterranean, Southern Africa, West Africa and the Sahel. These rapidly changing locations
410 represent interactions across climate systems, ecosystems and socio-economic human systems,
411 and are presented here to illustrate the extent to which risks can be avoided or reduced by
412 achieving the 1.5°C global warming goal (as opposed to 2.0°C).

413

414 [Insert Table 1 here]

415

416 Trajectories toward hotspots can also involve significant non-linearities or tipping points.
417 Tipping points refer to critical thresholds in a system that result in rapid systemic change when
418 exceeded (5). The risks associated with 1.5°C or higher levels of global warming reveal
419 relatively low risks for tipping points at 2.0°C but a substantial and growing set of risks as global
420 temperature increases to 3°C or more above the pre-industrial (Table 2) (5). For example,
421 increasing GMST to 3°C above the pre-industrial period substantially increases the risk of
422 tipping points such as permafrost collapse, Arctic sea ice habitat loss, major reductions in crop
423 production in Africa as well as globally, and persistent heat stress that is driving sharp increases
424 in human morbidity and mortality (Table 2) (5).

425

426 [Insert Table 2 here]

427

428 **Solutions: scalability, feasibility and ethics**

429

430 GMST will increase by 0.5°C between 2030 and 2052 and will multiply and intensify risks for
431 natural and human systems across different geographies, vulnerabilities, development pathways,
432 as well as adaptation and mitigation options (1, 43, 44, 56). To keep GMST to no more than
433 1.5°C above the pre-industrial period, the international community will need to bring GHG
434 emissions to net zero by 2050 while adapting to the risks associated with an additional 0.5°C
435 being added to GMST (3, 5) The impacts associated with limiting warming to 1.5°C, however,
436 will be far less than those at 2.0°C or higher (Table 1, 2). Aiming to limit warming to 1.5°C is
437 now a human imperative if escalating risks of dangerous if not catastrophic tipping points and
438 climate change hotspots are to be avoided (2, 5).

439

440 An important conclusion of the IPCC special report on 1.5°C is that limiting GMST to 1.5°C or
441 less is still possible (3, 60). This will require limiting GHG emissions to a budget of 420 Gt CO₂
442 for a 66% or higher probability of not exceeding 1.5°C (44). As global emissions are currently
443 around 42 Gt CO₂ per year, pathways should bring CO₂ emissions to net zero over the next few
444 decades (i.e. phase out fossil fuel use) alongside a substantial reduction (~35% relative to 2010)
445 in emissions of methane and black carbon over the same time scale (44). The current set of
446 national voluntary emission reduction pledges (Nationally Determined Contributions or NDCs),
447 however, will not achieve the goals of the Paris Agreement (2, 61), particularly when
448 considering the land-use sector (62). Instead, GMST is projected to increase by 3-4°C above the
449 pre-industrial period (1, 44), posing serious levels of risk for natural and human systems (3, 5,
450 20).

451

452 The majority of pathways for achieving 1.5°C also require the carbon dioxide removal (CDR)
453 from the atmosphere. Delays in bringing CO₂ emissions to net zero over the next 20-30 years
454 will also increase the likelihood of pathways that exceed 1.5°C (so-called ‘overshoot’ scenarios)
455 and hence a greater reliance on net negative emissions after mid-century if GMST to return to
456 1.5°C (Fig 2A). Technologies designed to remove CO₂ from the atmosphere are at an early stage
457 of development, with many questions as to their feasibility and scalability (5). For example,
458 bioenergy with carbon capture and storage (BECCS), afforestation and reforestation, blue carbon

459 (i.e. carbon sequestration by marine ecosystems and processes), soil carbon sequestration, direct
460 capture, biochar (i.e. charcoal for burial in soils), and enhanced weathering, variously struggle
461 from issues such as feasibility, scalability, and acceptability. These strategies are potentially in
462 competition with each other. For example, BECCS would require approximately 18% of global
463 land to sequester 12 Gt CO₂/yr (5). This requirement is likely, however, to drive an accelerating
464 the loss of primary forest and natural grassland which would increase GHG emissions (5). Early
465 emission reductions plus measures to conserve land carbon stocks may reduce these effects.
466 Policy options might limit the expansion of agriculture at the expense of natural ecosystems,
467 and/or safeguard agricultural productivity from reductions due to BECCS and/or biofuel
468 production (5).

469
470 There are CDR options, however, that do not rely as extensively on BECCS, but rather focus on
471 afforestation and/or the restoration of natural ecosystems. It is feasible, for example, to limit
472 warming to 1.5°C using strategies such as changing diets and promoting afforestation to remove
473 CO₂ (3, 5, 43, 44). Negative consequences of afforestation such as monoculture plantations on
474 local biodiversity might be countered by preferentially restoring natural ecosystems, re-
475 establishing the ability of native grasslands, peatlands, forests, mangroves, kelp forests, and
476 saltmarshes to sequester carbon. This creates a ‘win-win’ scenario in which both climate and
477 biodiversity benefit, contributing to SDG 15 ‘Life on Land’: and hence, simultaneously making
478 an enormous contribution to the goals of both CBD and UNFCCC. Compatible with this idea is
479 the recent UN establishment of the 2020s as the ‘Decade of Restoration’, with the intention to
480 build a global resolve to conserve biodiversity, increase its resilience to climate change, and use
481 it to sequester up to a total of 26 GtC (63).

482
483 Extensive adaptation to 1.5°C of global warming or higher will be very important, especially if
484 we have underestimated climate sensitivity. Developing socially-just and sustainable adaptation
485 responses will be increasingly necessary to help natural and human systems to prepare and
486 respond to rapid and complex changes in risk (43). The global adaptation stocktake instigated by
487 the Paris Agreement will help accountability through documentation and mechanisms that
488 inform enhancement at national levels (64, 65). It must also be acknowledged that there are
489 limits to adaptation for natural and human systems (66) and hence subsequent loss and damage

490 (5, 67–69). For example, actions to restore ecosystems may not always be possible given
491 available resources and it may not be feasible to protect all coastal regions from erosion and loss
492 of land. These challenges mean that identifying, assessing, prioritizing and implementing
493 adaptation options are very important for reducing the overall vulnerability to increasing climate-
494 related risks as GMST increases. It has become increasingly clear that long-term solutions to
495 climate change must also reduce disadvantage and poverty. Consequently, the recent IPCC
496 Special Report pursued its findings in the context of ‘strengthening the global response to the
497 threat of climate change, sustainable development, and efforts to eradicate poverty’ (3). While
498 previous reports recognized the importance of not aggravating disadvantage, few have
499 specifically focused on solutions that involve multiple elements of climate change, sustainable
500 development and poverty alleviation. For example, greater insights and knowledge are required
501 to understand how multiple Sustainable Development Goals (SDGs) interact with each other,
502 although many of these interactions are beneficially synergistic (70). Importantly, SDGs are far
503 more easily reached at 1.5°C versus 2.0°C or more of global warming (43).

504
505 The important issue of ‘loss and damage’ also highlights the inequity between nations that have
506 largely caused climate change (and have received the greatest benefits) and those who have not.
507 This inequity is particularly important for least developed countries (LDCs) and small island
508 developing States (SIDSs) that have contributed relatively little to global GHG emissions but
509 now face disproportionate risks and harm from climate change, even at 1.5°C (67–69, 71).
510 UNESCO has also emphasized the importance of ethics within a non-binding Declaration of
511 Ethical Principles in Relation to Climate Change in 2017 (72). Specifically, this declaration
512 states that “decision-making based on science is critically important for meeting the mitigation
513 and adaptation challenges of a rapidly changing climate. Decisions should be based on, and
514 guided by, the best available knowledge from natural and social sciences including
515 interdisciplinary and transitionary science and by considering (as appropriate) local, traditional
516 and indigenous knowledge”. These types of initiatives are especially important in the
517 development of policies and actions that avoid inequalities that arise through exclusion and
518 misinformation (61). A transformation toward climate-resilient and low-carbon societies needs to
519 be done in a way that addresses the issue of justice and equity, through ensuring that trade-offs
520 and synergies are identified and actioned (43).

521 **Conclusion**

522 Warming of 1.0°C since the mid-20th century has fundamentally transformed our planet and its
523 natural systems. Multiple lines of evidence reveal that a 1.5°C world will entail larger risks to
524 both human and natural systems. The risks of a 2°C world are much greater. This places us at a
525 critical time in human history where proportionate action taken today will almost certainly
526 minimize the dangerous impacts of a changing climate for hundreds of millions of people.
527 Our preliminary estimates suggest that the benefits of avoided damage by the year 2200 may
528 exceed the costs of mitigation by a factor of four or five. Current NDCs for 2030 are insufficient
529 to drive this even if followed by ‘very challenging increases in the scale and ambition of
530 mitigation after 2030’ (44)(p 95), because models based on the current understanding of
531 economic and technical dynamics cannot identify how to reduce GHG emissions to net zero by
532 2050 from the current NDC starting point in 2030. Rather, these ambitions are consistent with a
533 global warming level of 3-4°C which means that immediate and transformative action is required
534 between now and 2030 in order to greatly scale up current nationally stated plans for GHG
535 reductions. Strategies for responding to climate change must be scalable to the challenges of
536 climate change being faced today and into the future, while at the same time being feasible and
537 fair. Given the scope and threats associated with climate change, there is an increasing need for
538 large scale strategies such as the UN Climate Resilient Development Pathways (CRDP) or
539 ‘Green New Deal’ (UNEP) if society is to avoid potentially catastrophic circumstances over the
540 next few decades.
541

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744 **Acknowledgments:**

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 746 Report on the “Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related
 747 Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global
 748 Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate
 749 Poverty” (3). They are grateful for the support provided by the Intergovernmental Panel on
 750 Climate Change (IPCC), particularly that of the Technical Support Units for Working Groups I
 751 and II, as well as the large number of Contributing Authors and Science Officers involved in the
 752 IPCC Special Report (3). The findings, interpretations, and conclusions expressed in the work do
 753 not necessarily reflect the views of The World Bank, its Board of Executive Directors, or the
 754 governments they represent.

756 **Supplementary Materials online:**

757 Material and Methods

758

759 SM1: Calculation of benefits versus costs for stabilizing at 1.5°C versus 3.7°C.

760

761 Damages avoided can be estimated as those that accumulate under no mitigation scenarios (e.g.
 762 3.7°C by 2100), as compared to high mitigation scenarios in which GMST stabilizes at 1.5°C.
 763 Using PAGE09 model outputs, these are mean total damages of \$550 Trillion (US\$2008) versus
 764 \$54 Trillion (US\$2008)(3, 4) The investments in the energy system required for stabilizing at
 765 1.5°C are the sum of the required annual investments on the energy supply and demand side
 766 provided by IPCC (2018) over a 34-year period 2016-2050, amounting to a total of \$2.1-4.42
 767 Trillion (US\$2010) annually, or \$71-150 Trillion (US\$2010). Most of the mitigation costs
 768 accrue during the period ending in 2050 since this is the target date for net zero greenhouse gas
 769 emissions in IPCC scenarios limiting warming to 1.5°C.

770

771 The ratio is consequently approximately \$496 Trillion (US\$2008; mean damage avoided but no
 772 mitigation costs) versus \$71-150 Trillion (US\$2010; mitigation costs only) which means that the
 773 avoided damage is three and seven-fold higher than the cost of restraining GMST to 1.5°C. Total
 774 mitigation cost estimates (3) are used in this comparison, as they include the costs of mitigation

775 required to reach the NDCs and also the further measures required to limit warming to 1.5°C,
776 including measures which are required after 2030. If all the mitigation costs were incurred at the
777 mid-point of 2016 to 2050, their NPV in 2008 would be about half of the \$71-150 trillion
778 USD2010 (i.e. an even higher benefit to cost ratio). Furthermore, damages could be higher than
779 estimated, for reasons already outlined in the main text.

780

781 We also provide a further explanation of why other cost estimates provided in (3) were not the
782 appropriate for use in the comparison. (3) also states that “Global model pathways limiting
783 global warming to 1.5°C are projected to involve the annual average investment needs in the
784 energy system of around 2.4 trillion US\$2010 between 2016 and 2035” but as further costs could
785 arise after 2030, and the damage estimate calculation refers to the year 2200, this is not
786 appropriate to use for this comparison. (3) also provides an estimate of the costs of measures
787 which are *additional* to the countries’ Nationally Determined Contributions (NDCs). Since these
788 NDCs correspond to a global warming level of approximately 3-4°C, this figure is not suitable
789 for comparison with avoided damage costs that refer to a baseline level of warming of 3.66C.
790 The estimate of the additional costs is 150 billion to 1700 billion US\$2010 over the same time
791 period.

792

793 Table 1: Emergence and intensity of climate change ‘hotspots’ under different degrees of global warming (summary, updated, Table
 794 3.6 from Hoegh-Guldberg et al., 2018, see text in 3.5.4 (5) for supporting literature and discussion; not intended to be all inclusive).
 795 Calibrated uncertainty language is as defined by the Intergovernmental Panel on Climate Change (3).
 796

Region and/or Phenomenon	Warming of 1.5°C or less	Warming of 1.5°C–2°C	Warming of up to 3°C
Arctic sea ice	<p><u>Arctic summer sea ice</u> is <i>likely</i> to be maintained</p> <p><u>Habitat losses</u> for organisms such as polar bears, whales, seals and sea birds</p> <p><u>Benefits</u> for Arctic fisheries</p>	<p>The risk of an <u>ice-free Arctic</u> in summer is about 50% or higher</p> <p><u>Habitat losses</u> for organisms such as polar bears, whales, seals and sea birds may be critical if summers are ice free.</p> <p><u>Benefits</u> for Arctic fisheries</p>	<p>The Arctic is <i>very likely</i> to be ice free in summer</p> <p><u>Critical habitat losses</u> for organisms such as polar bears, whales, seals and sea birds</p> <p><u>Benefits</u> for Arctic fisheries</p>
Arctic land regions	<p><u>Cold extremes warm</u> by a factor of 2–3, reaching up to 4.5°C (<i>high confidence</i>)</p> <p><u>Biome shifts</u> in the tundra and permafrost deterioration are <i>likely</i></p>	<p><u>Cold extremes warm</u> by as much as 8°C (<i>high confidence</i>)</p> <p><u>Larger intrusions of trees and shrubs</u> in the tundra than under 1.5°C of warming are likely; larger but constrained losses in permafrost <i>are likely</i></p>	<p><u>Drastic regional warming</u> is <i>very likely</i></p> <p>A <u>collapse in permafrost may occur</u> (<i>low confidence</i>); a drastic biome shift from tundra to boreal forest is possible (<i>low confidence</i>)</p>
Alpine regions	<p><u>Severe shifts</u> in biomes are <i>likely</i></p>	<p><u>Even more severe shifts</u> are <i>likely</i></p>	<p><u>Critical losses</u> in alpine habitats are <i>likely</i></p>
Southeast Asia	<p><u>Risks for increased flooding</u> related to sea level rise</p> <p><u>Increases, heavy precipitation</u> events</p> <p><u>Significant risks</u> of crop yield reductions are avoided</p>	<p><u>Higher risks of increased flooding</u> related to sea level rise (<i>medium confidence</i>)</p> <p><u>Stronger increases, heavy precipitation</u> events (<i>medium confidence</i>)</p> <p><u>One-third decline</u> in per capita crop production (<i>medium confidence</i>)</p>	<p><u>Substantial increases in risks</u> related to flooding from sea level rise</p> <p><u>Substantial increase</u> in heavy precipitation and high-flow events</p> <p><u>Substantial reductions</u> in crop yield</p>

<p>Mediterranean</p>	<p><u>Increase in probability of extreme drought</u> (<i>medium confidence</i>)</p> <p><i>Medium confidence</i> in reduction in runoff of about 9% (likely range 4.5–15.5%)</p> <p><u>Risk of water deficit</u> (<i>medium confidence</i>)</p>	<p><u>Robust increase</u> in probability of extreme drought (<i>medium confidence</i>)</p> <p><i>Medium confidence</i> in further reductions (about 17%) in runoff (likely range 8–28%)</p> <p><u>Higher risks of water deficit</u> (<i>medium confidence</i>)</p>	<p><u>Robust and large increases</u> in extreme drought.</p> <p><u>Substantial reductions in precipitation</u> and in runoff (<i>medium confidence</i>)</p> <p><u>Very high risks</u> of water deficit (<i>medium confidence</i>)</p>
<p>West Africa & the Sahel</p>	<p><u>Increases in the number</u> of hot nights and longer and more frequent heatwaves are <i>likely</i></p> <p><u>Reduced maize and sorghum</u> production is <i>likely</i>, with area suitable for maize production reduced by as much as 40%</p> <p><u>Increased risks of undernutrition</u></p>	<p>Further increases in number of hot nights and longer and more frequent heatwaves are likely</p> <p>Negative impacts on maize and sorghum production likely larger than at 1.5°C; <i>medium confidence</i> that vulnerabilities to food security in the African Sahel will be higher at 2.0°C compared to 1.5°C</p> <p><u>Higher risks of undernutrition</u></p>	<p>Substantial increases in the number of hot nights and heatwave duration and frequency (<i>very likely</i>)</p> <p>Negative impacts on crop yield may result in major regional food insecurities (<i>medium confidence</i>)</p> <p><u>High risks of undernutrition</u></p>
<p>Southern Africa</p>	<p><u>Reductions in water availability</u> (<i>medium confidence</i>)</p> <p><u>Increases in number of hot nights</u> and longer and more frequent heatwaves (<i>high confidence</i>),</p> <p><u>High risks of increased mortality</u> from heatwaves</p> <p><u>High risk of undernutrition</u> in communities dependent on dryland agriculture and livestock</p>	<p><u>Larger reductions in rainfall</u> and water availability (<i>medium confidence</i>)</p> <p><u>Further increases in number of hot nights</u> and longer and more frequent heatwaves (<i>high confidence</i>), associated increases in risks of <u>increased mortality from heatwaves</u> compared to 1.5°C warming (<i>high confidence</i>)</p> <p><u>Higher risks of undernutrition</u> in communities dependent on dryland agriculture and livestock</p>	<p><u>Large reductions in rainfall</u> and water availability (<i>medium confidence</i>)</p> <p><u>Drastic increases</u> in the number of hot nights, hot days and heatwave duration and frequency to impact substantially on agriculture, livestock and human health and mortality (<i>high confidence</i>)</p> <p><u>Very high risks of undernutrition</u> in communities dependent on dryland agriculture and livestock</p>

<p>Tropics</p>	<p><u>Increases in the number of hot days</u> and hot nights as well as longer and more frequent heatwaves (<i>high confidence</i>)</p> <p><u>Risks to tropical crop yields</u> in West Africa, Southeast Asia and Central and South America are significantly less than under 2.0°C of warming</p>	<p><u>The largest increase in hot days</u> under 2.0°C compared to 1.5°C is projected for the tropics.</p> <p><u>Risks to tropical crop yields in West Africa, Southeast Asia and Central and South America</u> could be extensive</p>	<p><u>Oppressive temperatures</u> and accumulated heatwave duration <i>very likely</i> to directly impact human health, mortality and productivity</p> <p><u>Substantial reductions</u> in crop yield <i>very likely</i></p>
<p>Small islands</p>	<p><u>Land of 60,000 less people</u> exposed by 2150 on SIDS compared to impacts under 2.0°C of global warming</p> <p><u>Risks for coastal flooding</u> reduced by 20–80% for SIDS compared to 2.0°C of global warming</p> <p><u>Freshwater stress</u> reduced by 25% as compared to 2.0°C</p> <p><u>Increase in the number of warm days</u> for SIDS in the tropics</p> <p><u>Persistent heat stress</u> in cattle avoided</p> <p><u>Loss of 70–90% of coral reefs</u></p>	<p><u>Tens of thousands of people displaced</u> owing to inundation of SIDS</p> <p><u>High risks</u> for coastal flooding and increased frequency of extreme water-level events</p> <p><u>Freshwater stress</u> from projected aridity</p> <p><u>Further increase</u> of ca. 70 warm days/year</p> <p><u>Persistent heat stress</u> in cattle in SIDS</p> <p><u>Loss of most coral reefs</u> and weaker remaining structures owing to ocean acidification (i.e. less coastal protection)</p>	<p><u>Substantial and widespread impacts</u> through inundation of SIDS, coastal flooding, freshwater stress, persistent heat stress and loss of most coral reefs (<i>very likely</i>)</p> <p><u>Risk of multi-meter sea level</u> rise due to ice sheet instability</p>
<p>Fynbos biome</p>	<p><u>About 30% of suitable climate area</u> lost (<i>medium confidence</i>)</p>	<p><u>Increased losses (about 45%)</u> of suitable climate area (<i>medium confidence</i>)</p>	<p><u>Up to 80% of suitable climate area</u> lost (<i>medium confidence</i>)</p>

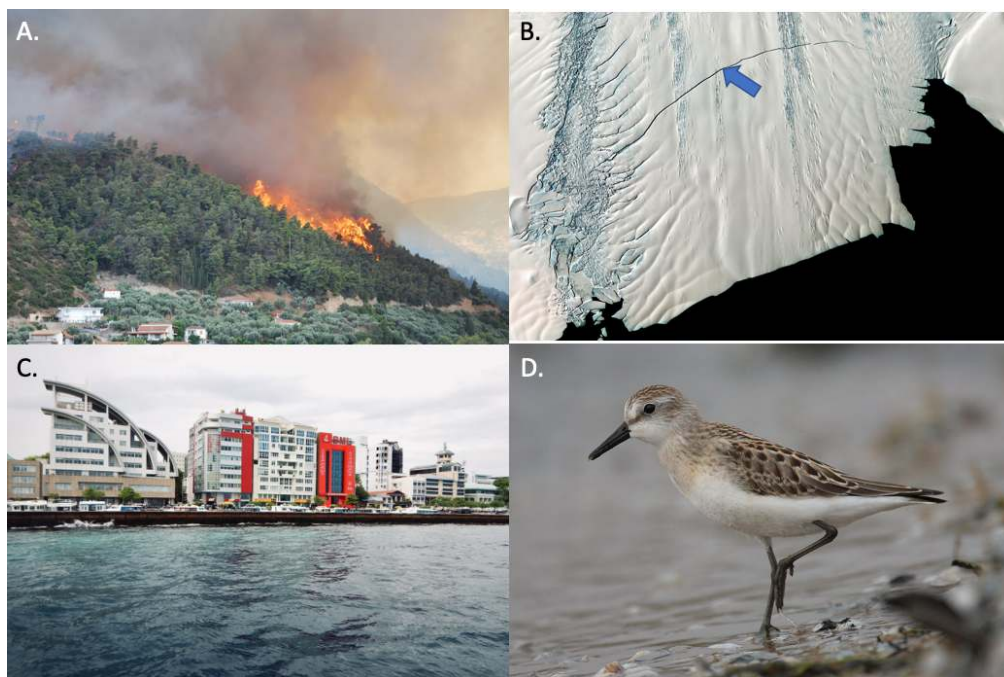
798 Table 2: Summary of enhanced risks in the exceedance of regional tipping points under different global temperature goals.
799 (summary, Table 3.7 from see text in 3.5.5(5), for supporting literature and discussion; updated, not intended to be exhaustive).
800

Tipping point	Warming of 1.5°C or less	Warming of 1.5°C–2°C	Warming of up to 3°C
Arctic sea ice	<u>Arctic summer sea ice</u> is <i>likely</i> to be maintained <u>Sea ice changes</u> reversible under suitable climate restoration	The risk of an <u>ice-free Arctic</u> in summer is about 50% or higher <u>Sea ice changes</u> reversible under suitable climate restoration	<u>Arctic</u> is <i>very likely</i> to be ice free in summer <u>Sea ice changes</u> reversible under suitable climate restoration
Tundra	<u>Decrease</u> in number of growing degree days below 0°C <u>Abrupt</u> increases in tree cover are <i>unlikely</i>	<u>Further decreases</u> in number of growing degree days below 0°C <u>Abrupt</u> increases in tree cover are <i>unlikely</i>	<u>Potential</u> for an abrupt increase in tree fraction (<i>low confidence</i>)
Permafrost	<u>17–44%</u> reduction in permafrost <u>Approximately 2 million km²</u> more permafrost maintained than under 2.0°C of global warming (<i>medium confidence</i>) Irreversible loss of stored carbon	<u>28–53%</u> reduction in permafrost with Irreversible loss of stored carbon	<u>Potential</u> for permafrost collapse (<i>low confidence</i>)
Asian monsoon	<i>Low confidence</i> in projected changes	<i>Low confidence</i> in projected changes	<u>Increases in the intensity of</u> monsoon precipitation <i>likely</i>
West African monsoon & Sahel	<u>Uncertain changes</u> ; <i>unlikely</i> that a tipping point is reached	<u>Uncertain changes</u> ; <i>unlikely</i> that tipping point is reached	<u>Strengthening of monsoon</u> with wetting and greening of the Sahel and Sahara (<i>low confidence</i>) <u>Negative associated impacts</u> through increases in extreme temperature events
Rainforests	<u>Reduced biomass</u> , deforestation and fire increases pose uncertain risks to forest dieback	<u>Larger biomass reductions</u> than under 1.5°C of warming; deforestation and fire increases pose uncertain risks to forest dieback	<u>Reduced extent of tropical rainforest</u> in Central America and large replacement of rainforest and savanna grassland <u>Potential tipping point</u> leading to pronounced forest dieback (<i>medium confidence</i>)

Coral reefs	<u>Increased mass coral bleaching and mortality</u> – decline in abundance to 10-30% of values of present day by 1.0°C (<i>high confidence</i>)	<u>High mortality - corals decrease to very low levels (<1%)</u> , impacts on organisms that dependent on coral reefs for habitat (fish, biodiversity, <i>high confidence</i>).	<u>Irreversible changes occur</u> with tipping point around 2°C–2.5°C – reefs are no longer resemble coral reef ecosystems – recovery potential very low (<i>medium confidence</i>).
Boreal forests	<u>Increased tree mortality</u> at southern boundary of boreal forest (<i>medium confidence</i>)	<u>Further increases in tree mortality</u> at southern boundary of boreal forest (<i>medium confidence</i>)	<u>Potential tipping point</u> at 3°C–4°C for significant dieback of boreal forest (<i>low confidence</i>)
Heatwaves, unprecedented heat and human health	<u>Continued increase</u> in occurrence of potentially deadly heatwaves (<i>likely</i>)	<u>Substantial increase</u> in potentially deadly heatwaves (<i>likely</i>) <u>More than 350 million more people</u> exposed to deadly heat by 2050 under a midrange population growth scenario (<i>likely</i>) <u>Annual occurrence of heatwaves</u> similar to the deadly 2015 heatwaves in India and Pakistan (<i>medium confidence</i>)	<u>Further increases</u> in potentially deadly heatwaves (<i>very likely</i>)
Agricultural systems: key staple crops	<u>Global maize crop reductions</u> of about 10%	<u>Larger reductions in maize crop</u> production than under 1.5°C of about 15%	<u>Drastic reductions in maize crop globally</u> and in Africa (<i>high confidence</i>) <u>potential tipping point</u> for collapse of maize crop in some regions (<i>low confidence</i>)
Livestock in the tropics and subtropics	<u>Increased heat stress</u>	<u>Onset of persistent heat stress</u> (<i>medium confidence</i>)	<u>Persistent heat stress</u> <i>likely</i>

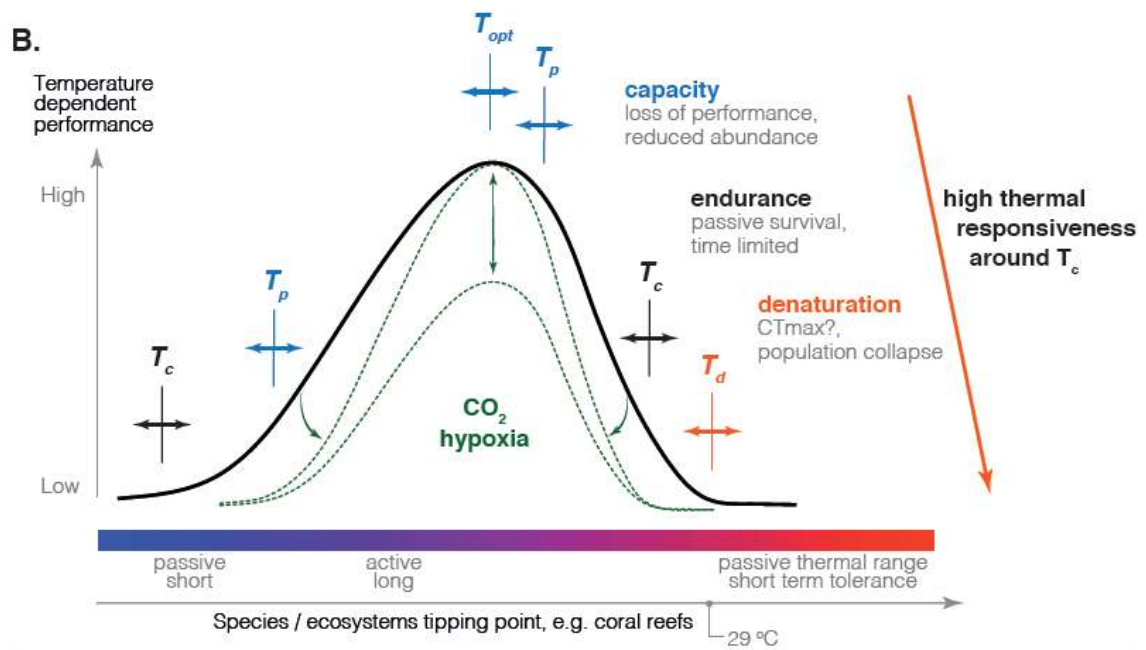
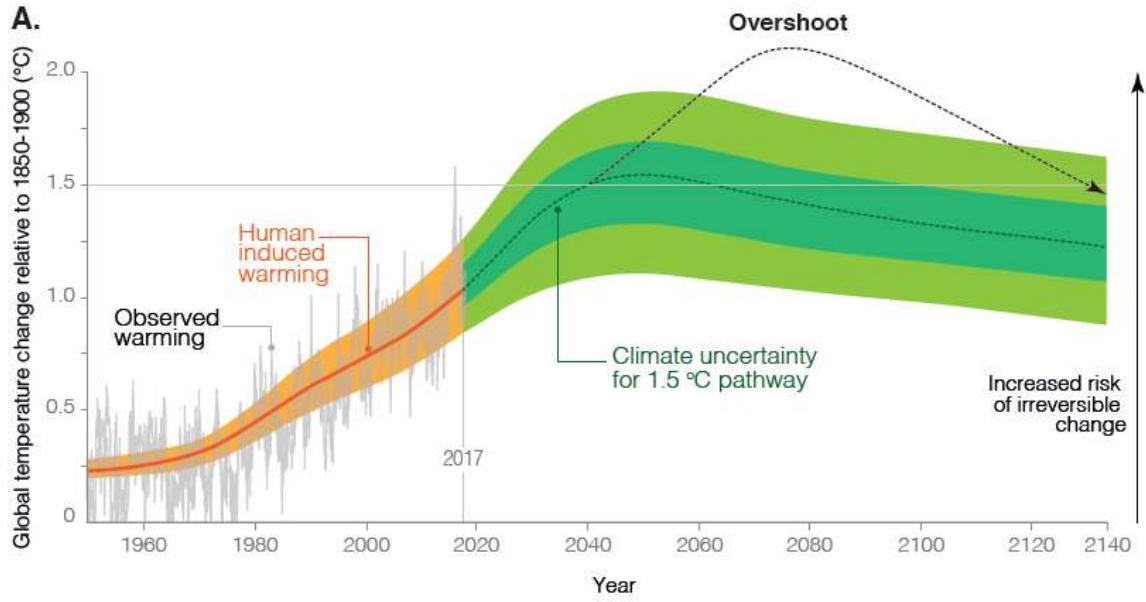
802 **Figure captions:**

803 Figure 1. Changes at 1.0°C of global warming. Increases in Global Mean Surface Temperature
 804 (GMST) of 1.0°C have already had major impacts on natural and human systems. Examples
 805 include: A. Increased temperatures and dryness in the Mediterranean region is driving longer
 806 and more intense fire seasons with serious impacts on people, infrastructure and natural
 807 ecosystems. Image shows tragic devastation of fire in the Greek village of Mati Greece in July
 808 25, 2018. B. Evidence of ice sheet disintegration is increasing (here showing a 30 km fracture
 809 across the Pine Island Glacier which is associated with the Western Antarctic Ice sheet, WAIS).
 810 The fracture (see arrow) appeared in mid-October 2011 and has increased concern that we may
 811 be approaching a tipping point with respect to disintegration of the WAIS. C. Many low-lying
 812 countries such as the Maldives experience flooding and will be at an increased threat from sea
 813 level rise and strengthening storms over time. D. Many insects and birds have shifted
 814 reproductive events or migration to early times in the season as conditions have warmed. Image
 815 credits: A. ‘Lotus R’, <https://www.flickr.com/photos/66012345@N00/964251167/>; B. Image
 816 credits: NASA/GSFC/METI/ERSDAC/JAROS and U.S./Japan ASTER Science Team Last
 817 Updated: Aug. 7, 2017, C. Male, Maldives (O. Hoegh-Guldberg) and D. Semipalmated Sand
 818 Piper (*Calidris pusilla*, Creative Commons (CC BY-SA 3.0, GNU Free Documentation License)



819

820 Figure 2A. Action on climate change can still result in stable or even decreasing global
821 temperatures, although variability around projections is substantial. Strategies that include
822 ‘overshoot’ (red dashed line, illustrative of a very high level of overshoot) require as yet early
823 stage technologies to ensure that overshoot is kept as short as possible. Also, the larger
824 overshoot, the higher the risk of irreversible change in affected systems. B. Responses to
825 changing conditions (shown here as a thermal performance curve) are typically tilted to the right
826 with a steep decline in performance such as growth, towards high temperature extremes. Beyond
827 a thermal optimum, T_{opt} , performance begins to decline beyond the *Pejus* temperature, T_p . A
828 critical temperature, T_c , characterizes a low level of performance and time limited passive
829 endurance when, as in ectothermic animals, oxygen supply capacity becomes insufficient to
830 cover oxygen supply, or, as in corals, a symbiosis between corals and their dinoflagellate
831 symbionts suddenly breaks down (coral bleaching) and corals go from appearing healthy to
832 experiencing large scale mortality over days-to-weeks. Accordingly, the high T_c characterizes a
833 temperature of high responsiveness to small increases in temperature extremes, such as by 0.5°C ,
834 especially, if some life stages have a narrow thermal range indicating high vulnerability(26).
835

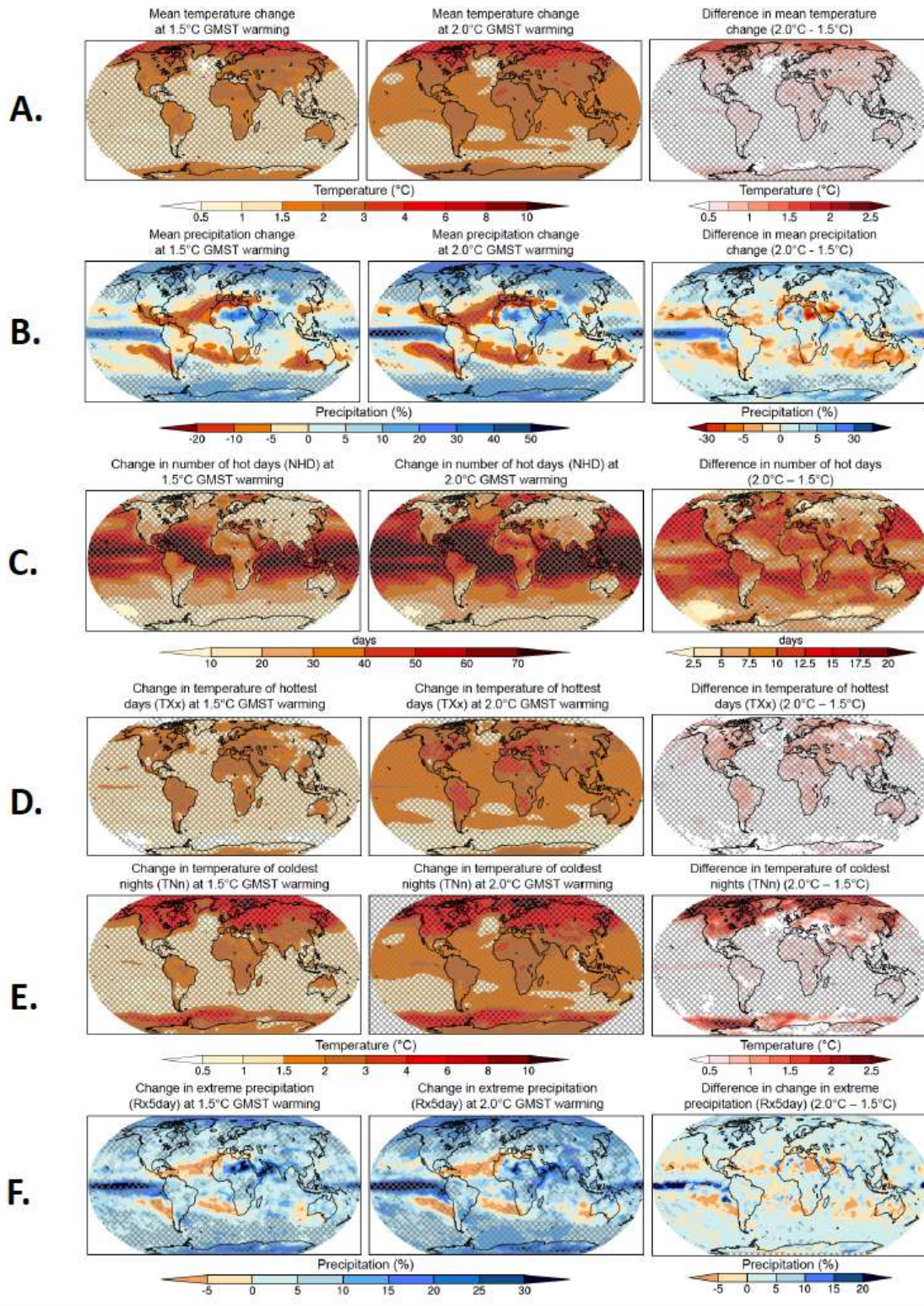


threshold line	T_{opt} Optimum temperature (performance maximum)	T_c Critical temperatures (transition to anaerobic metabolism)
acclimatization & adaptation	T_p Pejus temperatures (limit to long-term tolerance)	T_d Denaturation temperatures (the onset of cell damage)

836
837

838 Figure 3 Projected changes in A. Mean temperature, B. Mean precipitation, C. Number of hot
839 days (NHD; 10% warmest days), D. Temperature of hottest day (TXx), E. Temperature of
840 coldest night (TNn), and F. Change in extreme precipitation (Rx5day). Conditions are projected
841 for 1.5°C (left-hand column) and 2.0°C (middle-hand column) of global warming compared to
842 the pre-industrial period (1861–1880), with the difference between 1.5°C and 2.0°C of global
843 warming being shown in the third column. Cross-hatching highlights areas where at least two-
844 thirds of the models agree on the sign of change as a measure of robustness (18 or more out of
845 26). Values were assessed from the transient response over a 10-year period at a given warming
846 level, based on Representative Concentration Pathway (RCP) 8.5 Coupled Model
847 Intercomparison Project Phase 5 (CMIP5) model simulations (5)(3); adapted from (29, 73); see
848 Supplementary Material 3.SM.2 (5).
849

850 **Figure 3**



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855 Summary of Review

856

857 **Here today, gone tomorrow: the non-linearity of climate change.**

858

859 **Background:**

860 United Nations Framework Convention on Climate Change (UNFCCC) was established in 1992
861 with the central purpose to pursue the “stabilization of greenhouse gas (GHG) emissions at a
862 level that would prevent dangerous anthropogenic interferences with the climate system”. Since
863 1992, five major climate assessment reports have been completed by the UN Intergovernmental
864 Panel on Climate Change (IPCC). These reports identified rapidly growing climate related
865 impacts and risks, including more intense storms, collapsing ecosystems, and record heatwaves,
866 among many others. Once thought to be tolerable, increases in global mean surface temperature
867 (GMST) of 2.0°C or higher than the pre-industrial period look increasingly unmanageable and
868 hence dangerous to natural and human systems.

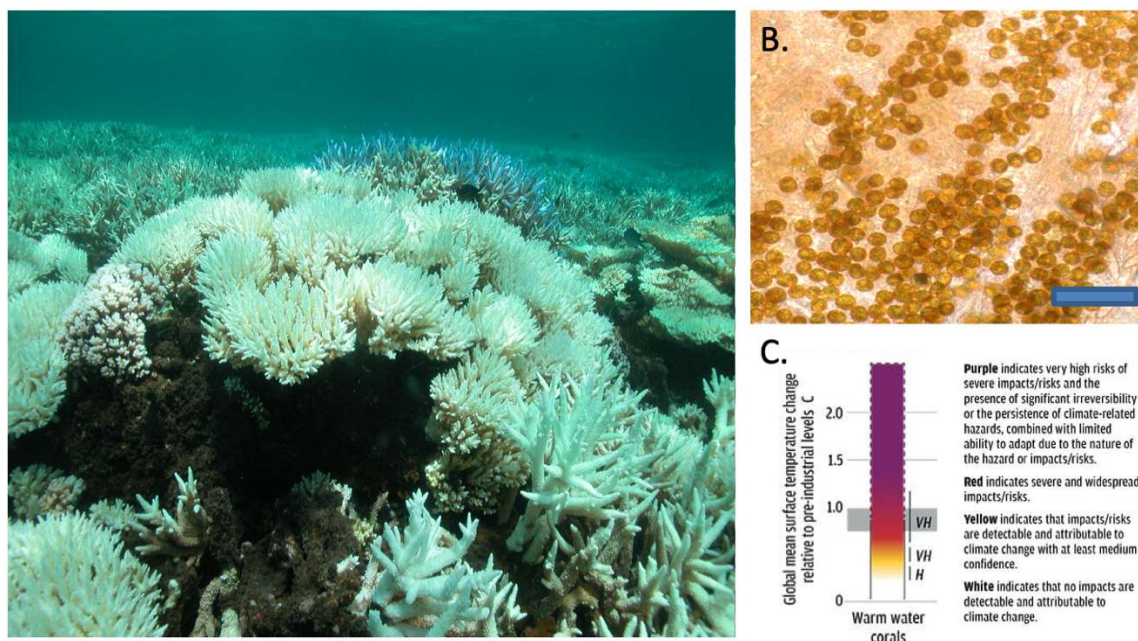
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870 The Paris Climate Agreement is the most recent attempt to establish international cooperation
871 over climate change (2). This agreement was designed to bring nations together voluntarily in
872 order for them to take ambitious action on mitigating climate change while also developing
873 adaptation options and strategies, and guaranteeing the means of implementation (e.g. climate
874 finance). Since that time, 185 countries have ratified the Agreement, including countries such as
875 diverse as USA, Saudi Arabia and China (74). The Agreement is aimed at “*holding the increase
876 in the global average temperature to well below 2.0°C above pre-industrial levels and pursuing
877 efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that
878 this would significantly reduce the risks and impacts of climate change.*” Many unanswered
879 questions regarding a 1.5°C target surround the feasibility, costs, and inherent risks to natural and
880 human systems. Consequently, the UNFCCC invited the IPCC to prepare a special report on the
881 “*the impacts of global warming of 1.5°C above pre-industrial levels and related global
882 greenhouse gas emission pathways, in the context of strengthening the global response to the
883 threat of climate change, sustainable development, and efforts to eradicate poverty.*” The Special
884 Report was completed and approved by the 48th Session of the IPCC in October 2018.

885

886 **Advances:**

887 We review multiple lines of evidence that indicate that the next 0.5°C above today (which will
 888 take GMST from 1.0°C to 1.5°C above the pre-industrial period) will involve greater risks per
 889 unit temperature than those seen in the last 0.5°C increase. This principle of ‘accelerating risk’ is
 890 also likely to drive proportionally higher risk levels in the transition from 1.5°C to 2.0°C above
 891 the pre-industrial period. We argue that this is a consequence of impacts accelerating as a
 892 function of distance from the optimal temperature (*Top*, Fig 2b) for an organism or process.
 893 Ecosystems like coral reefs (Fig 1), for example, often appear healthy right up until the onset of
 894 mass coral bleaching and mortality (Fig 2A,B), which can then rapidly destroy a coral reef
 895 within a few months. This also explains the observation of ‘tipping points’ where the condition
 896 of a group of organisms or an ecosystem can appear ‘healthy’ right up until they collapse,
 897 suggesting caution in extrapolating from measures of ecosystem condition (i.e. changes in the
 898 amount of coral cover). Information of this nature needs to be combined with an appreciation of
 899 where organisms are with respect to the optimal temperature (*Top*, see Fig 2, Hoegh-Guldberg et
 900 al. 2019, this issue).



901 Fig 1 (legend). Responses to climate change can be non-linear in nature, such exemplified by
 902 coral reefs. (A) Reef-building corals can suddenly lose their (B) dinoflagellate symbionts
 903 (bar=50µm) and die in response to increasing temperatures, exhibiting (C) non-linear changes in
 904 the amount of impact/risk from climate change. Attribution: A. Author, Hoegh-Guldberg ; B.
 905

906 *Author, Hoegh-Guldberg; C is adapted from (5), H (high) and VH (very high) are the levels of*
907 *confidence in the transition from one impact/risk level to another (i.e. colors).*

908

909 In a similar way, human systems tend to experience greater costs and risks as we move away
910 from optimal conditions, with an increasing risk of non-linear changes. Finally, we explore the
911 relative costs and benefits associated with acting when it comes to climate change, and come to
912 the preliminary conclusion that restraining average global temperature to 1.5°C above the pre-
913 industrial period may be 4-5 less costly than the damage due to inaction on global climate
914 change.

915

916 **Outlook:**

917 As an IPCC expert group, we were asked to assess the impact of recent climate change (1.0°C,
918 2017) and that likely over the next 0.5 - 1.0°C of global warming. At the beginning of this
919 exercise, many of us were concerned that the task would be hindered by a lack of expert
920 literature available for 1.5°C and 2.0°C warmer worlds. While this was the case at the time of the
921 Paris Agreement in 2015, it has not our experience four years later. With an accelerating amount
922 of peer-reviewed literature since the IPCC Special Report on 1.5°C, it is very clear that there is
923 an even more compelling case for deepening commitment and actions for stabilizing global mean
924 surface temperature at 1.5°C above the pre-industrial period.

925

926