Supplementary Materials:

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1.

Association between long-term exposure to ambient air pollution and COVID-19 severity: a prospective cohort study

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Abstract

Background: The tremendous global health burden related to COVID-19 means that identifying determinants of COVID-19 severity is important for prevention and intervention. We aimed to explore long-term exposure to ambient air pollution as a potential contributor to COVID-19 severity, given its known impact on the respiratory system.

Methods: We used a cohort of all people with confirmed SARS-CoV-2 infection, aged 20 years and older and not residing in a long-term care facility in Ontario, Canada, during 2020. We evaluated the association between long-term exposure to fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2) and ground-level ozone (O_3), and risk of COVID-19-related hospital admission, intensive care unit (ICU) admission and death. We ascertained individuals' long-term exposures to each air pollutant based on their residence from 2015 to 2019. We used logistic regression and adjusted for confounders and selection bias using various individual and contextual covariates obtained through data linkage.

Results: Among the 151 105 people with confirmed SARS-CoV-2 infection in Ontario in 2020, we observed 8630 hospital admissions, 1912 ICU admissions and 2137 deaths related to COVID-19. For each interquartile range increase in exposure to $PM_{2.5}$ (1.70 μg/m^3), we estimated odds ratios of 1.06 (95% confidence interval [CI] 1.01–1.12), 1.09 (95% CI 0.98–1.21) and 1.00 (95% CI 0.90–1.11) for hospital admission, ICU admission and death, respectively. Estimates were smaller for NO_2. We also estimated odds ratios of 1.15 (95% CI 1.06–1.23), 1.30 (95% CI 1.12–1.50) and 1.18 (95% CI 1.02–1.36) per interquartile range increase of 5.14 ppb in O_3 for hospital admission, ICU admission and death, respectively.

Interpretation: Chronic exposure to air pollution may contribute to severe outcomes after SARS-CoV-2 infection, particularly exposure to O_3.
By November 2021, COVID-19 had caused more than 5 million deaths globally[1] and more than 29 400 in Canada.[2] The clinical manifestations of SARS-CoV-2 infection range from being asymptomatic to multiple organ failure and death. Identifying risk factors for COVID-19 severity is important to better understand etiological mechanisms and identify populations to prioritize for screening, vaccination and medical treatment. Risk factors for severity of COVID-19 include male sex, older age, pre-existing medical conditions and being from racialized communities.[3–5] More recently, ambient air pollution has been implicated as a potential driver of COVID-19 severity.[6–10]
Long-term exposure to ambient air pollution, a major contributor to global disease burden,[11] could increase the risk of severe COVID-19 outcomes by several mechanisms. Air pollutants can reduce individuals' pulmonary immune responses and antimicrobial activities, boosting viral loads.[8] Air pollution can also induce chronic inflammation and overexpression of the alveolar angiotensin-converting enzyme 2 (ACE) receptor,[7] the key receptor that facilitates SARS-CoV-2 entry into cells.[12,13] Exposure to air pollution contributes to chronic conditions, such as cardiovascular disease, that are associated with unfavourable COVID-19 prognosis, possibly owing to persistent immune activation and excessive amplification of cytokine development.[10] Thus, greater exposure to long-term air pollution may lead to severe COVID-19 outcomes.
Reports exist of positive associations between long-term exposure to particulate matter with diameters equal to or smaller than 2.5 or 10 μm ($PM_{2.5}$ and PM_{10}), ground-level ozone (O_3) and nitrogen dioxide (NO_2), and metrics of COVID-19 severity (e.g., mortality and case fatality rate).[8–10] However, most studies to date have used ecological and cross-sectional designs, owing to limited access to individual data, which leads to ambiguity in interpreting the results, thus hindering their influence on policy. [6,14] Ecological designs do not allow for disentangling the relative impacts of air pollution on individual susceptibility to infection and disease severity.[14] Residual confounding by factors such as population mobility and social interactions is also problematic. Therefore, a cohort study with data on individuals with SARS-CoV-2 is a more appropriate design.[6,14] Studies that have used individual data were conducted in specific subpopulations[15,16] or populations with few severe cases,[17] or had limited data on individual exposure to air pollutants.[18] In Canada, 1 ecological study found a positive association between long-term exposure to $PM_{2.5}$ and COVID-19 incidence,[19] but no published study has explored the association between air pollution and COVID-19 severity.
We aimed to examine the associations between long-term exposure to 3 common air pollutants ($PM_{2.5}$, NO_2 and O_3) and key indicators of COVID-19 severity, including hospital admission, intensive care unit (ICU) admission and death, using a large prospective cohort of people with confirmed SARS-CoV-2 infection in Ontario, Canada, in 2020. The air contaminants $PM_{2.5}$, NO_2 and O_3 are regularly monitored by the Canadian government, and are key pollutants that are considered when setting air-quality policies. They originate from varying sources (NO_2 is primarily emitted during combustion of fuel, O_3 is primarily formed in air by chemical reactions of nitrogen oxides and volatile organic compounds, and $PM_{2.5}$ can be emitted during combustion or formed by reactions of chemicals like sulphur dioxide and nitrogen oxides in air) and they may affect human health differently.[20,21,22]

Methods

Study population and data sources

We constructed a population-based cohort comprising all people with confirmed SARS-CoV-2 infection aged 20 years or older and who did not reside in a long-term care facility in Ontario, Canada, throughout 2020. We excluded residents of long-term care facilities, given that their profile of frailty and air pollution exposure differs from that of the general population. We used data from Ontario's Case and Contact Management System and the Ontario Laboratories Information System, which recorded specimen collection date (date of diagnosis), demographics and socioeconomic status of people with SARS-CoV-2 infection, as well as the incidence of COVID-19–related hospital admission, ICU admission and death.[23,24] We followed up outcomes until their occurrence or May 2021, whichever came first.

Covariates and exposures

We obtained information on key factors that might confound the association between air pollution and COVID-19 severity (detailed list of data sources in Appendix 1, eTable 1, available at www.cmaj.ca/lookup/doi/10.1503/cmaj.220068/tab-related-content). Briefly, we obtained data on health care access and pre-existing conditions of individuals, using hospital discharge data from the Canadian Institute for Health Information Discharge Abstract Database and physician service claims in the Ontario Health Insurance Plan database. We linked the cohort to Ontario's Registered Persons Database, a registry of all Ontario residents with a health insurance number, to obtain individuals' annual residential address over the 5 years before 2020. We also obtained their neighbourhood-level socioeconomic status through linkage with Census data; details are described elsewhere. [25] We used annual exposure surfaces of $PM_{2.5}$, NO_2 and O_3 developed previously, which showed good performance in evaluations: the $PM_{2.5}$ surface exhibited R^2 = 0.73 in long-term cross-validation with measurements;[26] the NO_2 model accounted for 73% of the variability in annual measurements;[27] and the O_3 model's proportion of correct predicted values ranged from 65% to 93%, depending on the time of day[28] (Appendix 1, Section 1). Using these surfaces and individuals' annual residential address, we calculated their long-term exposures to air pollutants as the average postal code–specific annual concentrations at their residential addresses in the 5 years before the pandemic (2015 to 2019).

Statistical analysis

Data sets were linked using unique encoded identifiers and analyzed at ICES. We applied multivariable logistic regression models to investigate the associations between long-term exposure to 3 ambient air pollutants ($PM_{2.5}$, O_3 and NO_2) and 3 indicators of severity of COVID-19 (COVID-19–related hospital admission, ICU admission and death) separately after assessing relevant assumptions. We estimated odds ratios (ORs) to approximate risk ratios because these 3 outcomes were relatively rare. In this study, we focused on cumulative incidence of the outcomes over the entire follow-up period.

Because uncertainty exists regarding the mechanisms of how long-term exposure to air pollution might affect COVID-19 severity and data availability varies across studies, it has been suggested that different variables should be controlled for to reduce confounding in observational studies of COVID-19 severity.[14,16,29] We applied the "disjunctive cause criterion," which includes any pre-exposure covariate that is a cause of the exposure or the outcome, or both.[30] Additionally, we adjusted for contextual factors that correlate with air pollution and may also affect the probability of testing for SARS-CoV-2 in an attempt to account for selection bias.[31] This is because inclusion in the study cohort required that a person test positive for SARS-CoV-2 infection, which is affected by the severity of symptoms, thus creating a collider between exposure and outcome (see Appendix 1, eFigure 1 for a directed acyclic graph depicting this possible selection bias).[32] Using literature on air pollution and health in Canada,[33,34] evidence about the drivers of COVID-19 severity[3–5,16] and recently identified contextual factors associated with testing positive for SARS-CoV-2 infection in Ontario,[35] we considered 5 sequential models with different sets of covariates (model specifications in Appendix 1, Section 2), with Model 5 as the full model (see Appendix 1, eFigure 2 for the directed acyclic graph). Briefly, we adjusted for date of diagnosis, demographics (sex and age), being part of an outbreak, being an essential worker, neighbourhood income, health care access (number of outpatient visits in 2019, influenza vaccination status and distance to nearest health services), neighbourhood socioeconomic status (average household size and the Ontario Marginalization Index), and other contextual factors (rurality, population density and health regions). Because the Ontario Marginalization Index encompasses 4 dimensions of socioeconomic status using dissemination area–level Census data, we excluded Census variables that are included in the Ontario Marginalization Index, to avoid multicollinearity.[36] The same set of models was applied for all combinations of exposure and outcome.

We conducted sensitivity analyses (see details in Appendix 1, Section 3) considering 10 alternative models in which we explored additional sets of covariates and different exposure windows. We also evaluated whether the exposure–outcome association departed from linearity using restricted cubic spline, estimated the controlled direct effect by further adjusting for pre-existing conditions, excluded events that occurred more than 90 days after initial diagnosis, restricted to events that occurred after May 24, 2020 (when testing became available to asymptomatic people),[37] and excluded people with extreme exposures (> 99% or < 1%). We conducted all analyses using SAS (EG 7.11).

Ethics approval

Use of ICES data in this study was authorized under section 45 of the *Personal Health Information Protection Act* of Ontario, which does not require review by a Research Ethics Board.

Results

Among 151 105 people recorded as being infected with SARS-CoV-2 in Ontario in 2020 (Figure 1), we identified 8630 (5.7%), 1912 (1.3%) and 2137 (1.4%) COVID-19–related hospital admissions, ICU admissions and deaths, respectively. The median times between first diagnosis and hospital admission, ICU admission and death were 5 days, 8 days and 15 days, respectively. The medians (interquartile ranges [IQRs]) of long-term exposure to air pollutants were 7.64 μg/m^3 (6.43–8.13), 7.75 ppb (6.15–8.65) and 44.80 ppb (42.41–47.38) for $PM_{2.5}$, NO_2 and O_3, respectively. Cohort characteristics are summarized by outcome in Table 1 and by exposure in Appendix 1, eTable 2.

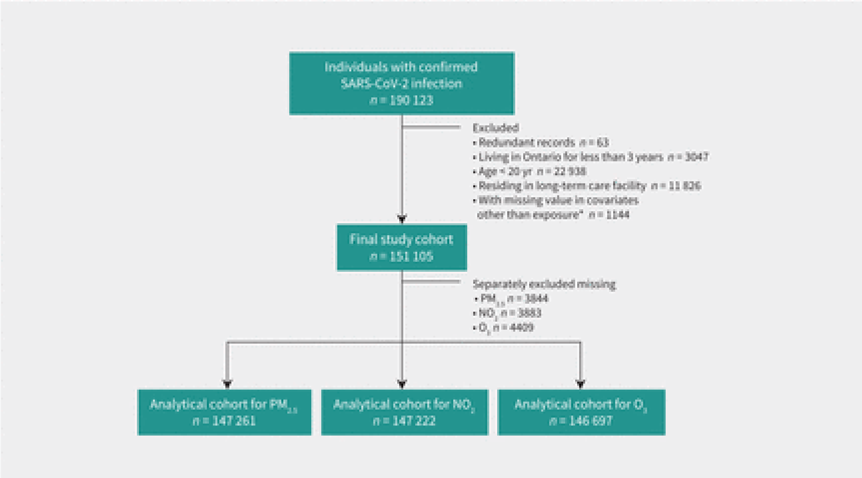

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Figure 1:
Flow chart showing the creation of the cohort. Note: *Based on covariates included in the final model (Model 5).

- View inline

Table 1:
Demographics, socioeconomic status, health behaviour and characteristics of infection in study cohort (all adults with SARS-CoV-2 infection in Ontario, Canada, in 2020) and in subcohorts experiencing COVID-19–related outcomes

Higher exposure to $PM_{2.5}$ was associated with an increased risk of both hospital and ICU admission in Models 1 to 3 (Appendix 1, eFigure 3). Adjustment for neighbourhood socioeconomic status attenuated the associations toward the null. In the final model adjusting for additional contextual factors (Figure 2), we obtained ORs of 1.06 (95% confidence interval [CI] 1.01–1.12) and 1.09 (95% CI 0.98–1.21) per IQR increase of 1.70 μg/m³ for hospital admission and ICU admission, respectively (Appendix 1, eTable 4). Although death was positively associated with $PM_{2.5}$ in Models 1 to 4, we did not observe an effect in the fully adjusted model (OR 1.00 [95% CI 0.90–1.11]).

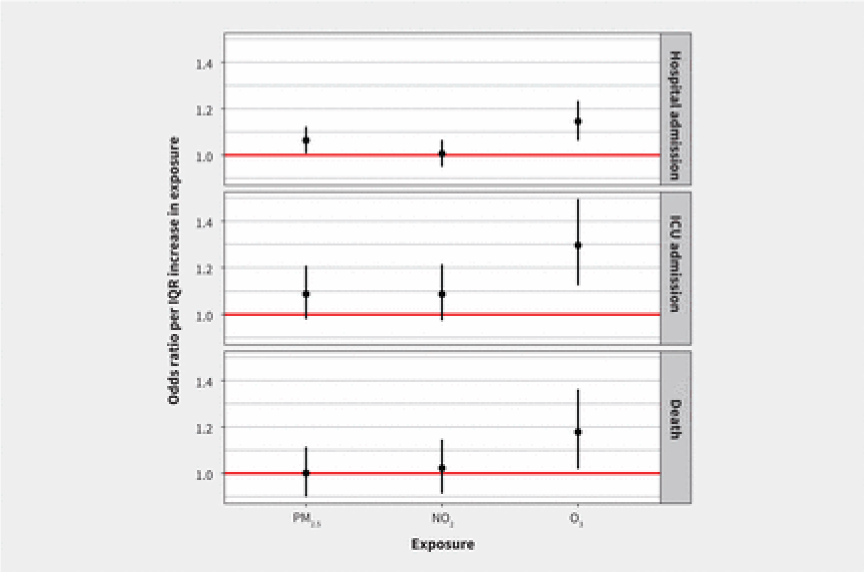

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Figure 2:
Association between average exposure to air pollutants and severe outcomes of SARS-CoV-2 infection in odds ratio per interquartile range (IQR)* increase in exposure for the final model (Model 5). Note: ICU = intensive care unit. *Interquartile range represents the difference between 75th and 25th percentile of the exposure.

For NO_2, we found similar patterns in results of sequential models (1–4) as for $PM_{2.5}$. In the fully adjusted model, we obtained ORs of 1.09 (95% CI 0.97–1.21) per IQR increase of 2.50 ppb NO_2 for ICU admission, while we did not observe an effect for hospital admission (OR 1.01 [95% CI 0.95–1.07]) or death (OR 1.02 [95% CI 0.91–1.15]).
For O_3, we found no evidence for an association in the partially adjusted models (Models 1–4). In the fully adjusted model, O_3 exposure was associated with an increased risk for all 3 outcomes, with ORs of 1.15 (95% CI 1.06–1.23), 1.30 (95% CI 1.12–1.50) and 1.18 (95% CI 1.02–1.36) per IQR increase of 5.14 ppb for hospital admission, ICU admission and death, respectively.
In sensitivity analyses, we found estimates similar to those of the main model when adjusting for additional covariates, using different exposure windows, restricting to events that occurred within 90 days of diagnosis (enrolment date), excluding people with extreme exposures, and accounting for the effect mediated through pre-existing conditions caused by air pollution (Appendix 1, eFigure 4). The associations increased for O_3 but attenuated for NO_2 and $PM_{2.5}$ in the period after May 24 (Appendix 1, Section 3). We observed no evidence of departure from linearity for the air pollutant–outcome associations based on likelihood ratio tests.

Interpretation

We observed that people with SARS-CoV-2 infection who lived in areas of Ontario with higher levels of common air pollutants ($PM_{2.5}$, NO_2 and O_3) were at elevated risk of being admitted to the ICU after we adjusted for individual and contextual confounding factors, even when the air pollution level was relatively low. In addition, we found that chronic exposure to $PM_{2.5}$ and O_3 was associated with elevated risk of COVID-19–related hospital admission, and exposure to O_3 was also associated with elevated risk of death due to COVID-19. These results suggest that chronic exposure to air pollution before SARS-CoV-2 infection may contribute to COVID-19 severity, particurlarly chronic exposure to O_3.

Previous ecological studies found positive associations between long-term exposure to $PM_{2.5}$, NO_2 and O_3, and COVID-19 mortality and case fatality rate.[29,38,39] In other, more limited, cohort studies, Bowe and colleagues found a relative risk of 1.09 (95% CI 1.07–1.11) per 1.70 μg/m^3 increase in $PM_{2.5}$ concentration for hospital admission among American veterans who received a diagnosis of COVID-19,[16] while Bozack and colleagues[15] found relative risks of 1.23 (95% CI 1.00–1.53) for ICU admission and 1.20 (95% CI 1.03–1.39) for death, but no association with NO_2 among people admitted to hospital with COVID-19. Using slightly different methods, a cohort study in Spain and a cohort study in the Mexico City metropolitan area also found a positive association between $PM_{2.5}$ and COVID-19 severity.[17,18] Our estimates are similar in direction of association but more modest, probably owing to differences in study population and our ability to adjust for many individual and contextual confounders. Given the ongoing pandemic, our findings that underscore the link between chronic exposure to air pollution and more severe COVID-19 could have important implications for public health and health systems.

Our study has several strengths. Our cohort captured major severe outcomes among all Ontario adults positive for SARS-CoV-2 infection who were not living in long-term care institutions. A recent modelling study identified little disparity in the officially reported COVID-19 death count and estimated excess mortality during the pandemic in Canada,[40] suggesting adequate surveillance. Using historical residential addresses in our assessment of exposure minimized concerns regarding exposure misclassification due to population mobility. We systematically considered confounding and selection bias, and estimates from the sequential models supported our covariate adjustment strategy. For example, because residing in rural areas is often associated with lower $PM_{2.5}$ exposure[41] and was associated with lower odds of getting tested for SARS-CoV-2 infection in Ontario,[35] restricting the study population to people with positive tests might lead to an artificially diminished association between $PM_{2.5}$ and COVID-19 severity (Appendix 1, eFigure 1). The slight increases in ORs from Model 4 to Model 5 in most combinations of exposures and outcomes might have resulted from the adjustment for selection bias by including rurality (and several other contextual factors) in this step. Consistent results from the main model and sensitivity analyses also alleviated our concerns about differential results due to selection bias, residual confounding, duration of the exposure and outcome misclassification.

Limitations

Race and ethnicity have been shown to be associated with COVID-19 severity,[4] likely mediated through social determinants of health, but we did not adjust for either race or ethnicity in this study. One study[35] showed that the association between race and ethnicity and the probability of testing positive for SARS-Cov-2 infection diminished after adjusting for social determinants of health (e.g., being an essential worker), which we accounted for in this study. We believe it is unlikely that confounding related to race and ethnicity could entirely account for the associations observed. Because we used average ambient air pollution levels at people's residential addresses as surrogates for individual exposure, some exposure misclassification is likely, owing to individuals' activity patterns, such as travel to work. However, studies have found minimal bias, or bias toward the null, from such exposure misclassification.[42,43] Generalization of our results, from all people with confirmed SARS-CoV-2 infection to all infected people, requires the assumption of similar associations between exposure to air pollution and severity of COVID-19 for those tested and not tested. Such an assumption is commonly made in studies evaluating vaccination effectiveness against clinical SARS-CoV-2 infections with a test-negative design.[44,45]

Finally, we focused on the period before widespread vaccination against SARS-CoV-2 or the use of effective medications in patients with COVID-19.

Conclusion

Using a cohort of all people with confirmed SARS-CoV-2 infection during 2020, we found empirical evidence that chronic exposure to air pollution may contribute to severe outcomes after SARS-CoV-2 infection, particularly exposure to O_3. However, uncertainty still remains in the mechanisms of how long-term air pollution might affect COVID-19 severity, which calls for future research.

Footnotes

- **Competing interests:** Jeff Kwong is supported by a Clinician Scientist Award from the Department of Family and Community Medicine, University of Toronto. Chen Chen reports receiving salary support by the funding of this project, from Health Canada. Megan Kirby-Mcgregor reports receiving doctoral student funding from Health Canada, paid through McGill University. Jay Kaufman reports receiving payments from Health Canada (paid to institution) for student salaries and other research expenses associated with this work. Hong Chen reports receiving support for the present manuscript from Health Canada. No other competing interests were declared.
- This article has been peer reviewed.
- **Contributors:** Chen Chen, Megan Kirby-McGregor, Jay Kaufman, Tarik Benmarhnia and Hong Chen contributed to the conception of the work. Chen Chen, John Wong, Megan Kirby-McGregor, Jay Kaufman, Tarik Benmarhnia, Jeff Kwong, JinHee Kim, Aaron van Donkelaar, Randall Martin, Perry Hystad, Yushan Su, Eric Lavigne and Hong Chen contributed to the design of the work. John Wong, Jeff Kwong, JinHee Kim, Aaron van Donkelaar, Randall Martin, Perry Hystad, Yushan Su, Eric Lavigne and Hong Chen contributed to the acquisition of data. Chen Chen, John Wong, Jay Kaufman, Tarik Benmarhnia and Hong Chen contributed to the analysis of data. All of the authors contributed to the interpretation of the data. Chen Chen, Jay Kaufman, Tarik Benmarhnia and Hong Chen drafted the manuscript. All of the authors revised the manuscript critically for important intellectual content, gave final approval of the version to be published and agreed to be accountable for all aspects of the work.
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- **Data sharing:** The data set from this study is held securely in coded form at ICES. While legal data-sharing agreements between ICES and data providers (e.g., health care organizations and government) prohibit ICES from making the data set publicly available, access may be granted to those who meet prespecified criteria for confidential access, available at https://www.ices.on.ca/DAS (email: das@ices.on.ca). The full data set creation plan and underlying analytic code are available from the authors upon request, understanding that the computer programs may rely upon coding templates or macros that are unique to ICES and are therefore either inaccessible or may require modification.

- **Disclaimer:** This study was funded by the Addressing Air Pollution Horizontal Initiative of the Government of Canada; it was also supported by Public Health Ontario (PHO) and ICES, which are funded by an annual grant from the Ontario Ministry of Health (MOH) and the Ministry of Long-Term Care (MLTC). Parts of this material are based on data and information compiled and provided by the Ontario MOH and the Canadian Institute for Health Information (CIHI) and on information on cancers provided by Cancer Care Ontario (CCO). However, the analyses, conclusions, opinions, and statements expressed herein are not necessarily those of CIHI, PHO, ICES, the Ontario MOH, the Ontario MLTC or CCO. No endorsement by ICES, the Ontario MOH or the Ontario MLTC is intended or should be inferred.
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2.

Avoidable Mortality Attributable to Anthropogenic Fine Particulate Matter ($PM_{2.5}$) in Australia

by

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Abstract
Ambient fine particulate matter <2.5 μm ($PM_{2.5}$) air pollution increases premature mortality globally. Some $PM_{2.5}$ is natural, but anthropogenic $PM_{2.5}$ is comparatively avoidable. We determined the impact of long-term exposures to the anthropogenic PM component on mortality in Australia. $PM_{2.5}$-attributable deaths were calculated for all Australian Statistical Area 2 (SA2; n = 2310) regions. All-cause death rates from Australian mortality and population databases were combined with annual anthropogenic $PM_{2.5}$ exposures for the years 2006–2016. Relative risk estimates were derived from the literature. Population-weighted average $PM_{2.5}$ concentrations were estimated in each SA2 using a satellite and land use regression model for Australia. $PM_{2.5}$-attributable mortality was calculated using a health-impact assessment methodology with life tables and all-cause death rates. The changes in life expectancy (LE) from birth, years of life lost (YLL), and economic cost of lost life years were calculated using the 2019 value of a statistical life. Nationally, long-term population-weighted average total and anthropogenic $PM_{2.5}$ concentrations were 6.5 μg/m^3 (min 1.2–max 14.2) and 3.2 μg/m^3 (min 0–max 9.5), respectively. Annually, anthropogenic $PM_{2.5}$-pollution is associated with 2616 (95% confidence intervals 1712, 3455) deaths, corresponding to a 0.2-year (95% CI 0.14, 0.28) reduction in LE for children aged 0–4 years, 38,962 (95%CI 25,391, 51,669) YLL and an average annual economic burden of $6.2 billion (95%CI $4.0 billion, $8.1 billion). We conclude that the anthropogenic $PM_{2.5}$-related costs of mortality in Australia are higher than community standards should allow, and reductions in emissions are recommended to achieve avoidable mortality.

Keywords: **anthropogenic air pollution**; **premature deaths**; **avoidable mortality**; **burden of disease**

1. Introduction

Long-term exposure to ambient air pollution is an established risk factor for a range of cardiovascular and respiratory diseases, contributing to premature mortality and reductions in life expectancy (LE) [1]. Demonstrated nonfatal health associations of air pollution include increased rates of hospitalisation [2], birth defects [3], impaired cognitive function [4], and increased medication usage [5].

Air pollutants that affect health include fine particulate matter (PM) < 2.5 μm ($PM_{2.5}$) in aerodynamic diameter [1]. $PM_{2.5}$ can be emitted from combustion or other processes (primary $PM_{2.5}$) or can be produced via chemical reactions of precursor emissions (secondary $PM_{2.5}$). As an ambient exposure, $PM_{2.5}$ can reach indoor environments and, under certain atmospheric conditions, can travel long distances over several days [6]. Current evidence suggests that there is no safe lower threshold of exposure to $PM_{2.5}$ for mortality because the exposure–response relationship is approximated by a linear function even at very low concentrations [7]. Nonetheless, this remains a strong assumption due to the lack of knowledge about the shape of the exposure–response association at these lower levels [8].

Natural $PM_{2.5}$ includes wind-blown dust, sea salt, organic aerosol from biogenic sources, and emissions from volcanoes and landscape fires. Given the spatial heterogeneity of PM from these sources and the influence of rainfall and wind on their local concentrations, natural $PM_{2.5}$ concentrations vary widely between locations and over time. Anthropogenic sources of $PM_{2.5}$ are responsible for substantial human exposure, emanating from transport and industrial processes such as mining and power generation. Residential wood heaters are also a major source of PM, for example they accounted for 19% of anthropogenic $PM_{2.5}$ emissions and 24% of $PM_{2.5}$ concentrations in Sydney, Australia, during 2010 and 2011 [9]. Although these sources of $PM_{2.5}$ might be expected to increase with population growth and increased economic activity [10], air-pollution control policies have effectively reduced $PM_{2.5}$ concentrations in some high-income countries, as shown by Carnell et al. in the United Kingdom [11]. Several studies show health benefits of reducing anthropogenic $PM_{2.5}$, as reviewed by Rich [12].

Only one study has related all-cause mortality to long-term exposure to $PM_{2.5}$ in the general population in Australia [7], although it was not possible to distinguish between risks from anthropogenic and natural PM sources. Health-impact assessments quantifying the effects on mortality of $PM_{2.5}$ from shipping emissions [13] as well as from wood heaters, traffic, and industrial activities [9] have demonstrated that years of life lost (YLL) and LE offer sensitive indicators of health burdens in Australia. These statistics can also be used to calculate economic costs [14].

Given the ubiquitous but modifiable nature of exposures to anthropogenic $PM_{2.5}$, robust estimates of human-health impacts could be used to inform air-pollution control policies. Herein, we quantified the effect of current levels of anthropogenic $PM_{2.5}$ on mortality in Australia in terms of $PM_{2.5}$-attributable mortality, changes in LE for children, and the economic costs of the associated YLL.

2. Materials and Methods

2.1. Study Region and Period

We calculated the effect of anthropogenic $PM_{2.5}$ on mortality in all 2310 Statistical Area level 2 (SA2) geographical areas in Australia with age-specific population counts from the Australian Bureau of Statistics (ABS) dataset "Population by Age and Sex, Regions of Australia, Estimated Residential Population 2006–2016" from ABS-TableBuilder (cat. no. 3235.0). We then aggregated attributable numbers of premature deaths, YLL and changes of LE for the entire population of Australia. We chose to start the study period in 2006 to coincide with that census year. $PM_{2.5}$ levels were relatively stable in most states and territories except NT and QLD for the study period 2006–2016 (Figure 1).

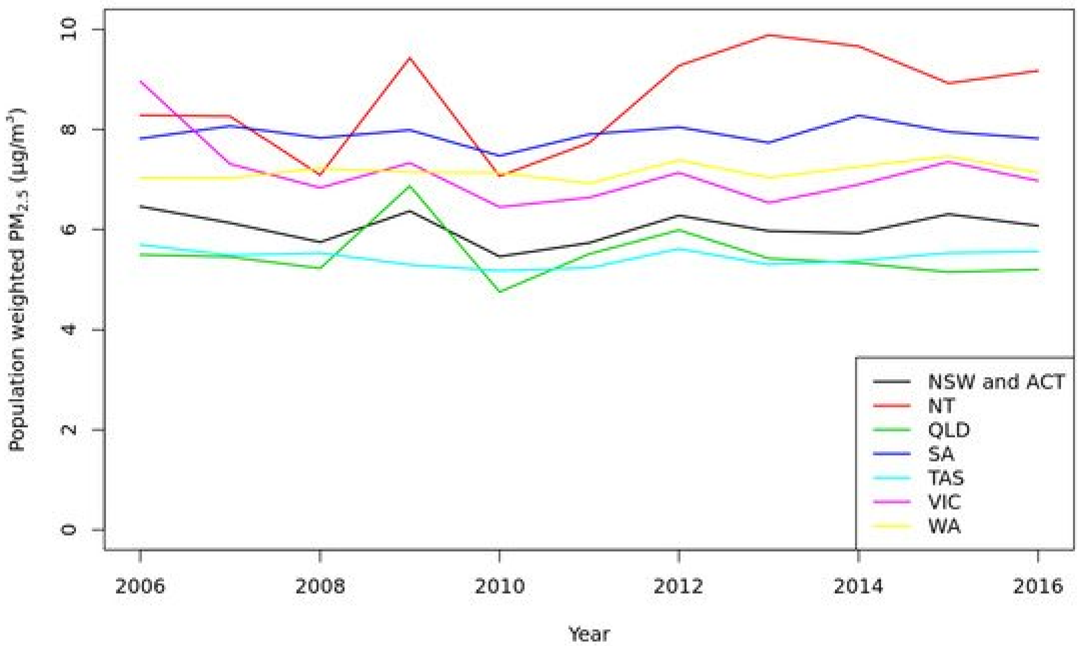

Figure 1. Time-series of population weighted ambient particulate matter ($PM_{2.5}$) concentrations (µg/m^3) across the years 2006–2016 for all Australian states—NSW, New South Wales; ACT, Australian Capital Territory; NT, Northern Territory; QLD, Queensland; SA, South Australia; TAS, Tasmania; VIC, Victoria; WA, Western Australia.

2.2. Assessment of Anthropogenic vs. Non-Anthropogenic $PM_{2.5}$ Concentrations

Annual average $PM_{2.5}$ concentrations were obtained from a validated satellite-based land-use regression (LUR) model, as described by Knibbs et al. [15]. The regression model uses satellite imagery, chemical-transport model (CTM) simulations and land-use data as predictors, and incorporates direct $PM_{2.5}$ measurements from ambient-air monitoring agencies in Australia [15]. The data are available on request from the Australian Centre for Air pollution, energy and health Research (CAR) https://cloudstor.aarnet.edu.au/plus/f/2454567279. The model was estimated for each mesh-block (MB), which is the smallest area in the Census geography (Figure 2). It is not possible to show MBs in Figure 2 due to the difference in spatial scale. Instead, we have added a small area map to the Supporting Information (Figure S1) to demonstrate the small sizes of MB regions, which enable high spatial resolution in our exposure assessment. Anthropogenic $PM_{2.5}$ was defined as the difference between estimated $PM_{2.5}$ concentrations and the 5th percentile of concentrations for all MBs in each state/territory per year. This definition accommodates differences in natural background concentrations between states/territories due to localised influences such as bushfire, dust, and sea salt in the diverse landscapes across the country. This approach is consistent with that taken by the global burden of disease study for estimating the counterfactual level of $PM_{2.5}$ [1].

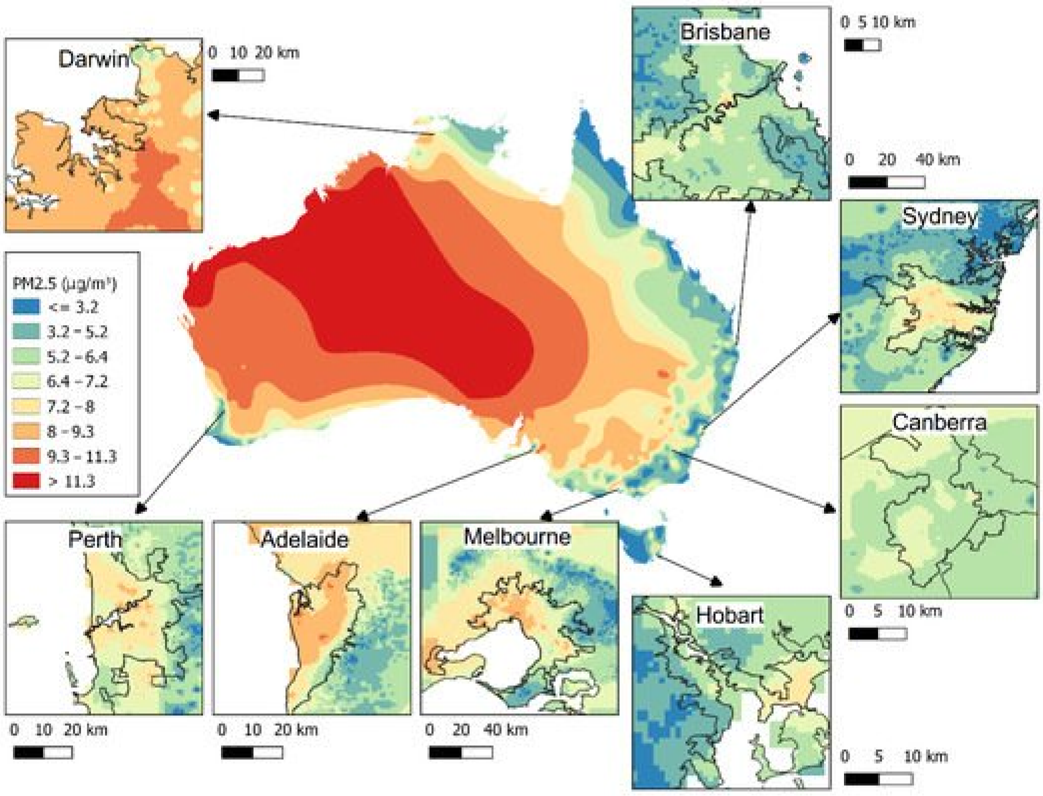

Figure 2. Map of Australia showing modelled estimates of annual average $PM_{2.5}$ (μg/m³) concentrations in 2015.

To validate our state/territory estimates of natural $PM_{2.5}$, we performed sensitivity analyses using 5th percentile $PM_{2.5}$ concentrations for all MBs in Bureau of Meteorology climate zones (Supporting Information S8). This approach gave similar results.

2.3. Health Outcomes

Mortality data for years 2006–2016 by age and state/territory and corresponding population data were accessed from the Australian Bureau of Statistics (Cat. No. 3302.0—Deaths, Australia, available from the ABS.Stat website: http://stat.data.abs.gov.au). Further information about these data sources is presented in the supporting information. No ethics approvals were needed because we used aggregated data from the public domain.

Age-specific death rates for each state/territory and year were linked with the age-specific populations by year within 2016 ABS SA2 geographical boundaries to calculate baseline mortality levels in each subpopulation. To smooth excess variability in annual deaths, we used three-year rolling average annual age-specific rates.

2.4. Quantification of Mortality Attributable to Anthropogenic $PM_{2.5}$

Due to the limited number of Australian epidemiological studies of long term $PM_{2.5}$ air pollution exposure and mortality, we used a relative risk (RR) function estimated from a meta-analysis of European and North American studies [16], as recommended by the World Health Organization (WHO) [17]. A pooled RR of 1.062 (95% CI 1.041, 1.084) per 10-μg/m^3 increments in long term annual average $PM_{2.5}$ exposures of people aged ≥30 years is recommended for health-impact assessments of $PM_{2.5}$ [16,17]. The reviewed studies were performed in countries with similar levels of economic development, similar demographic characteristics, and similar patterns of mortality as those in Australia, albeit with higher air-pollution concentrations [16]. We used this RR to estimate the attributable numbers (AN) of deaths caused by long-term $PM_{2.5}$ exposure for each SA2. We calculated AN based on estimates of local anthropogenic $PM_{2.5}$ and then aggregated to a national total using the following equation:

$$AN=\sum \left(1-e^{(-\beta \Delta X_{ij})}\right) \times Expected_{ij}$$

(1)

where $Expected_{ij}$ is the death count estimated by applying mortality rate in age-group i by age-specific population counts in SA2 2016 census area j, β = log (RR)/10 and ΔX_{ij} is the annual anthropogenic $PM_{2.5}$ concentration in SA2 j.

2.5. Life Expectancy Calculations

Life tables were generated for each year in each SA2, and LE at birth was calculated for 5-year age groups up to age 85-plus. To quantitatively assess the health impact of anthropogenic $PM_{2.5}$, LE for a hypothetical counterfactual population without anthropogenic $PM_{2.5}$ was calculated by subtracting $PM_{2.5}$-attributable numbers of deaths in each age group from expected numbers of deaths, as described by Miller and Hurley [18]. See **supporting information** for more details (**Supporting information Sections S5 and S6**).

2.6. Economic Valuation

To determine the economic value of removing all anthropogenic $PM_{2.5}$ in Australia, we discounted the 2019 willingness-to-pay value of a statistical life year (VSLY = $213,000) by 3% annually [19] and summed for each of the remaining potential life years in each age group. The resulting age-specific value of statistical life (VSL) estimates were then multiplied by corresponding attributable numbers of deaths (averaged for the years 2006–2016) and were summed across all age groups. For more details see **Supporting information Section S7**.

Data preparation and analyses were performed using the R language and environment for statistical computing (version 3.4.4, R Core Team Vienna, R Foundation for Statistical Computing, Vienna, Austria) and MS Excel (Microsoft, Redmond, Washington, DC, USA).

3. Results

3.1. Exposure Assessment

Nationally, the long-term population weighted average $PM_{2.5}$ concentration across the years 2006–2016 was 6.5 μg/m^3 (MB min 1.2–max 14.2), and the anthropogenic component was 3.2 μg/m^3 (MB min 0–max 9.5). **Figure 1** shows the modelled 2015 estimates of the annual average $PM_{2.5}$ in ABS MBs across the country and in the major cities. $PM_{2.5}$ concentrations clearly vary across Australia, reflecting the various natural and anthropogenic contributors to ambient PM, such as dust, sea salt, bushfire smoke, and emissions from transport, industry, agriculture, and residential wood heaters.

Table 1 shows estimated average anthropogenic, non-anthropogenic and total $PM_{2.5}$ concentrations in Australia based on the 5th percentile MB level of each state/territory for each year. Average total $PM_{2.5}$ for the entire country varied little between years (Table 1) but differed markedly between states (Figure 2), reflecting diverse ecological conditions across the country. In Queensland and the Northern Territory, $PM_{2.5}$ estimates varied considerably over the study period, due to droughts, floods, and landscape fires (dust storms, bushfire, and controlled burns). In contrast, population-weighted anthropogenic $PM_{2.5}$ concentrations varied little between years, indicating similar pollution sources in Australian capital cities, where most people live.

Table 1. Estimated population-weighted national anthropogenic, non-anthropogenic and total $PM_{2.5}$ (μg/m^3) by year.

3.2. Mortality Burden

We estimate an average annual mortality burden of 38,962 (95%CI 25,391, 51,669) YLL among people aged 30+ years attributed to anthropogenic $PM_{2.5}$ pollution in Australia between 2006–2016. This is approximately 2% of all mortality or 2616 (95%CI 1712, 3455) deaths. In Table 2, we present annual average mortality burdens in each Australian state and territory. These analyses show that more than 80% of premature deaths occurred in the more populous eastern states New South Wales (NSW), Australian Capital Territory (ACT), Victoria (VIC), and Queensland (QLD).

Table 2. Average annual mortality burden; Attributable Number (AN) of premature deaths and Years of Life Lost (YLL) in each Australian state and territory; NSW, New South Wales; ACT, Australian Capital Territory; VIC, Victoria' QLD, Queensland; WA, Western Australia; SA, South Australia; NT, Northern Territory.

Based on ANs among Australians of 30+ years-of-age, we estimate that LE among children <5 years-of-age was reduced by 76 (95%CI 50, 101) days due to anthropogenic $PM_{2.5}$ (assuming lifelong exposures). Using the 2019 VSLY of $213,000 with an annual social discount rate of 3% [19], we calculated the value of a statistical life (VSL) for each age group based on remaining LE and estimated an average annual mortality-related cost of anthropogenic $PM_{2.5}$ of $6.2 billion nationally (95%CI $4.0 billion, $8.1 billion).

4. Discussion

In this study, we estimate that the mortality burden of anthropogenic emissions of $PM_{2.5}$ in Australia was 2616 excess deaths per year on average (approximately 2% of total mortality), and 38,962 YLL were attributable. In an Australian study from 2016 [13], $PM_{2.5}$ from shipping activities, which use low-quality diesel fuel, were responsible for the loss of 220 years of life among people who died in 2010/11 in the greater metropolitan area (GMR) of Sydney. In a more recent study, 1.2% of all-cause mortality in the greater Sydney metropolitan area was attributed to $PM_{2.5}$ from all anthropogenic sources, corresponding with 5900 YLL annually [9]. In the same study, $PM_{2.5}$ concentrations were estimated using a chemical-transport model (CTM) of eight anthropogenic sources; the total population weighted $PM_{2.5}$ concentration was 5.5 μg/m^3 with an anthropogenic component of 2.1 μg/m^3. Our estimates for Sydney are consistent with this anthropogenic proportion, and our estimates of YLL were comparable (data not shown).

Our estimated annual mortality-related cost of anthropogenic $PM_{2.5}$ in Australia was $6.2 billion (95%CI $4.0 billion, $8.1 billion) nationally in 2019 dollars. This is supported by a recent estimate for the special report of the MJA-Lancet Countdown [20], which found that urban $PM_{2.5}$ costs equated to $5.3 billion in 2015 dollars. This is similar to our estimate after adjusting for inflation; however, our methods for exposure assessment and economic valuation with discounting were different. Therefore, comparisons of estimated health-cost estimates should be made with caution. Despite the relatively low levels of air pollution in Australia, the substantial health burden is of public health concern, both in societal and economic terms.

Increased anthropogenic emissions have been associated with increased industrial and economic activities [10], suggesting that concentrations of many pollutants will increase globally over the coming decades without substantial decreases in fossil fuel and biomass combustion [21]. However, economic development has been decoupled from increasing anthropogenic air-pollution emissions in some countries [22] where clean-air policies have been implemented [23]. Moreover, we found no increases in anthropogenic $PM_{2.5}$ over the period 2006–2016 in Australia.

Lelieveld, et al. [8] assessed global $PM_{2.5}$ concentrations and found global mean LE would increase by 1.7 (1.4–2.0) years if all potentially controllable anthropogenic emissions were removed. They estimated total lost LE from air pollution was 2.9 years, exceeded that of smoking (2.2 years of lost LE) [8]. Our estimated loss of life expectancy of 76 days (0.2 years) is similar to that found in [8] for Australia/Oceania combined, but is lower than the global average estimate (1.7 years), due to the lower exposure levels and related mortality rates in Australia. In another worldwide study by the Global Burden of Disease (GBD) 2019 project [24], 1625 (95%UI 508, 2877) deaths were attributed to ambient particulate air pollution in Australia in 2016, whereas our estimate was 2616 (95%CI 1712, 3455) for the period 2006–2016 (data available from Institute for Health Metrics and Evaluation (IHME) website **http://ghdx.healthdata.org/gbd-results-tool**). Our estimate is 60% higher than that from the GBD study. This difference can be explained by differing datasets used for exposure and death rates, and different exposure–response risk functions and counterfactual exposure.

For context, in a study of Australian smokers in NSW, individual LE of heavy smokers was reduced by 10 years [25]. Given the widespread exposure to anthropogenic $PM_{2.5}$, compared with that of heavy smoking, the population impact may be substantial. For example, the GBD report from 2020 ranked air pollution as the 4th highest risk factor for mortality, with 6.67 million attributable deaths during the period 1990–2019 [24].

We used high-resolution air-pollution models that were informed by monitor data, land-use data and satellite imaging. However, among limitations of this study, we did not analyse regions within states because mortality rates for small areas were not publicly available. Moreover, $PM_{2.5}$ is associated with a broad range of health effects, such as low birth weight and respiratory illnesses, that increase hospitalisation and general-practice visits. The costs of these are not captured by our VSLY estimates, thus only calculating the mortality burden will underestimate the overall impacts of $PM_{2.5}$ pollution on public health and health services. The present study is also limited by the absence of locally derived RR with only one cohort study published [7], and so we applied the RR from a meta-analysis as recommended by the WHO "Health risks of air pollution in Europe—HRAPIE project" recommendations [17]. However, a new meta-analysis has recently been published that found support for a higher RR (1.08), which we have included as a sensitivity analysis [26]. As expected, this showed an increase to our estimated health burden and costs, and supported our conclusion that the burden is substantial. In addition, the global exposure mortality model (GEMM), a non-linear exposure–response function that employs a low minimum-risk threshold was used by Lelieveld, et al. [8]. However, the two meta-analyses [17,26] support our application of a linear RR in the Australian context. A further limitation to our study was the lack of estimates of natural $PM_{2.5}$. We approximated these using the 5th percentile threshold, which is likely to vary less than in reality, but probably overestimates baseline $PM_{2.5}$. This limitation will only be addressed when natural $PM_{2.5}$ estimates from a suitable model are available for the entire country.

5. Conclusions

Our findings present some clear implications for policymakers. The estimated burden of premature death attributable to anthropogenic $PM_{2.5}$ shows that this environmental risk factor has a significant impact on public health in Australia, and the health benefits of exposure reductions have been demonstrated in multiple studies. Although ambient annual average $PM_{2.5}$ concentrations have remained relatively stable in major cities in Australia over the past several years, the exposure level is increasing due to increases in the population. Hence, given that the $PM_{2.5}$ exposure–response relationship appears to be linear at the low levels found in Australian cities, $PM_{2.5}$ reporting standards that prioritise continual reductions in $PM_{2.5}$ pollution are urgently required. These are likely to require reductions in emissions of primary $PM_{2.5}$ and of secondary $PM_{2.5}$ precursors across multiple sectors (road transport, domestic heating, industry, and agriculture). Health impact assessments such as this can inform decision-making for urban developments, the energy system, and future studies that assess the costs and benefits of anthropogenic air pollution.

Supplementary Materials

The following are available online at **https://www.mdpi.com/1660-4601/18/1/254/s1**, Figure S1: Average $PM_{2.5}$ in 2015 across the country and inset maps of the Sydney region and the small case study region in Western Sydney. Figure S2: Climate zones from Bureau of Meteorology rainfall levels. Figure S3: Map of Australia showing modelled estimates of annual average PM2.5 (μg/m3) concentrations in 2015. Climate boundaries are marked.

Author Contributions

Formal analysis, I.C.H. and T.B.C.; Methodology, I.C.H., R.A.B., M.C., M.D., J.S.H., J.A.H., B.J., F.H.J., L.D.K., G.P., S.V.H., and G.G.M.; Writing—original draft, I.C.H., T.B.C., K.H., E.J., S.V., and G.G.M.; Writing—review & editing, G.G.M. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Restrictions apply to the availability of these data. Data was obtained from Dr Luke D. Knibbs and are available from the Australian Centre for Air pollution, energy and health Research (CAR) at **https://cloudstor.aarnet.edu.au/plus/f/2454567279** with the permission of Dr Luke D. Knibbs.

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Conflicts of Interest

The authors declare no conflict of interest.

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Research
Children's Health

Risk of Asthmatic Episodes in Children Exposed to Sulfur Dioxide Stack Emissions from a Refinery Point Source in Montreal, Canada

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Abstract

Background

Little is known about the respiratory effects of short-term exposures to petroleum refinery emissions in young children. This study is an extension of an ecologic study that found an increased rate of hospitalizations for respiratory conditions among children living near petroleum refineries in Montreal (Canada).

Methods

We used a time-stratified case–crossover design to assess the risk of asthma episodes in relation to short-term variations in sulfur dioxide levels among children 2–4 years of age living within 0.5–7.5 km of the refinery stacks. Health data used to measure asthma episodes included emergency department (ED) visits and hospital admissions from 1996 to 2004. We estimated daily levels of SO_2 at the residence of children using *a*) two fixed-site SO_2 monitors located near the refineries and *b*) the AERMOD (American Meteorological

Society/Environmental Protection Agency Regulatory Model) atmospheric dispersion model. We used conditional logistic regression to estimate odds ratios associated with an increase in the interquartile range of daily SO_2 mean and peak exposures (31.2 ppb for AERMOD peaks). We adjusted for temperature, relative humidity, and regional/urban background air pollutant levels.

Results

The risks of asthma ED visits and hospitalizations were more pronounced for same-day (lag 0) SO_2 peak levels than for mean levels on the same day, or for other lags: the adjusted odds ratios estimated for same-day SO_2 peak levels from AERMOD were 1.10 [95% confidence interval (CI), 1.00–1.22] and 1.42 (95% CI, 1.10–1.82), over the interquartile range, for ED visits and hospital admissions, respectively.

Conclusions

Short-term episodes of increased SO_2 exposures from refinery stack emissions were associated with a higher number of asthma episodes in nearby children.

Keywords: asthma, case crossover, children, dispersion modeling, emergency department visits, hospital admissions, point source, refinery, short-term exposure, sulfur dioxide

Little is known about the risks associated with exposure to petroleum refinery emissions in young children or, indeed, across other age ranges. Furthermore, studies performed near point sources such as refineries have generally not addressed the effects of short-term exposures (e.g., Bhopal et al. 1998; Forastiere et al. 1994; Kim et al. 2001).

Refinery emissions may be an important source of sulfur dioxide on a local scale (Gower et al. 2008). The potential for short-term high-level SO_2 exposures to cause adverse health effects is well recognized. High SO_2 levels were implicated in the acute morbidity and mortality associated with the severe pollution episodes in Donora (Pennsylvania), London, and New York in the 1940s, 1950s, and 1960s (American Thoracic Society Committee of the Environmental and

Occupational Health Assembly 1996). Moreover, experimental SO_2 chamber studies have shown that adult asthmatics experience pronounced airway resistance after exercise after only minutes of exposure at levels similar to those encountered today in ambient air (Carlisle and Sharp 2001).

Epidemiologic studies of children have not demonstrated convincing evidence that daily increases in ambient SO_2 exposure at typical current levels are associated with respiratory effects (e.g., Ko et al. 2007; Lee et al. 2002). Time-series analyses based on administrative databases have shown only modest increased risks of emergency department (ED) visits and hospitalizations for respiratory problems; usually the increase was < 10% per increase in the inter-quartile range of SO_2 (e.g., Hajat et al. 1999; Lee et al. 2002; Luginaah et al. 2005; Sunyer et al. 1997; Wong et al. 2001). Other time-series and case–crossover analyses have found no association between ambient SO_2 levels and ED visits or hospital admissions, or that the risk apparently associated with ambient SO_2 disappeared after adjusting for the effect of other pollutants that were correlates of SO_2 (e.g., Fusco et al. 2001; Lee et al. 2006; Lin et al. 2005; Sunyer et al. 2003). Only modest short-term effects of SO_2 exposure were noted in panel studies of children (e.g., Aekplakorn et al. 2003; Henry et al. 1991; Schildcrout et al. 2006).

To date, epidemiologic studies that have investigated the acute risks of daily ambient SO_2 in children have been performed mostly in urban areas, with the aim of capturing associations with variable levels of regional air pollution (e.g., Hajat et al. 1999; Lee et al. 2006; Sunyer et al. 1997). Few studies have been performed near SO_2 point sources (e.g., Aekplakorn et al. 2003; Henry et al. 1991). Because SO_2 levels are higher near sources and vary widely in space, few studies could have estimated SO_2 levels at a spatial level fine enough to represent the variability of individual exposure. Indeed, most of the above studies have simply used a small number of centrally located SO_2 monitors to attribute a measure for an entire region, rather than attempt to capture intraregional variation.

Unlike past work, this study uses dispersion modeling to assign ambient pollution levels at an individual level. Incorporating information on both the spatial (geographic) and temporal variability of SO_2 levels likely improves characterization of individual exposures for community epidemiologic studies. Dispersion modeling approaches can be used to assign individual exposures that vary in time and space. Dispersion models are physical deterministic models that use existing data characterizing source emissions, meteorology, and topography to create maps of pollutant concentrations. Such maps can be used to predict source-specific exposures outside residences and to provide spatially resolved exposure for examining source-specific health effects. They are usually based on Gaussian plume dispersion equations [U.S. Environmental Protection Agency (EPA) 2008]. Although dispersion models overcome the limitation of central-site measurements that do not allow for the consideration of the spatial variation of pollutant levels, they have seldom been used in epidemiologic investigations and, as far as we know, have not previously been used to assess effects associated with short-term variations in exposure.

The present study is part of a larger assessment of possible health effects from time-variant exposure to emissions from the industrial complex of the East End of Montreal (Canada) where two petroleum refineries are located. In residential areas located near this industrial complex, annualized rates of hospitalizations for respiratory health conditions among children 2–4 years of age were approximately 25% higher than rates for Montreal Island children for 1996–2004 (Kosatsky et al. 2004). However, such a cross-sectional assessment could not establish if the excess is related to exposure to emissions from the industrial complex and, if so, whether the increased rates are related to short- or long-term exposures.

In this study, we used a case–crossover design to assess the risk of asthma episodes in children 2–4 years of age exposed to SO_2 refinery stack emissions from the industrial complex located in the East End of Montreal Island. According to the Canadian pollutant release inventory (Environment Canada 2008) and the emission inventory of the city of Montreal (Kosatsky et al. 2004), during the study period the two refineries emitted at least 8,000 metric tons of SO_2 annually. Peak daily SO_2 levels in residential areas near to the industrial complex can reach values that are > 50% higher than daily peaks measured in other areas of the city and in other Canadian cities such as Toronto, whereas mean levels are in the range typically measured in North American cities and are much lower than in developing countries concentrations (World Health Organization 2000). The specific objectives of this study were *a*) to assess in young children the risk of asthmatic episodes related to short-term exposure to refinery stack emissions as indicated by SO_2, *b*) to explore the influence of the SO_2 “exposure regime” using daily means and peaks at various lags, and *c*) to explore the value of a dispersion model versus fixed-site SO_2 monitors in characterizing exposure to a point source.

Go to:

Materials and Methods

Study Area, Period, and Population

This study covers the calendar period between 1996 and 2004. We defined the geographic area of the study by four postal service forward sortation areas (FSAs) of the East End of Montreal Island (H1A, H1B, H1K, H1L), Canada, where both residences and an industrial sector comprising two petroleum refinery complexes are located. Figure 1 presents the location of the four FSAs: H1A, H1B, H1K, and H1L. We estimated the geographic location of all residences within the four FSAs using the geographic centroids of their full six-character postal codes. Residences within these four FSAs are located as close as 0.5 km and up to 7.5 km from the refinery stacks. The median distance from the 3,469 six-character postal code centroids of all residences to the closest refinery stack is 2.4 km. The Island of Montreal has more than 30,000 residential postal codes; within the study area, a six-character postal code often corresponds to a single segment of road within which fewer than 50 individuals live. Figure 1 shows the location of the centroids of the six-character postal codes in the study area.

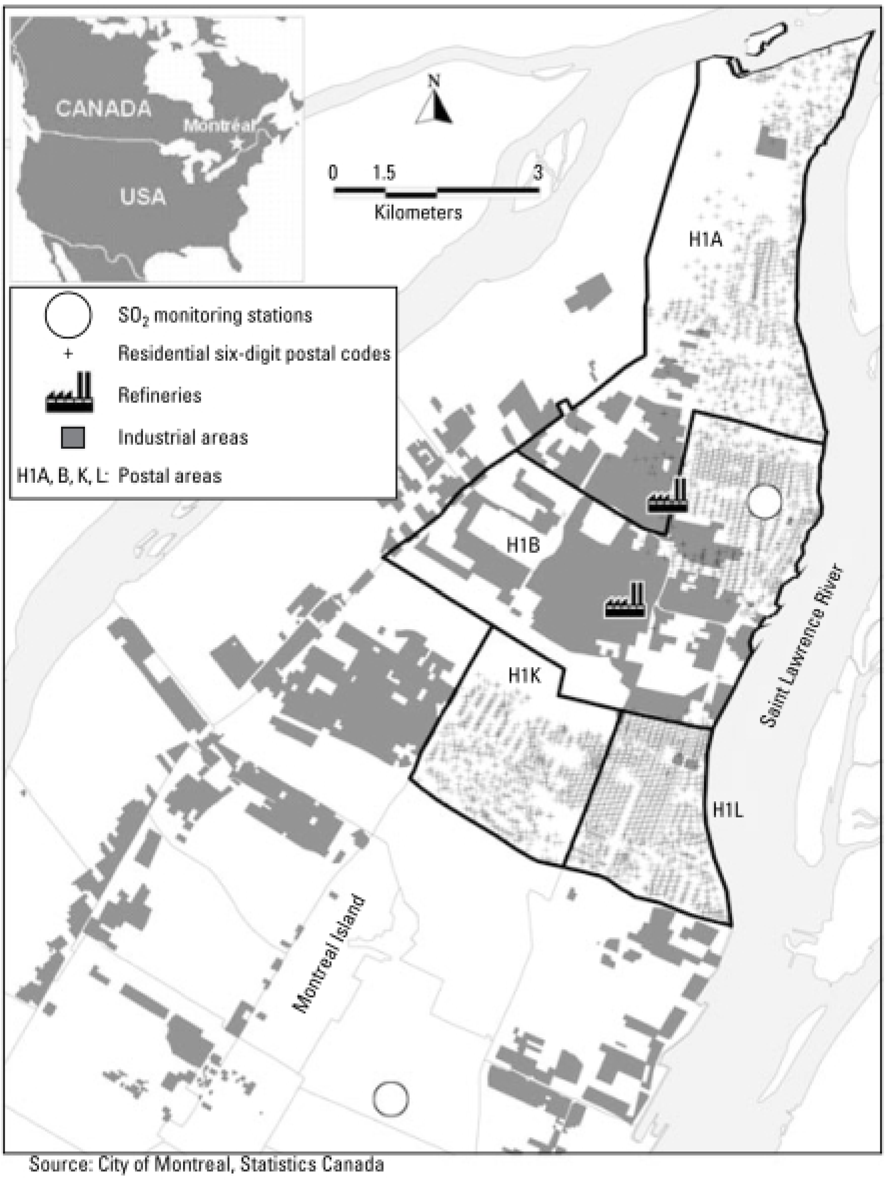

Figure 1

Area of the study, location of refineries and industrial area, SO_2 fixed-site monitors, three-character postal areas, and residential six-character postal codes. A six-character postal code represents a segment of road (block side) within which fewer than 50 individuals live.

The study population consisted of children who lived in one of the four FSAs who either visited an ED or were hospitalized for asthma between 1996 and 2004. We restricted analyses to children who were between 2 and 4 years of age at the time of their ED visit or hospitalization. Estimates of the number of children in this age range who resided in each of the four FSAs, based on the 2001 Canadian Census, were 960, 635, 1,020, and, 855 for FSAs H1A, H1B, H1K, and H1L, respectively. This project obtained approval from the Montreal Public Health Research Ethics Board.

Health Data

We obtained hospital ED visits and hospital admissions data for children living on the Island of Montreal, Canada, from the Quebec Health Insurance Board and the Quebec Ministry of Health and Social Services (MED-ECHO database), respectively, for the period 1996–2004. These two databases capture virtually all hospitalizations and ED visits for Quebec residents (Labrèche et al. 2008). Each ED visit or hospitalization included the following individual-level information: time and date of the health service used, the primary cause of the ED visit or hospitalization [*International Classification of Diseases, 9th Revision* (ICD-9; World Health Organization 1975)], and patient characteristics such as age, sex, and the six-character postal code of the current place of residence. The location of the hospital where the service took place was available for admission but not for ED visit data. These data indicated that 96% of hospital admissions among children who lived in the four FSAs were at institutions on the Island of Montreal or at its near eastern suburb; we expect a similar figure for ED visits.

We used asthma (ICD-9 code 493) as the cause of ED visit or hospitalization for the analyses. We included children ≥ 2 years of age because the diagnosis of asthma among younger children is problematic and often confused with bronchiolitis, viral infections, or other conditions that produce wheeze (Panettieri et al. 2008). This study focused on asthma outcomes among very young children because cross-sectional analyses revealed a more pronounced excess of asthma hospitalizations for this age group than for others, and because children 2–4 years of age are widely regarded to be more susceptible to possible adverse health effects of air pollution (Bateson and Schwartz 2008).

Pollution and Meteorological Data

Our primary exposure of interest was the SO_2 emitted by the refineries and estimated at the child's residence. In our assessment of the effects of emissions from the refineries of the East End of Montreal, we have considered the acute effects of exposure to SO_2 because *a*) SO_2 has been associated with adverse acute health outcomes in other studies and *b*) it serves as an indicator of stack emissions from the refineries.

Of course, stack-emitted SO_2 is likely to be correlated with other refinery emissions such as fine particles [particles with an aerodynamic diameter < 2.5 µm ($PM_{2.5}$)].

We used two fixed monitoring sites located near the refineries and estimates from the AERMOD (American Meteorological Society/Environmental Protection Agency Regulatory Model) atmospheric dispersion model (U.S. EPA 2008) to characterize ambient SO_2 exposures of children who visited the ED or who were admitted to hospital between 1996 and 2004. We also characterized exposure of the children to the "urban/regional background" levels of air pollutants with the use of all Montreal Island's fixed monitoring sites with available air pollutant data, excluding the two sites located near the refineries (see "Regional/urban air pollutant background levels," below). We computed daily SO_2 means and maxima from hourly measurements at fixed-site monitors and from hourly model estimates at 3,469 receptor locations (from 0000 to 2300 hours). We used daily maxima to allow us to represent the possible respiratory health effects from high-exposure episodes that occur during the day. We considered days with < 18 hr of SO_2 measurement as missing.

Fixed-site measurements of SO_2 levels near refineries

We considered daily SO_2 measurements made at the following locations by the Montreal Environmental Service and that capture the refinery emissions (see Figure 1 for location). First, to represent SO_2 exposure for those living in the FSAs HIA and H1B, we used data from the monitor close by and to the east of the refineries. Based on hourly wind data, winds blow from the refineries toward this monitor (winds from 210° to 290°) about 40% of the time. This monitor measured the highest SO_2 levels for winds from 210° to 290° (average levels with winds from 210° to 290°, 10.9 ± 13.0 ppb). This monitor is located within 3 km of the refinery stacks. The maximum distance from this monitor to the residences (more precisely, to the six-character postal codes) of these FSAs is 6.9 km; the median distance is 1.6 km.

Second, to represent SO_2 exposure for those living in the FSAs H1K or H1L, we used data from the monitor close by and to the southwest of the refineries. Winds blow from the refineries toward this monitor (winds from 0° to 60°) about 20% of the time (mostly in winter). This monitor is located outside of the four FSAs of the study and no more than 10 km from the refinery stacks. It can be as far as 9.1 km from some residences of the H1K and H1L FSAs (the median distance is 5.6 km). Although this monitoring site is far from many of the residences of these FSAs, SO_2 levels measured at this monitor are influenced by the refinery stack emissions when the wind is from the northeast (average levels with winds from 0° to 60°, 7.7 ± 10.6 ppb). No other SO_2 monitoring site was located closer to FSAs H1K and H1L.

Figure 2 presents the time series of the SO_2 levels at these two monitors.

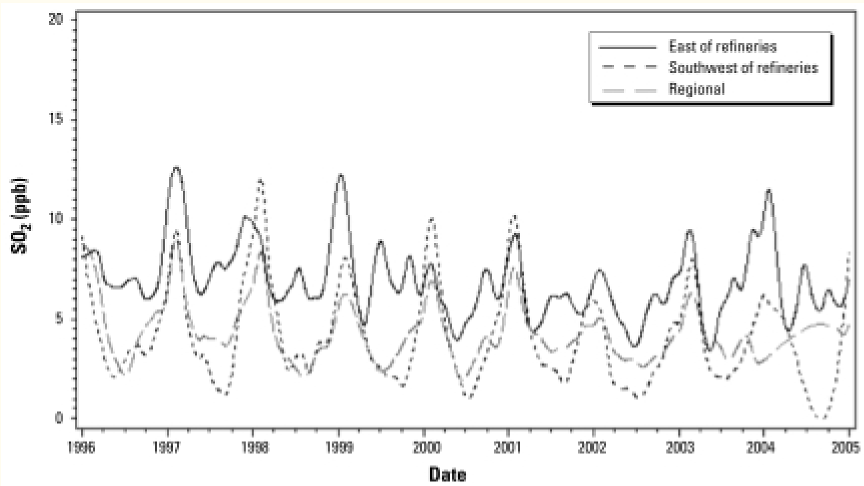

Figure 2

Time series of daily mean SO^2 measurements at fixed sites on the Island of Montreal (spline routing smoothing). Peaks at the southwest monitoring site occurred during winter.

Dispersion modeling of SO_2 levels

To obtain at-home estimates of daily exposure, we estimated SO_2 levels at the centroid of all children's residential six-character postal codes for all days between 1996 and 2004, using the AERMOD dispersion model as follows.

We used data for several point source emissions of the two refineries to model hourly SO_2 levels at 3,469 discrete receptor locations corresponding to the residential six-character postal code centroids in the East End of Montreal (in the FSAs H1A, H1B, H1K, H1L; Figure 1). The point source emissions included those from main vents and stacks that emit on a continuous schedule throughout the year (seven point-source emission sources for one refinery and five for the other). For each vent and stack, the longitude/latitude, emission temperature, height, and exit velocity were available. The selected vent and stack emissions of the two refineries represent approximately 90% of the total SO_2 emissions from these two refineries and represent more than 80% of the SO_2 emissions in the industrial area. We used annual emission data for each vent and stack to model hourly SO_2 levels. Although information on daily variation of SO_2 emissions was not available, monthly variation of total SO_2 refinery emissions was available for each facility for the study period (all point sources for each refinery considered together). We thus adjusted annual emissions data for the month-by-month emission levels of each facility, using the monthly variation of their total SO_2 refinery emissions.

Other smaller point sources of SO_2 are on Montreal Island, and additional "regional sources" are outside of Montreal. We did not represent these in the model, but we explored their influence on the risk of ED visit or hospitalization for asthma in children using regression models that incorporated the SO_2 regional/urban background levels.

The inputs to the dispersion model also included hourly meteorological records at the Pierre Elliott Trudeau Montreal International Airport, about 25 km from the area of the study, and upper air data from a rural monitoring site descriptive of the greater Montreal region. Missing hourly meteorological data at the International Airport monitoring site (< 0.1% of all hours) were replaced with the values for the previous or the next hour or interpolated from available data (when more than a few consecutive hours were missing). We acquired all meteorological data from Environment Canada (2008). The topographic characteristics across the area of interest were considered constant. We made allowances in the model for the nature of the local terrain, including both vegetated (grass) and paved surfaces.

We averaged hourly SO_2 predictions over the day and computed daily peaks for each six-character postal code. We linked daily SO_2 values with the case and control period intervals by date and by postal code.

Regional/urban air pollutant background levels and regional meteorological data

Pollutant measurements

The fixed-site monitors used to create hourly regional/urban background averages were not located in the immediate vicinity of the industrial complex. Of these fixed-site monitors, we used at least six for nitrogen dioxide and ozone, depending on the date; we used three monitors for SO_2 measurements and only one for $PM_{2.5}$. We used the three SO_2 monitors not located near the industrial sector to represent minor point sources of SO_2 on Montreal Island and additional regional sources outside of Montreal. The three monitors were influenced by the local refinery emissions when winds were from the northeast (0–60°) but to a lesser extent than the monitor also located to the west but in close proximity to the refineries. Because levels measured at the three monitors were not influenced by other wind directions, we presume that although these monitors may also capture emissions from other local sources, such influence is small compared with that from outside the Island of Montreal.

Meteorological measurements

We used daily mean outdoor temperatures and relative humidity (from 0000 to 2300 hours) from the Montreal International Airport.

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Data Analysis

We analyzed the study using a case–crossover design (Maclure 1991). In this design, which is analogous to a standard time-series design, we controlled for secular trends in hospital morbidity by selecting control days for each day in which one or more hospital visits (case day) occurred. This design also controls for time-invariant confounders (e.g., exposure to secondhand smoke) by making within-subject comparisons. We selected control days using the time-stratified approach (Lumley and Levy 2000) in which we divided the study period into monthly strata and selected control days for each case as the same days of the week in the month. The time-stratified approach removes bias from unwanted secular trends in the hospitalization/ED visit time series and leads to unbiased estimates of effect for case–control days selected within specific time windows (no "overlap bias") (Janes et al. 2005). Thus, if hospitalization occurred on Saturday, 22 August 1998 (corresponding to the hazard period, lag 0), the selected control periods were also Saturdays (1, 8, 15, and 29 August 1998).

We assessed the SO_2–hospitalization/ED visit relationships by conditional logistic regression analyses in which we compared the SO_2 exposure levels (AERMOD estimates or the fixed-site measurements near the refineries) for the case period with the matched control periods. We defined the case period as the day of hospitalization or ED visit. Exposure metrics examined included same-day average and peak SO_2 exposures, as well as lagged intervals extending from 1 to 4 days before the case or control event. We estimated the odds ratios (ORs) and their 95% confidence intervals (CIs) in relation to an increase in the interquartile range of SO_2.

Analyses performed with the SO_2 levels from the monitoring sites were done separately for children residing in the East End (including the FSAs H1A and H1B) and to the southwest (including H1K and H1L) of the refineries, as the two SO_2 fixed monitoring sites used, to represent the exposures of children living to the east or the southwest of the refineries, which differ the emission sources and to the residences of the children (Figure 1). As such, the SO_2 levels measured at the site farther away from the refineries are typically lower than those at the closer monitoring site (Figure 2). Thus, the two SO_2 fixed monitoring sites may not represent the exposure of children living to the east or the southwest of the refineries with equal accuracy. When using estimates from AERMOD, we performed analyses for the two areas separately, to compare results with those from analyses performed with the SO_2 levels from the two monitoring sites. However, we also performed analyses with AERMOD SO_2 estimates for all FSAs together, to increase the statistical power of the overall SO_2 effect estimate.

We first performed unadjusted conditional logistic models by including the AERMOD SO_2 exposure estimates or the fixed-site measurements near the refineries as an independent variable. We then used multivariable conditional logistic regression models to control for the potential confounding influences of the regional/urban background air pollutant levels and meteorological conditions. We adjusted for daily mean concentrations of regional SO_2, O_3, NO_2, and $PM_{2.5}$ levels, evaluated for the same lag period as for the SO_2 AERMOD estimates and the fixed-site measurements near the refineries. Similar to previously conducted time-series and case–crossover analyses (e.g., Luginaah et al. 2005), meteorological conditions that we examined included relative humidity and temperature at the same lag period as SO_2 exposure estimates. We verified the linearity of the relationship between temperature and ED visits or hospitalization using natural cubic spline functions. We constrained cubic basis functions to meet at the following cut points (knots): 5th, 33th, 66th, and 95th percentiles. Given no departure from linearity, we used linear relations.

We compared dispersion model predictions (SO_2 AERMOD daily mean and peak estimates) with measurements at the SO_2 fixed-site monitor located to the east of the refineries using Pearson correlations.

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Results

During the study period, there were 263 hospitalizations and 1,579 ED visits for asthma among children 2–4 years of age in the four FSAs of the study; 46% and 41% of the hospitalizations and of the ED visits were among children who lived to the east of the refineries (FSAs H1A and H1B). Based on 2001 census data (Statistics Canada 2008), these two FSAs accounted for a combined 46% of the overall population of the study area. The daily number of hospitalizations and ED visits ranged from 0 to 3 (mean, 0.1 ± 0.3) and from 0 to 5 (mean, 0.5 ± 0.7), respectively, during the study period.

Table 1 presents SO_2 descriptive data for the fixed-monitoring sites located near and to the east and southwest of the refineries, the AERMOD SO_2 estimates for all the receptor points located to the east or to the southwest of the refineries for all days of the study period, and the SO_2 AERMOD descriptive information for the four FSAs combined. Descriptive SO_2 data including only dates for those who used a health service were similar (data not shown) to results presented in Table 1. The monitor to the east of the refineries presented higher SO_2 levels than those measured at the monitor to the southwest, which is both farther away from the refineries and less frequently in the lee of refinery stack emissions. When both monitors were not subjected to winds blowing over the refineries, levels recorded were similar to those of the urban/regional background (data not shown). The distribution of the AERMOD estimates presents a lower mean than do the monitors. However, peak levels measured to the west of the refineries are lower than the AERMOD peak level estimates. As for the urban/regional background levels, SO_2 measurements showed limited variability compared with the levels recorded at the monitoring sites located near the refineries. NO_2 and O_3 levels monitored in proximity and to the east or southwest of the refineries were not higher than the urban/regional background levels (data not shown).

Table 1

SO_2 near refineries, regional air pollutants, and meteorological data for Montreal Island, 1996–2004.

Pollution variable	No. of days	Mean	SD	Median	Q1	Q3	IQR
SO_2 measured (ppb)[a]							
Monitoring site east of refineries							
Daily mean	3,177	6.9	5.7	5.5	2.9	9.2	6.3
Daily peak	3,177	23.8	22.2	16.9	8.9	31.9	23.1
5-day mean (lag 0 to lag 4)	3,055	6.9	3.5	6.3	4.4	8.7	4.4
Monitoring site southwest of refineries							
Daily mean	2,683	4.4	4.4	3.1	1.5	5.9	4.3
Daily peak	2,683	12.8	13.8	8.5	4.2	16.2	11.9
5-day mean (lag 0 to lag 4)	2,561	4.5	3.2	3.7	2.1	5.9	3.7
SO_2 modeled with AERMOD (ppb)							
East and southwest of refineries[b]							
Daily mean	11,406,072	3.0	4.8	0.8	0.0	4.3	4.3
Daily peak	11,406,072	17.5	20.0	10.8	0.0	31.2	31.2
5-day mean (lag 0 to lag 4)	11,392,196	3.0	3.2	2.0	0.7	4.3	3.6

Pollution variable	No. of days	Mean	SD	Median	Q1	Q3	IQR
East of refineries[c]							
Daily mean	5,592,888	3.7	5.1	1.6	0.0	5.5	5.5
Daily peak	5,592,888	19.2	19.2	16.0	0.1	31.7	31.6
5-day mean (lag 0 to lag 4)	5,586,084	3.7	3.4	2.8	1.0	5.3	4.3
Southwest of refineries[c]							
Daily mean	5,813,184	2.4	4.5	0.2	0.0	3.0	3.0
Daily peak	5,813,184	16.0	20.6	3.3	0.0	30.4	30.4
5-day mean (lag 0 to lag 4)	5,806,112	2.4	2.8	1.5	0.5	3.2	2.7
Regional data[d]							
$PM_{2.5}$ daily mean (μg/m^3)[e]	2,439	7.6	7.1	5.6	3.0	9.8	6.8
SO_2 daily mean (ppb)	2,920	4.3	2.9	3.6	2.4	5.3	2.9
NO_2 daily mean (ppb)	3,257	20.5	7.4	19.5	15.3	24.4	9.2
O_3 daily mean (ppb)	3,288	17.8	9.1	16.9	11.3	23.0	11.7
Daily temperature (°C)[f]	3,288	7.4	11.7	7.8	−1.5	17.8	19.3
Daily relative humidity[f]	3,177	70.1	12.8	70.5	61.5	79.4	19.9

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Abbreviations: IQR, interquartile range; Q1, first quartile; Q3, third quartile. This table presents values for all days and estimates at all locations, even if no ED visits or hospitalizations occurred at these days and places.
[a]Missing data were spread over the entire study period.
[b]Number of receptor points (3,469 six-character residential postal codes) × 3,288 days.
[c]Number of receptor points.
[d]Average of levels at urban/regional background monitoring sites, excluding monitoring sites east and southwest of refineries.
[e]Data missing in 1996 and half of 1997.
[f]Meteorological records from the Montreal International Airport meteorological monitoring site.

Correlation of the dispersion model predictions (SO_2 AERMOD daily mean and peak estimates) at the site of the fixed monitor located to the east of the refineries with SO_2 measured at that monitor was modest (daily mean, $r = 0.43$; peak, $r = 0.36$; $p < 0.001$).

Table 2 presents associations between AERMOD SO_2 estimates and hospitalizations and ED visits for children from analyses performed using combined data from the east and the southwest areas. We performed such combined analyses only for the SO_2 AERMOD estimates, given that the two fixed monitoring sites used to represent exposure in the east and in the southwest are located at different distances from the refineries and residences of the FSAs. Combined data show a greater OR for hospitalizations than for ED visits. Hospitalizations and ED visits were more strongly related to peak than to mean levels of SO_2; associations were most pronounced for SO_2 levels on the same day that the visit or the hospitalization took place (lag 0).

Table 2

Associations between AERMOD SO_2 estimates and asthma episodes in small children living near the Montreal refineries, 1996–2004.[a]

	OR (95% CI)	
SO_2 modeled with AERMOD (µg/m^3)	**Unadjusted[b]**	**Adjusted[b,c]**
Hospital admissions		
Daily mean, lag 0	1.14 (1.02–1.29)	1.14 (1.00–1.30)
Daily peak, lag 0	1.34 (1.08–1.67)	1.42 (1.10–1.82)
Daily mean, lag 1	0.99 (0.88–1.11)	1.03 (0.91–1.16)
Daily peak, lag 1	0.95 (0.75–1.19)	1.01 (0.79–1.29)
5-day mean	1.08 (0.92–1.27)	1.07 (0.87–1.31)
ED visits		
Daily mean, lag 0	1.06 (1.01–1.11)	1.04 (0.98–1.10)
Daily peak, lag 0	1.14 (1.04–1.25)	1.10 (1.00–1.22)
Daily mean, lag 1	1.04 (0.99–1.10)	1.05 (1.00–1.12)
Daily peak, lag 1	1.03 (0.94–1.13)	1.05 (0.95–1.16)
5-day mean	1.05 (0.97–1.14)	1.04 (0.94–1.14)

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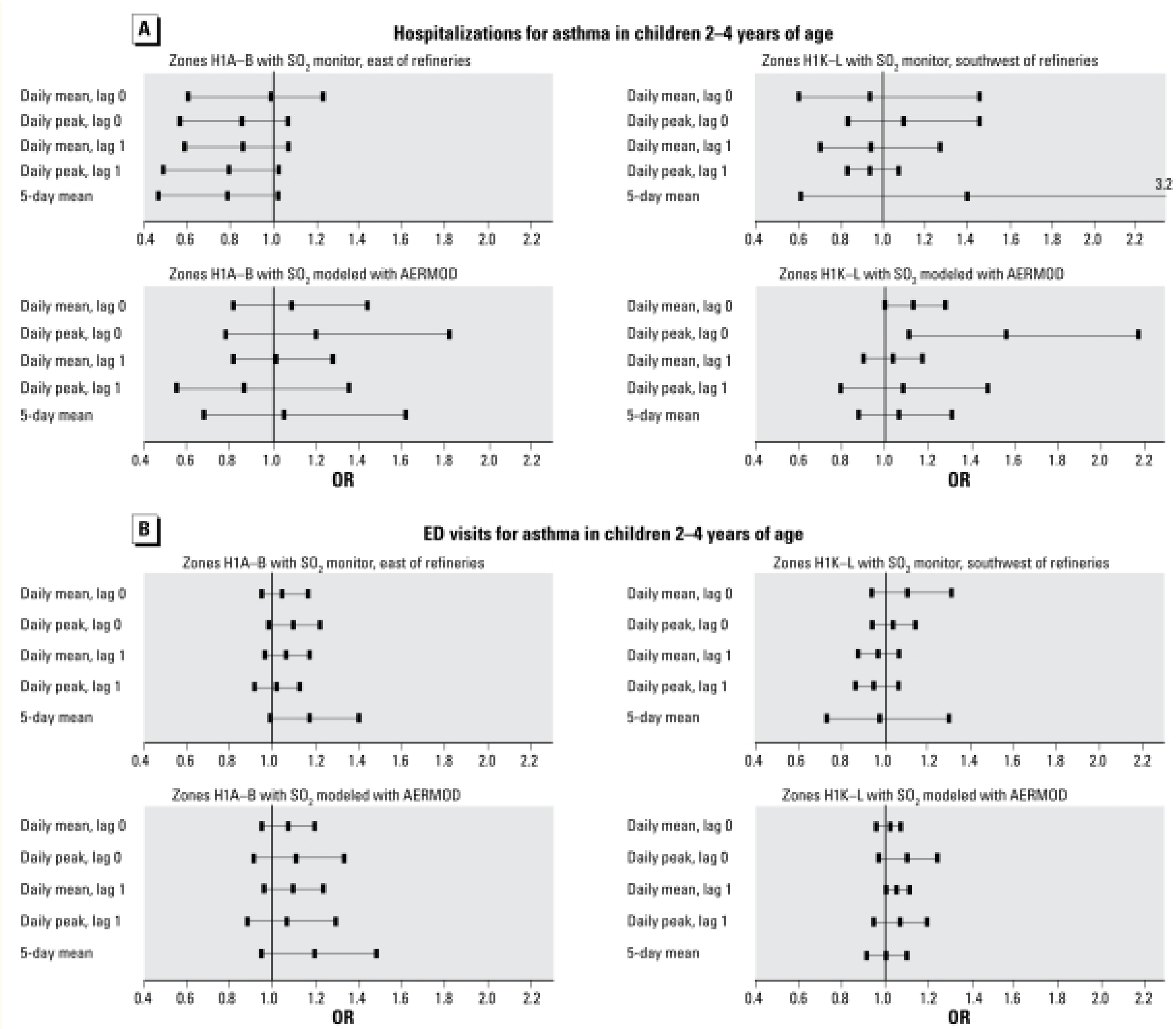
[a]Includes children 2–4 years of age living to the east and to the southwest of the refineries.
[b]ORs are expressed as increments of the interquartile range (see Table 1).
[c]Adjusted for daily air pollutant regional/urban background levels, regional temperature, and relative humidity, evaluated at the same lag period as SO_2 estimates from AERMOD.

Adjusting for daily ambient temperature, relative humidity, and the daily regional/urban background of SO_2, O_3, and NO_2 had little influence on the associations observed between SO_2 levels from refinery stack emissions and ED visits and hospitalizations (Table 2). Adjustment for the regional/urban background of

SO_2 “overcontrolled” for industrial SO_2 stack emissions, given its correlation with AERMOD SO_2 levels: The “background” of SO_2 was the ambient air pollutant most correlated to AERMOD estimates, but even this correlation was only moderate (AERMOD daily mean SO_2 estimates of all postal codes and daily mean background SO_2 levels, $r = 0.30$). Adjustment for the daily regional/urban background of $PM_{2.5}$ also had little influence on the associations observed. We did not adjust the ORs presented in Table 2 for $PM_{2.5}$ levels because measurements were missing for 1996 and 1997.

Figure 3 presents the adjusted associations between the SO_2 levels, measured or estimated with AERMOD, for the FSAs located to the east (H1A and H1B) and to the southwest (H1K and H1L) of the refineries, for the different exposure variables and lags, and hospitalizations and ED visits for asthma in children. The associations between SO_2 levels from fixed monitoring sites and hospitalizations for asthma in children do not show consistent evidence for adverse effects. Analyses with SO_2 levels modeled with AERMOD show that peak levels at lag 0 are associated with hospitalizations for asthma in children to the east but mostly to the southwest of refineries. Inconsistent results obtained with SO_2 levels measured or estimated with AERMOD may be attributable to the small number of hospitalizations of children in these four FSAs (n = 122 east and n = 141 southwest of refineries). For ED visits, ORs derived using SO_2 levels from the fixed monitoring sites or estimated with AERMOD followed similar tendencies only in the FSAs located to the east of the refineries (H1A and H1B): There were elevated ORs which were somewhat more pronounced for daily peak at lag 0 and for the 5-day mean SO_2 levels (Figure 3). For example, the OR for visiting an ED for asthma, for the interquartile range in the peak SO_2 levels (23 ppb) measured at the fixed site at lag 0, is 1.09 (95% CI, 0.98–1.21) for children living to the east of the refineries (Figure 3B, top left). For these children, the OR for visiting an ED for asthma for an interquartile range in the peak SO_2 levels estimated with AERMOD at lag 0 (32 ppb) is 1.10 (95% CI, 0.91–1.33; Figure 3B, bottom left).



[Figure 3](#)

Adjusted associations between SO_2 measurements at fixed-site monitors (located to the east and southwest of refineries) or SO_2 concentrations estimated with AERMOD, and hospitalizations (*A*) and ED visits (*B*) for asthma in children 2–4 years of age living near (to the southwest or east) of the refineries on the Montreal Island, between 1996 and 2004. We adjusted for daily ambient temperature, relative humidity, and daily regional/urban background of SO_2, O_3, and NO_2. ORs are expressed as increments of the interquartile range ([Table 1](#)). The SO_2 measurement site used to assess health risks in the postal areas H1K and H1L is farther away from refineries than is the monitoring site used for H1A and H1B (see [Figure 1](#)).

Go to:

Discussion

In this study we assessed the risk of asthma episodes in children exposed at their residence to SO_2 stack emissions from a refinery point source, using a case–crossover design. This is the first use of this design to assess the risks associated with point source emissions. The use of such a design allowed us to address the effects of short-term exposures. The study shows a modest association of same-day SO_2 levels with asthma ED visits and hospitalizations among children living near refineries. Risks appear more pronounced for daily SO_2 peak levels than for mean levels.

Little information is available to compare the above results on risks of childhood asthma episodes associated with SO_2 from a point source, because most studies of SO_2 and asthma have been performed in urban areas with the aim of establishing relationships between daily SO_2 levels and asthma episodes (e.g., Hajat et al. 1999; Lee et al. 2006; Lin et al. 2005; Schildcrout et al. 2006; Sunyer et al. 1997; Wong et al. 2001). Nonetheless, short lags have been demonstrated in a number of studies on asthma episodes related to other air pollutants such as $PM_{2.5}$ (U.S. EPA 2004). The results of our epidemiologic assessment are also concordant with those of experimental studies where exercising humans were exposed on a short-term basis to high levels of SO_2. Such studies have shown that some asthmatics experience change in pulmonary functions and respiratory symptoms after a peak exposure as short as 10 min (Carlisle and Sharp 2001).

Studies that noted a positive association between ED visits or hospitalizations for asthma and acute exposure to SO_2 have usually reported risks < 10% per SO_2 inter-quartile range of magnitude similar to or greater than in our study (e.g., Hajat et al. 1999; Lee et al. 2002; Luginaah et al. 2005; Sunyer et al. 1997; Wong et al. 2001). Such risks are similar to what we observed in the present study for ED visits; however, relative risks for hospitalizations appeared greater in the present study.

In this study, we estimated exposure to refinery stack emissions using both SO_2 fixed-site measurements and the AERMOD atmospheric dispersion model. SO_2 fixed-site monitors may not adequately represent exposure to refinery stacks emissions if located too far from the emission source. In our study, associations between ED visits and SO_2 from the fixed monitor located to the east of the refineries provided results similar to those with AERMOD estimates. On the other hand, associations between ED visits and exposures represented by the southwest monitor, which is more distant from the residences of interest, diverged with associations with the AERMOD estimates. Dispersion models may be useful to represent point source exposures in areas where there is no local monitor or where monitors are not close enough to appropriately represent exposure to emission sources. However, modeling errors associated with the source information (e.g., monthly emission data to compute daily estimates, use of upper air data from a location hundreds of kilometers away from the study area) and the limitations of the model to represent specific dispersion conditions should not be disregarded. As noted in Table 1, AERMOD SO_2 estimates present lower mean levels than those measured at fixed monitoring sites, because we omitted from the model SO_2 emission sources other than refinery emissions.

Several other limitations are associated with the estimates of SO_2 used in this study. First, SO_2 levels estimated at the residence of children may not adequately represent exposure because children are not always at home. However, children 2–4 years of age are more likely to be present in their neighborhood than are older children who attend school. Second, our SO_2 exposure estimates, which represent expected ambient residential SO_2 levels, may not adequately represent exposure because children are likely to spend most of their time indoors. SO_2 levels are lower indoors because absorption occurs on walls, furniture, and ventilation systems (World Health Organization 2000).

Finally, the associations observed in the present study, if causal, probably represent the effects of short-term exposures to a pollutant mixture, even after statistical control for the urban/regional background of pollutant levels. Indeed, the SO_2 exposure estimates used in this study are likely correlated with other stack and/or fugitive refinery emissions such as $PM_{2.5}$ and volatile organic compounds. From a policy perspective, we need to better disentangle their effects to determine which emissions to control.

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Conclusion

We initiated this study to clarify whether higher hospital admission rates for respiratory problems for children in the East End of Montreal were related to short-term variations in refinery emissions. Our results suggest that same-day SO_2 peak levels, rather than daily mean levels, were associated with asthmatic episodes in young children who lived in close proximity to the refineries.

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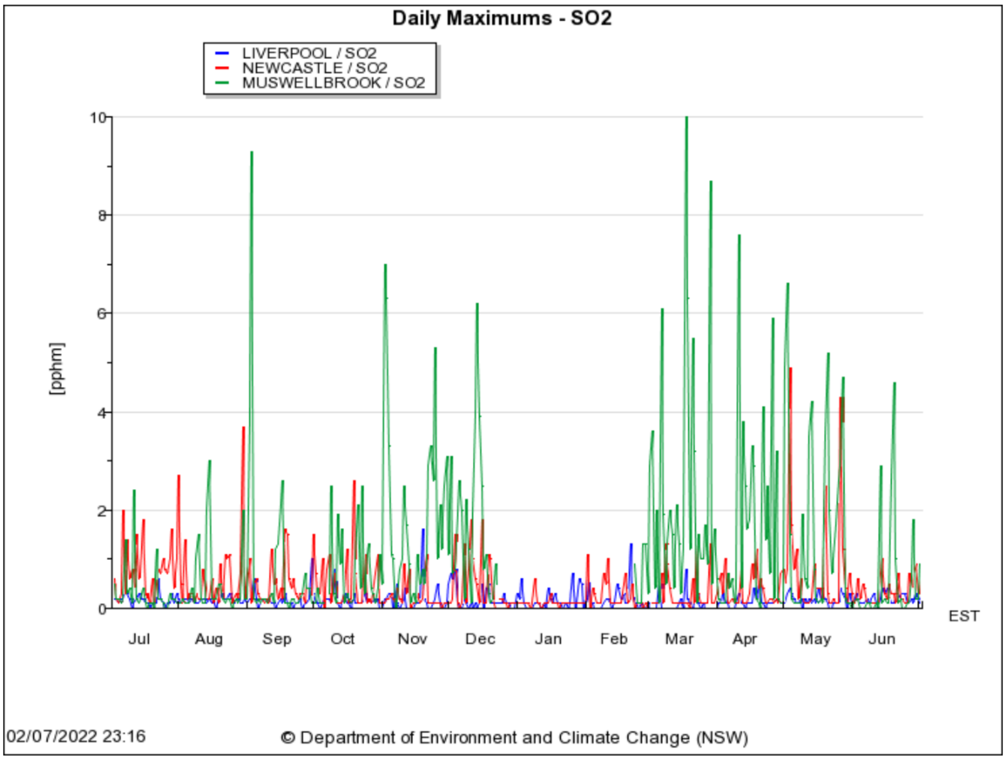
Footnotes

We thank F. Tessier, G. Morneau, Y. Bourassa, and Y. Otis for technical support, Environment Canada and the City of Montreal for air pollution and meteorologic data, and the Montreal refineries that provided emission data.

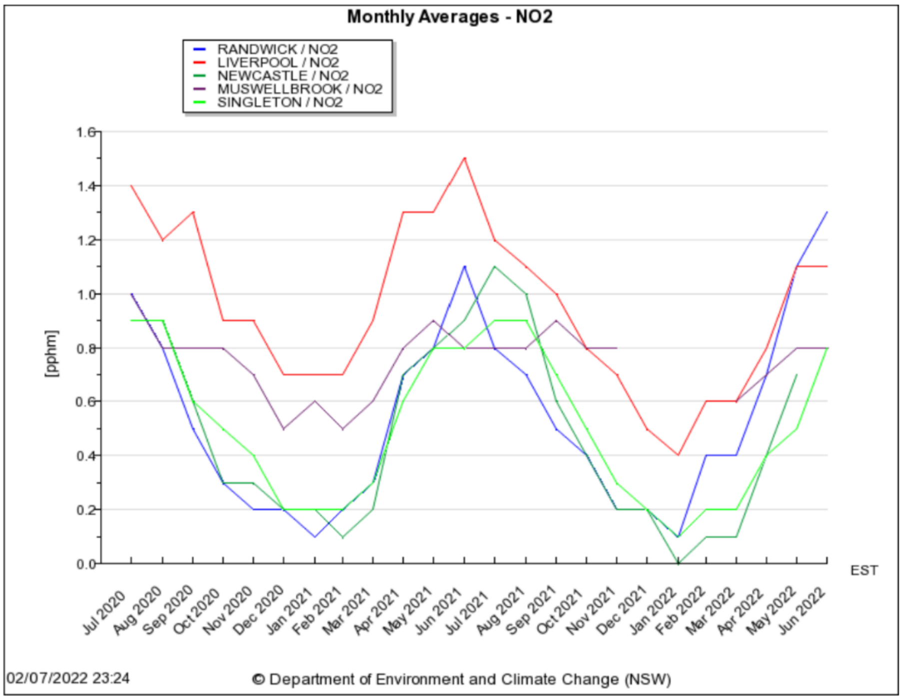
This study was funded by the Quebec Ministry of Health and Social Services and by the Biostatistics and Epidemiology Division of Health Canada.

4.

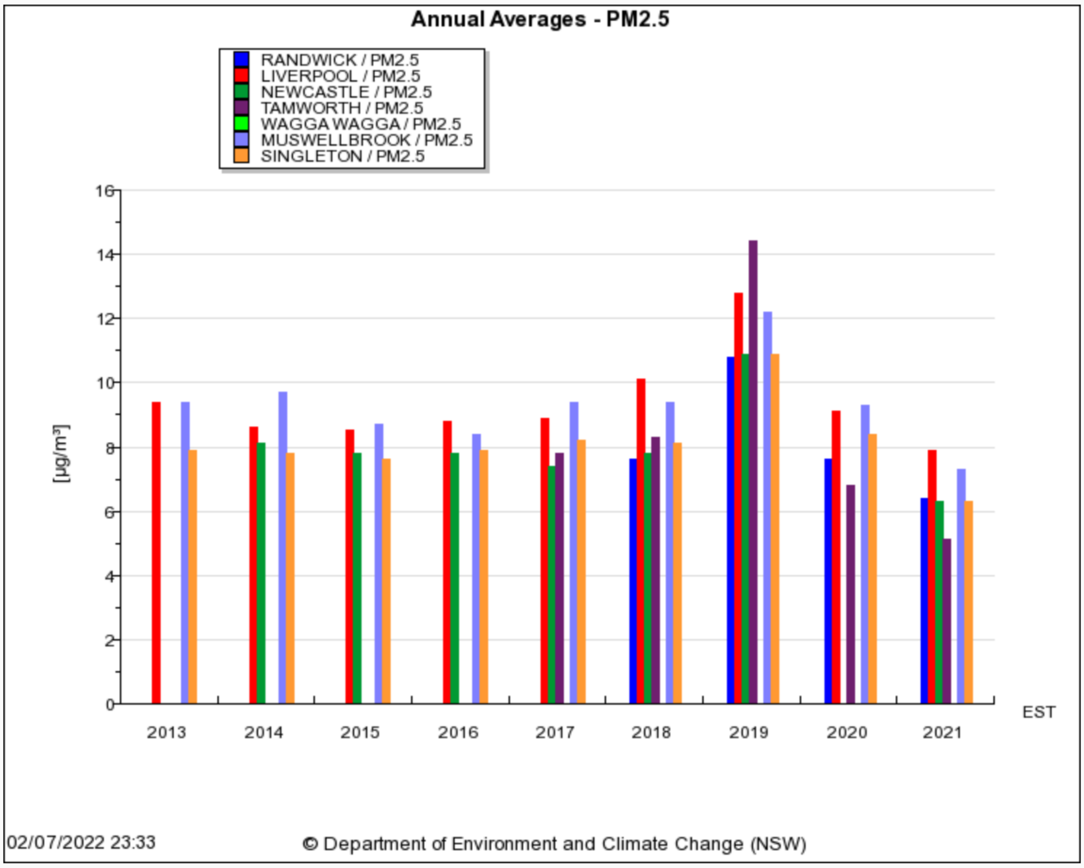
NSW EPA Data Download Facility results



Note, SO2 monitoring not available for Muswellbrook Dec-Feb. No valid reason given by EPA.



Note, NO2 monitoring not available for Muswellbrook Dec 21 - Feb 22. No valid reason given by EPA.



5.

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IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-3 Total pages: 35 SPM.A: Introduction This Summary for Policymakers (SPM) presents key findings of the Working Group II (WGII) contribution to the Sixth Assessment Report (AR6) of the IPCC1 . The report builds on the WGII contribution to the Fifth Assessment Report (AR5) of the IPCC, three Special Reports2 , and the Working Group I (WGI) contribution to the AR6 cycle. This report recognizes the interdependence of climate, ecosystems and biodiversity3 , and human societies (Figure SPM.1) and integrates knowledge more strongly across the natural, ecological, social and economic sciences than earlier IPCC assessments. The assessment of climate change impacts and risks as well as adaptation is set against concurrently unfolding non-climatic global trends e.g., biodiversity loss, overall unsustainable consumption of natural resources, land and ecosystem degradation, rapid urbanisation, human demographic shifts, social and economic inequalities and a pandemic. The scientific evidence for each key finding is found in the 18 chapters of the underlying report and in the 7 cross-chapter papers as well as the integrated synthesis presented in the Technical Summary (hereafter TS) and referred to in curly brackets {}. Based on scientific understanding, key findings can be formulated as statements of fact or associated with an assessed level of confidence using the IPCC calibrated language4 . The WGII Global to Regional Atlas (Annex I) facilitates exploration of key synthesis findings across the WGII regions. 1 Decision IPCC/XLVI-3, The assessment covers scientific literature accepted for publication by 1 September 2021. 2 The three Special Reports are: 'Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (SR1.5)'; 'Climate Change and Land. An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCCL)'; 'IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC)' 3 Biodiversity: Biodiversity or biological diversity means the variability among living organisms from all sources including, among other things, terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems. 4 Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, e.g., medium confidence. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99-100% probability, very likely 90-100%, likely 66-100%, as likely as not 33-66%, unlikely 0-33%, very unlikely 0-10%, exceptionally unlikely 0-1%. Assessed likelihood is typeset in italics, e.g., very likely. This is consistent with AR5 and the other AR6 Reports. APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-4 Total pages: 35 Figure SPM.1: This report has a strong focus on the interactions among the coupled systems climate, ecosystems (including their biodiversity) and human society. These interactions are the basis of emerging risks from climate change, ecosystem degradation and biodiversity loss and, at the same time, offer opportunities for the future. (a) Human society causes climate change. Climate change, through hazards, exposure and vulnerability generates impacts and risks that can surpass limits to adaptation and result in losses and damages. Human society can adapt to, maladapt and mitigate climate change, ecosystems can adapt and mitigate within limits. Ecosystems and their biodiversity provision livelihoods and ecosystem services. Human society impacts ecosystems and can restore and conserve them. (b) Meeting the objectives of climate resilient development thereby supporting human, ecosystem and planetary health, as well as human well-being, requires society and ecosystems to move over (transition) to a more resilient state. The recognition of climate risks can strengthen adaptation and mitigation actions and transitions that reduce risks. Taking action is enabled by governance, finance, knowledge and capacity building, technology and catalysing conditions. Transformation entails system transitions strengthening the resilience of ecosystems and society (Section D). In a) arrow colours represent principle human society interactions (blue), ecosystem (including biodiversity) interactions (green) and the impacts of climate change and human activities, including losses and damages, under continued climate change (red). In b) arrow colours represent human system interactions (blue), ecosystem (including biodiversity) interactions (green) and reduced impacts from climate change and human activities (grey). {1.2, Figure 1.2, Figure TS.1} The concept of risk is central to all three AR6 Working Groups. A risk framing and the concepts of adaptation, vulnerability, exposure, resilience, equity and justice, and transformation provide alternative, overlapping, complementary, and widely used entry points to the literature assessed in this WGII report. Across all three AR6 working groups, risk5 provides a framework for understanding the increasingly severe, interconnected and often irreversible impacts of climate change on ecosystems, biodiversity, and human systems; differing impacts across regions, sectors and communities; and how to best reduce adverse 5 Risk is defined as the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-5 Total pages: 35 consequences for current and future generations. In the context of climate change, risk can arise from the dynamic interactions among climate-related hazards6 (see Working Group I), the exposure7 and vulnerability8 of affected human and ecological systems. The risk that can be introduced by human responses to climate change is a new aspect considered in the risk concept. This report identifies 127 key risks9 . {1.3, 16.5} The vulnerability of exposed human and natural systems is a component of risk, but also, independently, an important focus in the literature. Approaches to analysing and assessing vulnerability have evolved since previous IPCC assessments. Vulnerability is widely understood to differ within communities and across societies, regions and countries, also changing through time. Adaptation10 plays a key role in reducing exposure and vulnerability to climate change. Adaptation in ecological systems includes autonomous adjustments through ecological and evolutionary processes. In human systems, adaptation can be anticipatory or reactive, as well as incremental and/ or transformational. The latter changes the fundamental attributes of a social-ecological system in anticipation of climate change and its impacts. Adaptation is subject to hard and soft limits11. Resilience12 in the literature has a wide range of meanings. Adaptation is often organized around resilience as bouncing back and returning to a previous state after a disturbance. More broadly the term describes not just the ability to maintain essential function, identity and structure, but also the capacity for transformation. This report recognises the value of diverse forms of knowledge such as scientific, as well as Indigenous knowledge and local knowledge in understanding and evaluating climate adaptation processes and actions to reduce risks from human-induced climate change. AR6 highlights adaptation solutions which are effective, feasible13, and conform to principles of justice14. The term climate justice, while used in different ways in different contexts by different communities, generally includes three principles: distributive justice which refers to the allocation of burdens and benefits among individuals, nations and generations; procedural justice which refers to who decides and participates in decision-making; and recognition which entails basic respect and robust engagement with and fair consideration of diverse cultures and perspectives. 6 Hazard is defined as the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources. Physical climate conditions that may be associated with hazards are assessed in Working Group I as climatic impact-drivers. 7 Exposure is defined as the presence of people; livelihoods; species or ecosystems; environmental functions, services and resources; infrastructure; or economic, social or cultural assets in places and settings that could be adversely affected. 8 Vulnerability in this report is defined as the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. 9 Key risks have potentially severe adverse consequences for humans and social-ecological systems resulting from the interaction of climate related hazards with vulnerabilities of societies and systems exposed. 10 Adaptation is defined, in human systems, as the process of adjustment to actual or expected climate and its effects in order to moderate harm or take advantage of beneficial opportunities. In natural systems, adaptation is the process of adjustment to actual climate and its effects; human intervention may facilitate this. 11 Adaptation Limits: The point at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions. • Hard adaptation limit - No adaptive actions are possible to avoid intolerable risks. • Soft adaptation limit - Options may exist but are currently not available to avoid intolerable risks through adaptive action. 12 Resilience in this report is defined as the capacity of social, economic and ecosystems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure as well as biodiversity in case of ecosystems while also maintaining the capacity for adaptation, learning and transformation. Resilience is a positive attribute when it maintains such a capacity for adaptation, learning, and/or transformation. 13 Feasibility refers to the potential for an adaptation option to be implemented. 14 Justice is concerned with setting out the moral or legal principles of fairness and equity in the way people are treated, often based on the ethics and values of society. Social justice comprises just or fair relations within society that seek to address the distribution of wealth, access to resources, opportunity and support according to principles of justice and fairness. Climate justice comprises justice that links development and human rights to achieve a rights-based approach to addressing climate change. APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-6 Total pages: 35 Effectiveness refers to the extent to which an action reduces vulnerability and climate-related risk, increases resilience, and avoids maladaptation15. This report has a particular focus on transformation16 and system transitions in energy; land, ocean, coastal and freshwater ecosystems; urban, rural and infrastructure; and industry and society. These transitions make possible the adaptation required for high levels of human health and wellbeing, economic and social resilience, ecosystem health17, and planetary health18 (Figure SPM.1). These system transitions are also important for achieving the low global warming levels (WGIII) that would avoid many limits to adaptation11. The report also assesses economic and non-economic losses and damages19. This report labels the process of implementing mitigation and adaptation together in support of sustainable development for all as climate resilient development20. [START BOX SPM.1 HERE] Box SPM.1: AR6 Common Climate Dimensions, Global Warming Levels and Reference Periods Assessments of climate risks consider possible future climate change, societal development and responses. This report assesses literature including that based on climate model simulations that are part of the fifth and sixth Coupled Model Intercomparison Project phase (CMIP5, CMIP6) of the World Climate Research Programme. Future projections are driven by emissions and/or concentrations from illustrative Representative Concentration Pathways (RCPs)21 and Shared Socio-economic Pathways (SSPs)22 scenarios, respectively23. Climate impacts literature is based primarily on climate projections assessed in AR5 or earlier, or assumed global warming levels, though some recent impacts literature uses newer projections based on the CMIP6 exercise. Given differences in the impacts literature regarding socioeconomic details and assumptions, WGII chapters contextualize impacts with respect to exposure, vulnerability and adaptation as appropriate for their literature, this includes assessments regarding sustainable development and climate resilient development. There are many emissions and socioeconomic pathways that are consistent with a given global warming outcome. These represent a broad range of possibilities as available in the literature assessed that affect future climate change exposure and vulnerability. Where available, WGII also assesses literature that is based on an integrative SSP-RCP framework where climate projections obtained under the RCP scenarios are analysed against the backdrop of various illustrative SSPs22. The WGII assessment combines multiple lines of evidence including impacts modelling driven by climate projections, observations, and process understanding. {1.2, 16.5, 18.2, CCB CLIMATE, WGI SPM.C, WGI Box SPM.1, WGI 1.6, WGI Ch.12, AR5 WGI} 15 Maladaptation refers to actions that may lead to increased risk of adverse climate-related outcomes, including via increased greenhouse gas emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, or diminished welfare, now or in the future. Most often, maladaptation is an unintended consequence. 16 Transformation refers to a change in the fundamental attributes of natural and human systems. 17 Ecosystem health: a metaphor used to describe the condition of an ecosystem, by analogy with human health. Note that there is no universally accepted benchmark for a healthy ecosystem. Rather, the apparent health status of an ecosystem is judged on the ecosystem's resilience to change, with details depending upon which metrics (such as species richness and abundance) are employed in judging it and which societal aspirations are driving the assessment. 18 Planetary health: a concept based on the understanding that human health and human civilisation depend on ecosystem health and the wise stewardship of ecosystems. 19 In this report, the term 'losses and damages' refers to adverse observed impacts and/or projected risks and can be economic and/or non-economic. 20 In the WGII report, climate resilient development refers to the process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development for all. 21 RCP-based scenarios are referred to as RCPy, where 'y' refers to the level of radiative forcing (in watts per square meter, or W m-2) resulting from the scenario in the year 2100. 22 SSP-based scenarios are referred to as SSPx-y, where 'SSPx' refers to the Shared Socio-economic Pathway describing the socioeconomic trends underlying the scenarios, and 'y' refers to the level of radiative forcing (in watts per square meter, or W m-2) resulting from the scenario in the year 2100. 23 IPCC is neutral with regard to the assumptions underlying the SSPs, which do not cover all possible scenarios. Alternative scenarios may be considered or developed. APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-7 Total pages: 35 A common set of reference years and time periods are adopted for assessing climate change and its impacts and risks: the reference period 1850–1900 approximates pre-industrial global surface temperature, and three future reference periods cover the near-term (2021–2040), mid-term (2041–2060) and long-term (2081–2100). {CCB CLIMATE} Common levels of global warming relative to 1850-1900 are used to contextualize and facilitate analysis, synthesis and communication of assessed past, present and future climate change impacts and risks considering multiple lines of evidence. Robust geographical patterns of many variables can be identified at a given level of global warming, common to all scenarios considered and independent of timing when the global warming level is reached. {16.5, CCB CLIMATE, WGI 4.2, WGI CCB11.1, WGI Box SPM.1} WGI assessed increase in global surface temperature is 1.09 [0.95 to 1.20]24 °C in 2011-2020 above 1850- 1900. The estimated increase in global surface temperature since AR5 is principally due to further warming since 2003–2012 (+0.19 [0.16 to 0.22] °C).25 Considering all five illustrative scenarios assessed by WGI, there is at least a greater than 50% likelihood that global warming will reach or exceed 1.5°C in the near-term, even for the very low greenhouse gas emissions scenario26. {WGI CCB 2.3, WGI SPM A1.2, WGI SPM B1.3, WGI Table SPM.1} [END BOX SPM.1 HERE] SPM.B: Observed and Projected Impacts and Risks Since AR5, the knowledge base on observed and projected impacts and risks generated by climate hazards, exposure and vulnerability has increased with impacts attributed to climate change and key risks identified across the report. Impacts and risks are expressed in terms of their damages, harms, economic, and noneconomic losses. Risks from observed vulnerabilities and responses to climate change are highlighted. Risks are projected for the near-term (2021-2040), the mid (2041-2060) and long term (2081-2100), at different global warming levels and for pathways that overshoot 1.5°C global warming level for multiple decades27. Complex risks result from multiple climate hazards occurring concurrently, and from multiple risks interacting, compounding overall risk and resulting in risks transmitting through interconnected systems and across regions. Observed Impacts from Climate Change SPM.B.1 Human-induced climate change, including more frequent and intense extreme events, has caused widespread adverse impacts and related losses and damages to nature and people, beyond natural climate variability. Some development and adaptation efforts have reduced vulnerability. Across sectors and regions the most vulnerable people and systems are observed to be disproportionately affected. The rise in weather 24 In the WGI report, square brackets [x to y] are used to provide the assessed very likely range, or 90% interval. 25 Since AR5, methodological advances and new datasets have provided a more complete spatial representation of changes in surface temperature, including in the Arctic. These and other improvements have also increased the estimate of global surface temperature change by approximately 0.1°C, but this increase does not represent additional physical warming since AR5. 26 Global warming of 1.5°C relative to 1850–1900 would be exceeded during the 21st century under the intermediate, high and very high greenhouse gas emissions scenarios considered in this report (SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively). Under the five illustrative scenarios, in the near term (2021–2040), the 1.5°C global warming level is very likely to be exceeded under the very high greenhouse gas emissions scenario (SSP5-8.5), likely to be exceeded under the intermediate and high greenhouse gas emissions scenarios (SSP2-4.5 and SSP3-7.0), more likely than not to be exceeded under the low greenhouse gas emissions scenario (SSP1-2.6) and more likely than not to be reached under the very low greenhouse gas emissions scenario (SSP1-1.9). Furthermore, for the very low greenhouse gas emissions scenario (SSP1-1.9), it is more likely than not that global surface temperature would decline back to below 1.5°C toward the end of the 21st century, with a temporary overshoot of no more than 0.1°C above 1.5°C global warming. 27 Overshoot: In this report, pathways that first exceed a specified global warming level (usually 1.5°C, by more than 0.1°C), and then return to or below that level again before the end of a specified period of time (e.g., before 2100). Sometimes the magnitude and likelihood of the overshoot is also characterized. The overshoot duration can vary from at least one decade up to several decades. APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-8 Total pages: 35 and climate extremes has led to some irreversible impacts as natural and human systems are pushed beyond their ability to adapt. (high confidence) (Figure SPM.2) {1.3, 2.3, 2.4, 2.6, 3.3, 3.4, 3.5, 4.2, 4.3, 5.2, 5.12, 6.2, 7.2, 8.2, 9.6, 9.8, 9.10, 9.11, 10.4, 11.3, 12.3, 12.4, 13.10, 14.4, 14.5, 15.3, 16.2, CCP1.2, CCP3.2, CCP4.1, CCP5.2, CCP6.2, CCP7.2, CCP7.3, CCB EXTREMES, CCB ILLNESS, CCB SLR, CCB NATURAL, CCB DISASTER, CCB MIGRATE, Figure TS.5, TS B1 SPM.B.1.1 Widespread, pervasive impacts to ecosystems, people, settlements, and infrastructure have resulted from observed increases in the frequency and intensity of climate and weather extremes, including hot extremes on land and in the ocean, heavy precipitation events, drought and fire weather (high confidence). Increasingly since AR5, these observed impacts have been attributed28 to human-induced climate change particularly through increased frequency and severity of extreme events. These include increased heatrelated human mortality (medium confidence), warm-water coral bleaching and mortality (high confidence), and increased drought related tree mortality (high confidence). Observed increases in areas burned by wildfires have been attributed to human-induced climate change in some regions (medium to high confidence). Adverse impacts from tropical cyclones, with related losses and damages19, have increased due to sea level rise and the increase in heavy precipitation (medium confidence). Impacts in natural and human systems from slow-onset processes29 such as ocean acidification, sea level rise or regional decreases in precipitation have also been attributed to human induced climate change (high confidence). {1.3, 2.3, 2.4, 2.5, 3.2, 3.4, 3.5, 3.6, 4.2, 5.2, 5.4, 5.6, 5.12, 7.2, 9.6, 9.8, 9.7, 9.8, 9.11, 11.3, Box 11.1, Box 11.2, Table 11.9, 12.3, 12.4, 13.3, 13.5, 13.10, 14.2,14.5, 15.7, 15.8, 16.2, Box CCP5.1, CCP1.2, CCP2.2, CCP7.3, CCB EXTREME, CCB ILLNESS, CCB DISASTER, WG1 9, WGI 11.3-11.8, WGI SPM.3, SROCC Ch. 4} SPM.B.1.2 Climate change has caused substantial damages, and increasingly irreversible losses, in terrestrial, freshwater and coastal and open ocean marine ecosystems (high confidence). The extent and magnitude of climate change impacts are larger than estimated in previous assessments (high confidence). Widespread deterioration of ecosystem structure and function, resilience and natural adaptive capacity, as well as shifts in seasonal timing have occurred due to climate change (high confidence), with adverse socioeconomic consequences (high confidence). Approximately half of the species assessed globally have shifted polewards or, on land, also to higher elevations (very high confidence). Hundreds of local losses of species have been driven by increases in the magnitude of heat extremes (high confidence), as well as mass mortality events on land and in the ocean (very high confidence) and loss of kelp forests (high confidence). Some losses are already irreversible, such as the first species extinctions driven by climate change (medium confidence). Other impacts are approaching irreversibility such as the impacts of hydrological changes resulting from the retreat of glaciers, or the changes in some mountain (medium confidence) and Arctic ecosystems driven by permafrost thaw (high confidence). (Figure SPM.2a). {2.3, 2.4, 3.4, 3.5, 4.2, 4.3, 4.5, 9.6, 10.4, 11.3, 12.3, 12.8, 13.3, 13.4, 13.10, 14.4, 14.5, 14.6, 15.3, 16.2, CCP1.2; CCP3.2, CCP4.1, CCP5.2, CCP6.1, CCP6.2, CCP7.2, CCP7.3, CCP5.2, Figure CCP5.4, CCB PALEO, CCB EXTREMES, CCB ILLNESS, CCB SLR, CCB NATURAL, CCB MOVING PLATE, Figure TS.5, TS B1, SROCC 2.3} 28 Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with an assessment of confidence. {Annex II Glossary, CWGB ATTRIB} 29 Impacts of climate change are caused by slow onset and extreme events. Slow onset events are described among the climatic-impact drivers of the WGI AR6 and refer to the risks and impacts associated with e.g., increasing temperature means, desertification, decreasing precipitation, loss of biodiversity, land and forest degradation, glacial retreat and related impacts, ocean acidification, sea level rise and salinization (https://interactive-atlas.ipcc.ch). APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-9 Total pages: 35 Figure SPM.2: Observed global and regional impacts on ecosystems and human systems attributed to climate change. Confidence levels reflect uncertainty in attribution of the observed impact to climate change. Global assessments focus on large studies, multi-species, meta-analyses and large reviews. For that reason they can be assessed with higher confidence than regional studies, which may often rely on smaller studies that have more limited data. Regional assessments consider evidence on impacts across an entire region and do not focus on any country in particular. (a) Climate change has already altered terrestrial, freshwater and ocean ecosystems at global scale, with multiple impacts evident at regional and local scales where there is sufficient literature to make an assessment. Impacts are evident on ecosystem structure, species geographic ranges and timing of seasonal life cycles (phenology) (for methodology and detailed references to chapters and cross-chapter papers see SMTS.1 and SMTS.1.1). (b) Climate change has already had diverse adverse impacts on human systems, including on water security and food production, health and well-being, and cities, settlements and infrastructure. The + and – symbols indicate the direction of observed impacts, with a – denoting APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-10 Total pages: 35 an increasing adverse impact and a ± denoting that, within a region or globally, both adverse and positive impacts have been observed (e.g., adverse impacts in one area or food item may occur with positive impacts in another area or food item). Globally, '–' denotes an overall adverse impact; 'Water scarcity' considers, e.g., water availability in general, groundwater, water quality, demand for water, drought in cities. Impacts on food production were assessed by excluding non-climatic drivers of production increases; Global assessment for agricultural production is based on the impacts on global aggregated production; 'Reduced animal and livestock health and productivity' considers, e.g., heat stress, diseases, productivity, mortality; ‘Reduced fisheries yields and aquaculture production’ includes marine and freshwater fisheries/production; ‘Infectious diseases’ include, e.g., water-borne and vector-borne diseases; ‘Heat, malnutrition and other’ considers, e.g., human heat-related morbidity and mortality, labour productivity, harm from wildfire, nutritional deficiencies; ‘Mental health’ includes impacts from extreme weather events, cumulative events, and vicarious or anticipatory events; ‘Displacement’ assessments refer to evidence of displacement attributable to climate and weather extremes; ‘Inland flooding and associated damages’ considers, e.g., river overflows, heavy rain, glacier outbursts, urban flooding; ‘Flood/storm induced damages in coastal areas’ include damages due to, e.g., cyclones, sea level rise, storm surges. Damages by key economic sectors are observed impacts related to an attributable mean or extreme climate hazard or directly attributed. Key economic sectors include standard classifications and sectors of importance to regions (for methodology and detailed references to chapters and cross-chapter papers see SMTS.1 and SMTS.1.2). SPM.B.1.3 Climate change including increases in frequency and intensity of extremes have reduced food and water security, hindering efforts to meet Sustainable Development Goals (high confidence). Although overall agricultural productivity has increased, climate change has slowed this growth over the past 50 years globally (medium confidence), related negative impacts were mainly in mid- and low latitude regions but positive impacts occurred in some high latitude regions (high confidence). Ocean warming and ocean acidification have adversely affected food production from shellfish aquaculture and fisheries in some oceanic regions (high confidence). Increasing weather and climate extreme events have exposed millions of people to acute food insecurity30 and reduced water security, with the largest impacts observed in many locations and/or communities in Africa, Asia, Central and South America, Small Islands and the Arctic (high confidence). Jointly, sudden losses of food production and access to food compounded by decreased diet diversity have increased malnutrition in many communities (high confidence), especially for Indigenous Peoples, small-scale food producers and low-income households (high confidence), with children, elderly people and pregnant women particularly impacted (high confidence). Roughly half of the world’s population currently experience severe water scarcity for at least some part of the year due to climatic and non-climatic drivers (medium confidence). (Figure SPM.2b) {3.5, Box 4.1, 4.3, 4.4, 5.2, 5.4, 5.8, 5.9, 5.12, 7.1, 7.2, 9.8, 10.4, 11.3, 12.3, 13.5, 14.4, 14.5, 15.3, 16.2, CCP5.2, CCP6.2} SPM.B.1.4 Climate change has adversely affected physical health of people globally (very high confidence) and mental health of people in the assessed regions (very high confidence). Climate change impacts on health are mediated through natural and human systems, including economic and social conditions and disruptions (high confidence). In all regions extreme heat events have resulted in human mortality and morbidity (very high confidence). The occurrence of climate-related food-borne and water-borne diseases has increased (very high confidence). The incidence of vector-borne diseases has increased from range expansion and/or increased reproduction of disease vectors (high confidence). Animal and human diseases, including zoonoses, are emerging in new areas (high confidence). Water and food-borne disease risks have increased regionally from climate-sensitive aquatic pathogens, including Vibrio spp. (high confidence), and from toxic substances from harmful freshwater cyanobacteria (medium confidence). Although diarrheal diseases have decreased globally, higher temperatures, increased rain and flooding have increased the occurrence of diarrheal diseases, including cholera (very high confidence) and other gastrointestinal infections (high confidence). In assessed regions, some mental health challenges are associated with increasing temperatures (high confidence), trauma from weather and climate extreme events (very high confidence), and loss of livelihoods and culture (high confidence). Increased exposure to wildfire smoke, atmospheric dust, and aeroallergens have been associated with climate-sensitive cardiovascular and respiratory distress (high confidence). Health services have been disrupted by extreme events such as floods (high confidence). {4.3, 5.12, 7.2, Box 7.3, 8.2, 8.3, Figure 8.10, 30

Acute food insecurity can occur at any time with a severity that threatens lives, livelihoods or both, regardless of the causes, context or duration, as a result of shocks risking determinants of food security and nutrition, and used to assess the need for humanitarian action (IPC Global Partners, 2019). APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-11 Total pages: 35 Box 8.6, 9.10, Figure 9.33, Figure 9.34, 10.4, 11.3, 12.3, 13.7, 14.4, 14.5, Figure 14.8, 15.3, 16.2, Table CCP5.1, CCP5.2.5, CCP6.2, Figure CCP6.3, Table CCB ILLNESS.1} SPM.B.1.5 In urban settings, observed climate change has caused impacts on human health, livelihoods and key infrastructure (high confidence). Multiple climate and non-climate hazards impact cities, settlements and infrastructure and sometimes coincide, magnifying damage (high confidence). Hot extremes including heatwaves have intensified in cities (high confidence), where they have also aggravated air pollution events (medium confidence) and limited functioning of key infrastructure (high confidence). Observed impacts are concentrated amongst the economically and socially marginalized urban residents, e.g., in informal settlements (high confidence). Infrastructure, including transportation, water, sanitation and energy systems have been compromised by extreme and slow-onset events, with resulting economic losses, disruptions of services and impacts to wellbeing (high confidence). {4.3, 6.2, 7.1, 7.2, 9.9, 10.4, 11.3, 12.3, 13.6, 14.5, 15.3, CCP2.2, CCP4.2, CCP5.2} SPM.B.1.6 Overall adverse economic impacts attributable to climate change, including slow-onset and extreme weather events, have been increasingly identified (medium confidence). Some positive economic effects have been identified in regions that have benefited from lower energy demand as well as comparative advantages in agricultural markets and tourism (high confidence). Economic damages from climate change have been detected in climate-exposed sectors, with regional effects to agriculture, forestry, fishery, energy, and tourism (high confidence), and through outdoor labour productivity (high confidence). Some extreme weather events, such as tropical cyclones, have reduced economic growth in the short-term (high confidence). Non-climatic factors including some patterns of settlement, and siting of infrastructure have contributed to the exposure of more assets to extreme climate hazards increasing the magnitude of the losses (high confidence). Individual livelihoods have been affected through changes in agricultural productivity, impacts on human health and food security, destruction of homes and infrastructure, and loss of property and income, with adverse effects on gender and social equity (high confidence). {3.5, 4.2, 5.12, 6.2, 7.2, 8.2, 9.6, 10.4, 13.10, 14.5, Box 14.6, 16.2, Table 16.5, 18.3, CCP6.2, CCB GENDER, CWGB ECONOMICS} SPM.B.1.7 Climate change is contributing to humanitarian crises where climate hazards interact with high vulnerability (high confidence). Climate and weather extremes are increasingly driving displacement in all regions (high confidence), with small island states disproportionately affected (high confidence). Flood and drought-related acute food insecurity and malnutrition have increased in Africa (high confidence) and Central and South America (high confidence). While non-climatic factors are the dominant drivers of existing intrastate violent conflicts, in some assessed regions extreme weather and climate events have had a small, adverse impact on their length, severity or frequency, but the statistical association is weak (medium confidence). Through displacement and involuntary migration from extreme weather and climate events, climate change has generated and perpetuated vulnerability (medium confidence). {4.2, 4.3, 5.4, 7.2, 9.8, Box 9.9, Box 10.4, 12.3, 12.5, CCB MIGRATE, CCB DISASTER, 16.2} Vulnerability and Exposure of Ecosystems and People SPM.B.2 Vulnerability of ecosystems and people to climate change differs substantially among and within regions (very high confidence), driven by patterns of intersecting socio-economic development, unsustainable ocean and land use, inequity, marginalization, historical and ongoing patterns of inequity such as colonialism, and governance31 (high confidence). Approximately 3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate change (high confidence). A high proportion of species is vulnerable to climate change (high confidence). Human and ecosystem vulnerability are interdependent (high confidence). Current unsustainable development patterns are increasing exposure of ecosystems and people to climate hazards (high confidence). {2.3, 2.4, 3.5, 4.3, 6.2, 8.2, 8.3, 9.4, 9.7, 10.4, 12.3, 14.5, 15.3, CCP5.2, CCP6.2, CCP7.3, CCP7.4, CCB GENDER} 31 Governance: The structures, processes and actions through which private and public actors interact to address societal goals. This includes formal and informal institutions and the associated norms, rules, laws and procedures for deciding, managing, implementing and monitoring policies and measures at any geographic or political scale, from global to local. APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-12 Total pages: 35 SPM.B.2.1 Since AR5 there is increasing evidence that degradation and destruction of ecosystems by humans increases the vulnerability of people (high confidence). Unsustainable land-use and land cover change, unsustainable use of natural resources, deforestation, loss of biodiversity, pollution, and their interactions, adversely affect the capacities of ecosystems, societies, communities and individuals to adapt to climate change (high confidence). Loss of ecosystems and their services has cascading and long-term impacts on people globally, especially for Indigenous Peoples and local communities who are directly dependent on ecosystems, to meet basic needs (high confidence). {2.3, 2.5, 2.6, 3.5, 3.6, 4.2, 4.3, 4.6, 5.1, 5.4, 5.5, 5.7, 5.8, 7.2, 8.1, 8.2, 8.3, 8.4, 8.5, 9.6, 10.4, 11.3, 12.2, 12.5. 13.8, 14.4, 14.5, 15.3, CCP1.2, CCP1.3, CCP2.2, CCP3, CCP4.3, CCP5.2, CCP6.2, CCP7.2, CCP7.3, CCP7.4, CCB ILLNESS, CCB MOVING PLATE, CCB SLR} SPM.B.2.2 Non-climatic human-induced factors exacerbate current ecosystem vulnerability to climate change (very high confidence). Globally, and even within protected areas, unsustainable use of natural resources, habitat fragmentation, and ecosystem damage by pollutants increase ecosystem vulnerability to climate change (high confidence). Globally, less than 15% of the land, 21% of the freshwater and 8% of the ocean are protected areas. In most protected areas, there is insufficient stewardship to contribute to reducing damage from, or increasing resilience to, climate change (high confidence). {2.4, 2.5, 2.6, 3.4, 3.6, 4.2, 4.3, 5.8, 9.6, 11.3, 12.3, 13.3, 13.4, 14.5, 15.3, CCP1.2 Figure CCP1.15, CCP2.1, CCP2.2, CCP4.2, CCP5.2, CCP 6.2, CCP7.2, CCP7.3, CCB NATURAL} SPM.B.2.3 Future vulnerability of ecosystems to climate change will be strongly influenced by the past, present and future development of human society, including from overall unsustainable consumption and production, and increasing demographic pressures, as well as persistent unsustainable use and management of land, ocean, and water (high confidence). Projected climate change, combined with non-climatic drivers, will cause loss and degradation of much of the world's forests (high confidence), coral reefs and low-lying coastal wetlands (very high confidence). While agricultural development contributes to food security, unsustainable agricultural expansion, driven in part by unbalanced diets32, increases ecosystem and human vulnerability and leads to competition for land and/or water resources (high confidence). {2.2, 2.3, 2.4, 2.6, 3.4, 3.5, 3.6, 4.3, 4.5, 5.6, 5.12, 5.13, 7.2, 12.3, 13.3, 13.4, 13.10, 14.5, CCP1.2, CCP2.2, CCP5.2, CCP6.2, CCP7.2, CCP7.3, CCB NATURAL, CCB HEALTH} SPM.B.2.4 Regions and people with considerable development constraints have high vulnerability to climatic hazards (high confidence). Global hotspots of high human vulnerability are found particularly in West-, Central- and East Africa, South Asia, Central and South America, Small Island Developing States and the Arctic (high confidence). Vulnerability is higher in locations with poverty, governance challenges and limited access to basic services and resources, violent conflict and high levels of climate-sensitive livelihoods (e.g., smallholder farmers, pastoralists, fishing communities) (high confidence). Between 2010-2020, human mortality from floods, droughts and storms was 15 times higher in highly vulnerable regions, compared to regions with very low vulnerability (high confidence). Vulnerability at different spatial levels is exacerbated by inequity and marginalization linked to gender, ethnicity, low income or combinations thereof (high confidence), especially for many Indigenous Peoples and local communities (high confidence). Present development challenges causing high vulnerability are influenced by historical and ongoing patterns of inequity such as colonialism, especially for many Indigenous Peoples and local communities (high confidence). {4.2, 5.12, 6.2, 6.4, 7.1, 7.2, Box 7.1, 8.2, 8.3, Box 8.4, Figure 8.6, Box 9.1, 9.4, 9.7, 9.9, 10.3, 10.4, 10.6, 12.3, 12.5, Box 13.2, 14.4, 15.3, 15.6, 16.2, CCP6.2, CCP7.4} SPM.B.2.5 Future human vulnerability will continue to concentrate where the capacities of local, municipal and national governments, communities and the private sector are least able to provide infrastructures and basic services (high confidence). Under the global trend of urbanization, human vulnerability will also concentrate in informal settlements and rapidly growing smaller settlements (high confidence). In rural areas vulnerability will be heightened by compounding processes including high emigration, reduced habitability and high reliance on climate-sensitive livelihoods (high confidence). Key infrastructure systems including sanitation, water, health, transport, communications and energy will be increasingly vulnerable if design 32 Balanced diets feature plant-based foods, such as those based on coarse grains, legumes fruits and vegetables, nuts and seeds, and animal-source foods produced in resilient, sustainable and low-greenhouse gas emissions systems, as described in SRCCL. APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-13 Total pages: 35 standards do not account for changing climate conditions (high confidence). Vulnerability will also rapidly rise in low-lying Small Island Developing States and atolls in the context of sea level rise and in some mountain regions, already characterised by high vulnerability due to high dependence on climate-sensitive livelihoods, rising population displacement, the accelerating loss of ecosystem services and limited adaptive capacities (high confidence). Future exposure to climatic hazards is also increasing globally due to socio-economic development trends including migration, growing inequality and urbanization (high confidence). {4.5, 5.5, 6.2, 7.2, 8.3, 9.9, 9.11, 10.3, 10.4, 12.3, 12.5, 13.6, 14.5, 15.3, 15.4, 16.5, CCP2.3, CCP4.3, CCP5.2, CCP5.3, CCP5.4, CCP6.2, CCB MIGRATE} Risks in the near term (2021-2040) SPM.B.3 Global warming, reaching 1.5°C in the near-term, would cause unavoidable increases in multiple climate hazards and present multiple risks to ecosystems and humans (very high confidence). The level of risk will depend on concurrent near-term trends in vulnerability, exposure, level of socioeconomic development and adaptation (high confidence). Near-term actions that limit global warming to close to 1.5°C would substantially reduce projected losses and damages related to climate change in human systems and ecosystems, compared to higher warming levels, but cannot eliminate them all (very high confidence). (Figure SPM.3, Box SPM.1) {WGI Table SPM.1, 16.4, 16.5, 16.6, CCP1.2, CCP5.3, CCB SLR, WGI SPM B1.3} SPM.B.3.1 Near-term warming and increased frequency, severity and duration of extreme events will place many terrestrial, freshwater, coastal and marine ecosystems at high or very high risks of biodiversity loss (medium to very high confidence, depending on ecosystem). Near-term risks for biodiversity loss are moderate to high in forest ecosystems (medium confidence), kelp and seagrass ecosystems (high to very high confidence), and high to very high in Arctic sea-ice and terrestrial ecosystems (high confidence) and warmwater coral reefs (very high confidence). Continued and accelerating sea level rise will encroach on coastal settlements and infrastructure (high confidence) and commit low-lying coastal ecosystems to submergence and loss (medium confidence). If trends in urbanisation in exposed areas continue, this will exacerbate the impacts, with more challenges where energy, water and other services are constrained (medium confidence). The number of people at risk from climate change and associated loss of biodiversity will progressively increase (medium confidence). Violent conflict and, separately, migration patterns, in the near-term will be driven by socio-economic conditions and governance more than by climate change (medium confidence). (Figure SPM.3) {2.5, 3.4, 4.6, 6.2, 7.3, 8.7, 9.2, 9.9, 11.6, 12.5, 13.6, 13.10, 14.6, 15.3, 16.5, 16.6, CCP1.2, CCP2.1, CCP2.2, CCP5.3, CCP6.2, CCP6.3, CCB SLR, CCB MIGRATE} SPM.B.3.2 In the near term, climate-associated risks to natural and human systems depend more strongly on changes in their vulnerability and exposure than on differences in climate hazards between emissions scenarios (high confidence). Regional differences exist, and risks are highest where species and people exist close to their upper thermal limits, along coastlines, in close association with ice or seasonal rivers (high confidence). Risks are also high where multiple non-climate drivers persist or where vulnerability is otherwise elevated (high confidence). Many of these risks are unavoidable in the near-term, irrespective of emission scenario (high confidence). Several risks can be moderated with adaptation (high confidence). (Figure SPM.3, Section C) {2.5, 3.3, 3.4, 4.5, 6.2, 7.1, 7.3, 8.2, 11.6, 12.4, 13.6, 13.7, 13.10, 14.5, 16.4, 16.5, CCP2.2, CCP4.3, CCP5.3, CCB SLR, WGI Table SPM.1} SPM.B.3.3 Levels of risk for all Reasons for Concern (RFC) are assessed to become high to very high at lower global warming levels than in AR5 (high confidence). Between 1.2°C and 4.5°C global warming level very high risks emerge in all five RFCs compared to just two RFCs in AR5 (high confidence). Two of these transitions from high to very high risk are associated with near-term warming: risks to unique and threatened systems at a median value of 1.5°C [1.2 to 2.0] °C (high confidence) and risks associated with extreme weather events at a median value of 2°C [1.8 to 2.5] °C (medium confidence). Some key risks contributing to the RFCs are projected to lead to widespread, pervasive, and potentially irreversible impacts at global warming levels of 1.5–2°C if exposure and vulnerability are high and adaptation is low (medium confidence). Near-term actions that limit global warming to close to 1.5°C would substantially reduce projected losses and damages related to climate change in human systems and ecosystems, compared to higher warming levels, but cannot eliminate them all (very high confidence). (Figure SPM.3b) {16.5, 16.6, CCB SLR} APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-14 Total pages: 35 Mid to Long-term Risks (2041–2100) SPM.B.4 Beyond 2040 and depending on the level of global warming, climate change will lead to numerous risks to natural and human systems (high confidence). For 127 identified key risks, assessed mid- and longterm impacts are up to multiple times higher than currently observed (high confidence). The magnitude and rate of climate change and associated risks depend strongly on near-term mitigation and adaptation actions, and projected adverse impacts and related losses and damages escalate with every increment of global warming (very high confidence). (Figure SPM.3) {2.5, 3.4, 4.4, 5.2, 6.2, 7.3, 8.4, 9.2, 10.2, 11.6, 12.4, 13.2, 13.3, 13.4, 13.5, 13.6, 13.7, 13.8, 14.6, 15.3, 16.5, 16.6, CCP1.2; CCP2.2, CCP3.3, CCP4.3, CCP5.3, CCP6.3, CCP7.3} SPM.B.4.1 Biodiversity loss, and degradation, damages to and transformation of ecosystems are already key risks for every region due to past global warming and will continue to escalate with every increment of global warming (very high confidence). In terrestrial ecosystems, 3 to 14% of species assessed33 will likely face very high risk of extinction34 at global warming levels of 1.5°C, increasing up to 3 to 18% at 2°C, 3 to 29% at 3°C, 3 to 39% at 4°C, and 3 to 48% at 5°C. In ocean and coastal ecosystems, risk of biodiversity loss ranges between moderate and very high by 1.5°C global warming level and is moderate to very high by 2°C but with more ecosystems at high and very high risk (high confidence), and increases to high to very high across most ocean and coastal ecosystems by 3°C (medium to high confidence, depending on ecosystem). Very high extinction risk for endemic species in biodiversity hotspots is projected to at least double from 2% between 1.5°C and 2°C global warming levels and to increase at least tenfold if warming rises from 1.5°C to 3°C (medium confidence). (Figure SPM.3c, d, f) {2.4, 2.5, 3.4, 3.5,12.3, 12.5, Table 12.6, 13.4, 13.10, 16.4, 16.6, CCP1.2, Figure CCP1.6; Figure CCP1.7, CCP5.3, CCP6.3, CCB PALEO} SPM.B.4.2 Risks in physical water availability and water-related hazards will continue to increase by the midto long-term in all assessed regions, with greater risk at higher global warming levels (high confidence). At approximately 2°C global warming, snowmelt water availability for irrigation is projected to decline in some snowmelt dependent river basins by up to 20%, and global glacier mass loss of 18 ± 13% is projected to diminish water availability for agriculture, hydropower, and human settlements in the mid- to long-term, with these changes projected to double with 4°C global warming (medium confidence). In small islands, groundwater availability is threatened by climate change (high confidence). Changes to streamflow magnitude, timing and associated extremes are projected to adversely impact freshwater ecosystems in many watersheds by the mid- to long-term across all assessed scenarios (medium confidence). Projected increases in direct flood damages are higher by 1.4 to 2 times at 2°C and 2.5 to 3.9 times at 3°C compared to 1.5°C global warming without adaptation (medium confidence). At global warming of 4°C, approximately 10% of the global land area is projected to face increases in both extreme high and low river flows in the same location, with implications for planning for all water use sectors (medium confidence). Challenges for water management will be exacerbated in the near, mid and long term, depending on the magnitude, rate and regional details of future climate change and will be particularly challenging for regions with constrained resources for water management (high confidence). {2.3, Box 4.2, 4.4, 4.5, Figure 4.20, 15.3, CCB DISASTER, CCP5.3, SROCC 2.3} SPM.B.4.3 Climate change will increasingly put pressure on food production and access, especially in vulnerable regions, undermining food security and nutrition (high confidence). Increases in frequency, intensity and severity of droughts, floods and heatwaves, and continued sea level rise will increase risks to food security (high confidence) in vulnerable regions from moderate to high between 1.5°C and 2°C global warming level, with no or low levels of adaptation (medium confidence). At 2°C or higher global warming level in the mid-term, food security risks due to climate change will be more severe, leading to malnutrition and micro-nutrient deficiencies, concentrated in Sub-Saharan Africa, South Asia, Central and South America and Small Islands (high confidence). Global warming will progressively weaken soil health and ecosystem 33 Numbers of species assessed are in the tens of thousands globally. 34 The term 'very high risks of extinction' is used here consistently with the IUCN categories and criteria and equates with 'critically endangered'. APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-15 Total pages: 35 services such as pollination, increase pressure from pests and diseases, and reduce marine animal biomass, undermining food productivity in many regions on land and in the ocean (medium confidence). At 3ºC or higher global warming level in the long term, areas exposed to climate-related hazards will expand substantially compared with 2ºC or lower global warming level (high confidence), exacerbating regional disparity in food security risks (high confidence). (Figure SPM.3) {1.1, 3.3, CCB SLR, 4.5, 5.2, 5.4, 5.5, 5.8, 5.9, 5.12, CCB MOVING PLATE, 7.3, 8.3, 9.11,13.5,15.3, 16.5, 16.6} SPM.B.4.4 Climate change and related extreme events will significantly increase ill health and premature deaths from the near- to long-term (high confidence). Globally, population exposure to heatwaves will continue to increase with additional warming, with strong geographical differences in heat-related mortality without additional adaptation (very high confidence). Climate-sensitive food-borne, water-borne, and vector-borne disease risks are projected to increase under all levels of warming without additional adaptation (high confidence). In particular, dengue risk will increase with longer seasons and a wider geographic distribution in Asia, Europe, Central and South America and sub-Saharan Africa, potentially putting additional billions of people at risk by the end of the century (high confidence). Mental health challenges, including anxiety and stress, are expected to increase under further global warming in all assessed regions, particularly for children, adolescents, elderly, and those with underlying health conditions (very high confidence). {4.5, 5.12, Box 5.10, 7.3, Fig 7.9, 8.4, 9.10, Fig 9.32, Fig 9.35, 10.4, Fig 10.11, 11.3, 12.3, Fig 12.5, Fig 12.6, 13.7, Fig 13.23, Fig 13.24, 14.5, 15.3, CCP6.2} SPM.B.4.5 Climate change risks to cities, settlements and key infrastructure will rise rapidly in the mid- and long-term with further global warming, especially in places already exposed to high temperatures, along coastlines, or with high vulnerabilities (high confidence). Globally, population change in low-lying cities and settlements will lead to approximately a billion people projected to be at risk from coastal-specific climate hazards in the mid-term under all scenarios, including in Small Islands (high confidence). The population potentially exposed to a 100-year coastal flood is projected to increase by about 20% if global mean sea level rises by 0.15 m relative to 2020 levels; this exposed population doubles at a 0.75 m rise in mean sea level and triples at 1.4 m without population change and additional adaptation (medium confidence). Sea level rise poses an existential threat for some

Small Islands and some low-lying coasts (medium confidence). By 2100 the value of global assets within the future 1-in-100 year coastal floodplains is projected to be between US$7.9 and US$12.7 trillion (2011 value) under RCP4.5, rising to between US$8.8 and US$14.2 trillion under RCP8.5 (medium confidence). Costs for maintenance and reconstruction of urban infrastructure, including building, transportation, and energy will increase with global warming level (medium confidence), the associated functional disruptions are projected to be substantial particularly for cities, settlements and infrastructure located on permafrost in cold regions and on coasts (high confidence). {6.2, 9.9, 10.4, 13.6, 13.10, 15.3, 16.5, CCP2.1, CCP2.2, CCP5.3, CCP6.2, CCB SLR, SROCC 2.3, SROCC CCB9} SPM.B.4.6 Projected estimates of global aggregate net economic damages generally increase non-linearly with global warming levels (high confidence).35 The wide range of global estimates, and the lack of comparability between methodologies, does not allow for identification of a robust range of estimates (high confidence). The existence of higher estimates than assessed in AR5 indicates that global aggregate economic impacts could be higher than previous estimates (low confidence).36 Significant regional variation in aggregate economic damages from climate change is projected (high confidence) with estimated economic damages per capita for developing countries often higher as a fraction of income (high confidence). Economic damages, including both those represented and those not represented in economic markets, are projected to be lower at 1.5°C than at 3°C or higher global warming levels (high confidence). {4.4, 9.11, 11.5, 13.10, Box 14.6, 16.5, CWGB ECONOMICS} SPM.B.4.7 In the mid- to long-term, displacement will increase with intensification of heavy precipitation and associated flooding, tropical cyclones, drought and, increasingly, sea level rise (high confidence). At progressive levels of warming, involuntary migration from regions with high exposure and low adaptive 35 The assessment found estimated rates of increase in projected global economic damages that were both greater than linear and less than linear as global warming level increases. There is evidence that some regions could benefit from low levels of warming (high confidence). {CWGB ECONOMICS} 36 Low confidence assigned due to the assessed lack of comparability and robustness of global aggregate economic damage estimates. {CWGB ECONOMICS} APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-16 Total pages: 35 capacity would occur (medium confidence). Compared to other socioeconomic factors the influence of climate on conflict is assessed as relatively weak (high confidence). Along long-term socioeconomic pathways that reduce non-climatic drivers, risk of violent conflict would decline (medium confidence). At higher global warming levels, impacts of weather and climate extremes, particularly drought, by increasing vulnerability will increasingly affect violent intrastate conflict (medium confidence). {7.3, 16.5, CCB MIGRATE, TSB7.4} APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-17 Total pages: 35 Figure SPM.3: Synthetic diagrams of global and sectoral assessments and examples of regional key risks. Diagrams show the change in the levels of impacts and risks assessed for global warming of 0-5°C global surface temperature change relative to pre-industrial period (1850-1900) over the range. (a) Global surface temperature changes in °C relative to 1850–1900. These changes were obtained by combining CMIP6 model simulations with observational constraints based on past simulated warming, as well as an updated assessment of equilibrium climate sensitivity (Box SPM.1). Changes relative to 1850–1900 based on 20-year averaging periods are calculated by adding 0.85°C (the observed global surface temperature increase from 1850–1900 to 1995–2014) to simulated changes relative to 1995–2014. Very likely ranges are shown for SSP1-2.6 and SSP3- APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-18 Total pages: 35 7.0 (WGI Figure SPM.8). Assessments were carried out at the global scale for (b), (c), (d) and (e). (b) The Reasons for Concern (RFC) framework communicates scientific understanding about accrual of risk for five broad categories. Diagrams are shown for each RFC, assuming low to no adaptation (i.e., adaptation is fragmented, localized and comprises incremental adjustments to existing practices). However, the transition to a very high risk level has an emphasis on irreversibility and adaptation limits. Undetectable risk level (white) indicates no associated impacts are detectable and attributable to climate change; moderate risk (yellow) indicates associated impacts are both detectable and attributable to climate change with at least medium confidence, also accounting for the other specific criteria for key risks; high risk (red) indicates severe and widespread impacts that are judged to be high on one or more criteria for assessing key risks; and very high risk level (purple) indicates very high risk of severe impacts and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks. The horizontal line denotes the present global warming of 1.09°C which is used to separate the observed, past impacts below the line from the future projected risks above it. RFC1: Unique and threatened systems: ecological and human systems that have restricted geographic ranges constrained by climate-related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its Indigenous Peoples, mountain glaciers and biodiversity hotspots. RFC2: Extreme weather events: risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heatwaves, heavy rain, drought and associated wildfires, and coastal flooding. RFC3: Distribution of impacts: risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability. RFC4: Global aggregate impacts: impacts to socio-ecological systems that can be aggregated globally into a single metric, such as monetary damages, lives affected, species lost or ecosystem degradation at a global scale. RFC5: Large-scale singular events: relatively large, abrupt and sometimes irreversible changes in systems caused by global warming, such as ice sheet disintegration or thermohaline circulation slowing. Assessment methods are described in SM16.6 and are identical to AR5, but are enhanced by a structured approach to improve robustness and facilitate comparison between AR5 and AR6. Risks for (c) terrestrial and freshwater ecosystems and (d) ocean ecosystems. For c) and d), diagrams shown for each risk assume low to no adaptation. The transition to a very high risk level has an emphasis on irreversibility and adaptation limits. (e) Climate-sensitive human health outcomes under three scenarios of adaptation effectiveness. The assessed projections were based on a range of scenarios, including SRES, CMIP5, and ISIMIP, and, in some cases, demographic trends. The diagrams are truncated at the nearest whole ºC within the range of temperature change in 2100 under three SSP scenarios in panel (a). (f) Examples of regional key risks. Risks identified are of at least medium confidence level. Key risks are identified based on the magnitude of adverse consequences (pervasiveness of the consequences, degree of change, irreversibility of consequences, potential for impact thresholds or tipping points, potential for cascading effects beyond system boundaries); likelihood of adverse consequences; temporal characteristics of the risk; and ability to respond to the risk, e.g., by adaptation. The full set of 127 assessed global and regional key risks is given in SM16.7. Diagrams are provided for some risks. The development of synthetic diagrams for Small Islands, Asia and Central and South America were limited by the availability of adequately downscaled climate projections, with uncertainty in the direction of change, the diversity of climatologies and socio-economic contexts across countries within a region, and the resulting low number of impact and risk projections for different warming levels. Absence of risks diagrams does not imply absence of risks within a region. (Box SPM.1) {16.5, 16.6, Figure 16.15, SM16.3, SM16.4, SM16.5, SM16.6 (methodologies), SM16.7, Figure 2.11, Figure SM3.1, Figure 7.9, Figure 9.6, Figure 11.6, Figure 13.28, Figure CCP6.5, Figure CCP4.8, Figure CCP4.10, Figure TS.4, WGI Figure SPM.8, WGI SPM A.1.2, Box SPM.1, WGI Ch. 2} Complex, Compound and Cascading Risks SPM.B.5 Climate change impacts and risks are becoming increasingly complex and more difficult to manage. Multiple climate hazards will occur simultaneously, and multiple climatic and non-climatic risks will interact, resulting in compounding overall risk and risks cascading across sectors and regions. Some responses to climate change result in new impacts and risks. (high confidence) {1.3, 2.4, Box 2.2, Box 9.5, 11.5, 13.5, 14.6, Box 15.1, CCP1.2, CCP2.2, CCB DISASTER, CCB INTERREG, CCB SRM, CCB COVID} APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-19 Total pages: 35 SPM.B.5.1 Concurrent and repeated climate hazards occur in all regions, increasing impacts and risks to health, ecosystems, infrastructure, livelihoods and food (high confidence). Multiple risks interact, generating new sources of vulnerability to climate hazards, and compounding overall risk (high confidence). Increasing concurrence of heat and drought events are causing crop production losses and tree mortality (high confidence). Above 1.5°C global warming increasing concurrent climate extremes will increase risk of simultaneous crop losses of maize in major food-producing regions, with this risk increasing further with higher global warming levels (medium confidence). Future sea level rise combined with storm surge and heavy rainfall will increase compound flood risks (high confidence). Risks to health and food production will be made more severe from the interaction of sudden food production losses from heat and drought, exacerbated by heat-induced labour productivity losses (high confidence). These interacting impacts will increase food prices, reduce household incomes, and lead to health risks of malnutrition and climate-related mortality with no or low levels of adaptation, especially in tropical regions (high confidence). Risks to food safety from climate change will further compound the risks to health by increasing food contamination of crops from mycotoxins and contamination of seafood from harmful algal blooms, mycotoxins, and chemical contaminants (high confidence). {5.2, 5.4, 5.8, 5.9, 5.11, 5.12, 7.2, 7.3, 9.8, 9.11, 10.4, 11.3, 11.5, 12.3, 13.5, 14.5, 15.3, Box 15.1, 16.6, CCP1.2, CCP6.2, Figure TS10C, WG1 SPM A.3.1, A.3.2 and C.2.7} SPM.B.5.2 Adverse impacts from climate hazards and resulting risks are cascading across sectors and regions (high confidence), propagating impacts along coasts and urban centres (medium confidence) and in mountain regions (high confidence). These hazards and cascading risks also trigger tipping points in sensitive ecosystems and in significantly and rapidly changing social-ecological systems impacted by ice melt, permafrost thaw and changing hydrology in polar regions (high confidence). Wildfires, in many regions, have affected ecosystems and species, people and their built assets, economic activity, and health (medium to high confidence). In cities and settlements, climate impacts to key infrastructure are leading to losses and damages across water and food systems, and affect economic activity, with impacts extending beyond the area directly impacted by the climate hazard (high confidence). In Amazonia, and in some mountain regions, cascading impacts from climatic (e.g., heat) and non-climatic stressors (e.g., land use change) will result in irreversible and severe losses of ecosystem services and biodiversity at 2°C global warming level and beyond (medium confidence). Unavoidable sea level rise will bring cascading and compounding impacts resulting in losses of coastal ecosystems and ecosystem services, groundwater salinisation, flooding and damages to coastal infrastructure that cascade into risks to livelihoods, settlements, health, well-being, food and water security, and cultural values in the near to longterm (high confidence). (Figure SPM.3) {2.5, 3.4, 3.5, Box 7.3, Box 8.7, Box 9.4, Box 11.1, 11.5, 12.3, 13.9, 14.6, 15.3, 16.5, 16.6, CCP1.2, CCP2.2, CCP5.2, CCP5.3, CCP6.2, CCP6.3, Box CCP6.1, Box CCP6.2, CCB EXTREMES, Figure TS.10, WGI SPM Figure SPM.8d} SPM.B.5.3 Weather and climate extremes are causing economic and societal impacts across national boundaries through supply-chains, markets, and natural resource flows, with increasing transboundary risks projected across the water, energy and food sectors (high confidence). Supply chains that rely on specialized commodities and key infrastructure can be disrupted by weather and climate extreme events. Climate change causes the redistribution of marine fish stocks, increasing risk of transboundary management conflicts among fisheries users, and negatively affecting equitable distribution of food provisioning services as fish stocks shift from lower to higher latitude regions, thereby increasing the need for climate-informed transboundary management and cooperation (high confidence). Precipitation and water availability changes increases the risk of planned infrastructure projects, such as hydropower in some regions, having reduced productivity for food and energy sectors including across countries that share river basins (medium confidence). {Figure TS.10e-f, 3.4, 3.5, 4.5, 5.8, 5.13, 6.2, 9.4, Box 9.5,14.5, Box 14.5, Box 14.6, CCP5.3, CCB EXTREMES, CCB MOVING PLATE, CCB INTERREG, CCB DISASTER} SPM B.5.4 Risks arise from some responses that are intended to reduce the risks of climate change, including risks from maladaptation and adverse side effects of some emission reduction and carbon dioxide removal measures (high confidence). Deployment of afforestation of naturally unforested land, or poorly implemented bioenergy, with or without carbon capture and storage, can compound climate-related risks to biodiversity, water and food security, and livelihoods, especially if implemented at large scales, especially in regions with insecure land tenure (high confidence). {Box 2.2, 4.1, 4.7, 5.13, Table 5.18, Box 9.3, Box 13.2, CCB NATURAL, CWGB BIOECONOMY} APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-20 Total pages: 35 SPM B.5.5 Solar radiation modification approaches, if they were to be implemented, introduce a widespread range of new risks to people and ecosystems, which are not well understood (high confidence). Solar radiation modification approaches have potential to offset warming and ameliorate some climate hazards, but substantial residual climate change or overcompensating change would occur at regional scales and seasonal timescales (high confidence). Large uncertainties and knowledge gaps are associated with the potential of solar radiation modification approaches to reduce climate change risks. Solar radiation modification would not stop atmospheric CO2 concentrations from increasing or reduce resulting ocean acidification under continued anthropogenic emissions (high confidence). {XWGB SRM} Impacts of Temporary Overshoot SPM.B.6 If global warming transiently exceeds 1.5°C in the coming decades or later (overshoot)37, then many human and natural systems will face additional severe risks, compared to remaining below 1.5°C (high confidence). Depending on the magnitude and duration of overshoot, some impacts will cause release of additional greenhouse gases (medium confidence) and some will be irreversible, even if global warming is reduced (high confidence). (Figure SPM.3) {2.5, 3.4, 12.3, 16.6, CCB SLR, CCB DEEP, Box SPM.1} SPM.B.6.1 While model-based assessments of the impacts of overshoot pathways are limited, observations and current understanding of processes permit assessment of impacts from overshoot. Additional warming, e.g., above 1.5°C during an overshoot period this century, will result in irreversible impacts on certain ecosystems with low resilience, such as polar, mountain, and coastal ecosystems, impacted by ice-sheet, glacier melt, or by accelerating and higher committed sea level rise (high confidence).38 Risks to human systems will increase, including those to infrastructure, low-lying coastal settlements, some ecosystem-based adaptation measures, and associated livelihoods (high confidence), cultural and spiritual values (medium confidence). Projected impacts are less severe with shorter duration and lower levels of overshoot (medium confidence). {2.5, 3.4, 12.3, 13.2, 16.5, 16.6, CCP 1.2, CCP5.3, CCP6.1, CCP6.2, CCP2.2, CCB SLR, Box TS4, SROCC 2.3, SROCC 5.4, WG1 SPM B5 and C3} SPM.B.6.2 Risk of severe impacts increase with every additional increment of global warming during overshoot (high confidence). In high-carbon ecosystems (currently storing 3,000 to 4,000 GtC)39 such impacts are already observed and are projected to increase with every additional increment of global warming, such as increased wildfires, mass mortality of trees, drying of peatlands, and thawing of permafrost, weakening natural land carbon sinks and increasing releases of greenhouse gases (medium confidence). The resulting contribution to a potential amplification of global warming indicates that a return to a given global warming level or below would be more challenging (medium confidence). {2.4, 2.5, CCP4.2, WG1 SPM B.4.3, SROCC 5.4} SPM.C: Adaptation Measures and Enabling Conditions Adaptation, in response to current climate change, is reducing climate risks and vulnerability mostly via adjustment of existing systems. Many adaptation options exist and are used to help manage projected climate change impacts, but their implementation depends upon the capacity and effectiveness of governance and decision-making processes. These and other enabling conditions can also support

Climate Resilient Development (Section D). Current Adaptation and its Benefits 37 In this report, overshoot pathways exceed 1.5°C global warming and then return to that level, or below, after several decades. 38 Despite limited evidence specifically on the impacts of a temporary overshoot of 1.5°C, a much broader evidence base from process understanding and the impacts of higher global warming levels allows a high confidence statement on the irreversibility of some impacts that would be incurred following such an overshoot. 39 At the global scale, terrestrial ecosystems currently remove more carbon from the atmosphere (-3.4 ± 0.9 Gt yr-1) than they emit (+1.6 ± 0.7 Gt yr-1), a net sink of -1.9 ± 1.1 Gt yr-1 . However, recent climate change has shifted some systems in some regions from being net carbon sinks to net carbon sources. APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-21 Total pages: 35 SPM.C.1 Progress in adaptation planning and implementation has been observed across all sectors and regions, generating multiple benefits (very high confidence). However, adaptation progress is unevenly distributed with observed adaptation gaps40 (high confidence). Many initiatives prioritize immediate and nearterm climate risk reduction which reduces the opportunity for transformational adaptation (high confidence). {2.6, 5.14, 7.4, 10.4, 12.5, 13.11, 14.7, 16.3, 17.3, CCP5.2, CCP5.4} SPM.C.1.1 Adaptation planning and implementation have continued to increase across all regions (very high confidence). Growing public and political awareness of climate impacts and risks has resulted in at least 170 countries and many cities including adaptation in their climate policies and planning processes (high confidence). Decision support tools and climate services are increasingly being used (very high confidence). Pilot projects and local experiments are being implemented in different sectors (high confidence). Adaptation can generate multiple additional benefits such as improving agricultural productivity, innovation, health and well-being, food security, livelihood, and biodiversity conservation as well as reduction of risks and damages (very high confidence). {1.4, CCB ADAPT, 2.6, CCB NATURE, 3.5, 3.6, 4.7, 4.8, 5.4, 5.6, 5.10, 6.4.2, 7.4, 8.5, 9.3, 9.6, 10.4, 12.5, 13.11, 15.5, 16.3, 17.2, 17.3, 17.5 CCP5.4} SPM.C.1.2 Despite progress, adaptation gaps exist between current levels of adaptation and levels needed to respond to impacts and reduce climate risks (high confidence). Most observed adaptation is fragmented, small in scale, incremental, sector-specific, designed to respond to current impacts or near-term risks, and focused more on planning rather than implementation (high confidence). Observed adaptation is unequally distributed across regions (high confidence), and gaps are partially driven by widening disparities between the estimated costs of adaptation and documented finance allocated to adaptation (high confidence). The largest adaptation gaps exist among lower income population groups (high confidence). At current rates of adaptation planning and implementation the adaptation gap will continue to grow (high confidence). As adaptation options often have long implementation times, long-term planning and accelerated implementation, particularly in the next decade, is important to close adaptation gaps, recognising that constraints remain for some regions (high confidence). {1.1, 1.4, 5.6, 6.3, Figure 6.4, 7.4, 8.3, 10.4, 11.3, 11.7, 15.2, Box 13.1, 13.11, 15.5, Box16.1, Figure 16.4, Figure 16.5, 16.3, 16.5, 17.4, 18.2, CCP2.4, CCP5.4, CCB FINANCE, CCB SLR} 40 Adaptation gaps are defined as the difference between actually implemented adaptation and a societally set goal, determined largely by preferences related to tolerated climate change impacts and reflecting resource limitations and competing priorities. APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-22 Total pages: 35 Figure SPM.4: (a) Climate responses and adaptation options, organized by System Transitions and Representative Key Risks (RKRs), are assessed for their multidimensional feasibility at global scale, in the near term and up to 1.5°C global APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-23 Total pages: 35 warming. As literature above 1.5°C is limited, feasibility at higher levels of warming may change, which is currently not possible to assess robustly. Climate responses and adaptation options at global scale are drawn from a set of options assessed in AR6 that have robust evidence across the feasibility dimensions. This figure shows the six feasibility dimensions (economic, technological, institutional, social, environmental and geophysical) that are used to calculate the potential feasibility of climate responses and adaptation options, along with their synergies with mitigation. For potential feasibility and feasibility dimensions, the figure shows high, medium, or low feasibility. Synergies with mitigation are identified as high, medium, and low. Insufficient evidence is denoted by a dash. {CCB FEASIB., Table SMCCB FEASIB.1.1; SR1.5 4.SM.4.3} Figure SPM.4: (b) Climate responses and adaptation options, organized by System Transitions and Representative Key Risks, are assessed at global scale for their likely ability to reduce risks for ecosystems and social groups at risk, as well as their relation with the 17 Sustainable Development Goals (SDGs). Climate responses and adaptation options are assessed for observed benefits (+) to ecosystems and their services, ethnic groups, gender equity, and low-income groups, or observed dis-benefits (-) for these systems and groups. Where there is highly diverging evidence of benefits/ disbenefits across the scientific literature, e.g., based on differences between regions, it is shown as not clear or mixed (•). Insufficient evidence is shown by a dash. The relation with the SDGs is assessed as having benefits (+), dis-benefits (-) or not clear or mixed (•) based on the impacts of the climate response and adaptation option on each SDG. Areas not coloured indicate there is no evidence of a relation or no interaction with the respective SDG. The climate responses and adaptation options are drawn from two assessments. For comparability of climate responses and adaptation options see Table SM17.5. {17.2, 17.5; CCB FEASIB} Future Adaptation Options and their Feasibility SPM.C.2 There are feasible41 and effective42 adaptation options which can reduce risks to people and nature. The feasibility of implementing adaptation options in the near-term differs across sectors and regions (very high confidence). The effectiveness of adaptation to reduce climate risk is documented for specific contexts, sectors and regions (high confidence) and will decrease with increasing warming (high confidence). Integrated, multi-sectoral solutions that address social inequities, differentiate responses based on climate risk and cut across systems, increase the feasibility and effectiveness of adaptation in multiple sectors (high confidence). (Figure SPM.4) {Figure TS.6e, 1.4, 3.6, 4.7, 5.12, 6.3, 7.4, 11.3, 11.7, 13.2, 15.5, 17.6, CCB FEASIB, CCP2.3} Land, Ocean and Ecosystems Transition SPM.C.2.1 Adaptation to water-related risks and impacts make up the majority of all documented adaptation (high confidence). For inland flooding, combinations of non-structural measures like early warning systems and structural measures like levees have reduced loss of lives (medium confidence). Enhancing natural water retention such as by restoring wetlands and rivers, land use planning such as no build zones or upstream forest management, can further reduce flood risk (medium confidence). On-farm water management, water storage, soil moisture conservation and irrigation are some of the most common adaptation responses and provide economic, institutional or ecological benefits and reduce vulnerability (high confidence). Irrigation is effective in reducing drought risk and climate impacts in many regions and has several livelihood benefits, but needs appropriate management to avoid potential adverse outcomes, which can include accelerated depletion of groundwater and other water sources and increased soil salinization (medium confidence). Large scale irrigation can also alter local to regional temperature and precipitation patterns (high confidence), including both alleviating and exacerbating temperature extremes (medium confidence). The effectiveness of most waterrelated adaptation options to reduce projected risks declines with increasing warming (high confidence). {4.1, 41 In this report, feasibility refers to the potential for a mitigation or adaptation option to be implemented. Factors influencing feasibility are context-dependent, temporally dynamic, and may vary between different groups and actors. Feasibility depends on geophysical, environmental-ecological, technological, economic, socio-cultural and institutional factors that enable or constrain the implementation of an option. The feasibility of options may change when different options are combined and increase when enabling conditions are strengthened. 42 Effectiveness refers to the extent to which an adaptation option is anticipated or observed to reduce climate-related risk. APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-24 Total pages: 35 4.6, 4.7, Box 4.3, Box 4.6, Box 4.7, Figure 4.28, Figure 4.29, Table 4.9, 9.3, 9.7, 11.3, 12.5, 13.1, 13.2, 16.3, CCP5.4, Figure 4.22} SPM.C.2.2 Effective adaptation options, together with supportive public policies enhance food availability and stability and reduce climate risk for food systems while increasing their sustainability (medium confidence). Effective options include cultivar improvements, agroforestry, community-based adaptation, farm and landscape diversification, and urban agriculture (high confidence). Institutional feasibility, adaptation limits of crops and cost effectiveness also influence the effectiveness of the adaptation options (limited evidence, medium agreement). Agroecological principles and practices, ecosystem-based management in fisheries and aquaculture, and other approaches that work with natural processes support food security, nutrition, health and well-being, livelihoods and biodiversity, sustainability and ecosystem services (high confidence). These services include pest control, pollination, buffering of temperature extremes, and carbon sequestration and storage (high confidence). Trade-offs and barriers associated with such approaches include costs of establishment, access to inputs and viable markets, new knowledge and management (high confidence) and their potential effectiveness varies by socio-economic context, ecosystem zone, species combinations and institutional support (medium confidence). Integrated, multi-sectoral solutions that address social inequities and differentiate responses based on climate risk and local situation will enhance food security and nutrition (high confidence). Adaptation strategies which reduce food loss and waste or support balanced diets33 (as described in the IPCC Special Report on Climate Change and Land) contribute to nutrition, health, biodiversity and other environmental benefits (high confidence). {3.2, 4.7, 4.6, Box 4.3, 5.4, 5.5, 5.6, 5.8, 5.9, 5.10, 5.11, 5.12, 5.13, 5.14, 7.4, Box 5.10, Box 5.13, 6.3, 10.4, 12.5, 13.5, 13.10, 14.5, CWGB BIOECONOMY, CCB MOVING PLATE, CCB NATURAL, CCB FEASIB, CCP5.4, CCB HEALTH} SPM.C.2.3 Adaptation for natural forests43 includes conservation, protection and restoration measures. In managed forests44, adaptation options include sustainable forest management, diversifying and adjusting tree species compositions to build resilience, and managing increased risks from pests and diseases and wildfires. Restoring natural forests and drained peatlands and improving sustainability of managed forests, generally enhances the resilience of carbon stocks and sinks. Cooperation, and inclusive decision making, with local communities and Indigenous Peoples, as well as recognition of inherent rights of Indigenous Peoples, is integral to successful forest adaptation in many areas. (high confidence) {2.6, Box 2.2, CCB NATURAL, CCB FEASIB, CCB INDIG, 5.6, 5.13, 11.4, 12.5, 13.5, Box 14.1, Box 14.2, Table 5.23, Box CCP7.1, CCP7.5}. SPM.C.2.4 Conservation, protection and restoration of terrestrial, freshwater, coastal and ocean ecosystems, together with targeted management to adapt to unavoidable impacts of climate change, reduces the vulnerability of biodiversity to climate change (high confidence). The resilience of species, biological communities and ecosystem processes increases with size of natural area, by restoration of degraded areas and by reducing non-climatic stressors (high confidence). To be effective, conservation and restoration actions will increasingly need to be responsive, as appropriate, to ongoing changes at various scales, and plan for future changes in ecosystem structure, community composition and species' distributions, especially as 1.5°C global warming is approached and even more so if it is exceeded (high confidence). Adaptation options, where circumstances allow, include facilitating the movement of species to new ecologically appropriate locations, particularly through increasing connectivity between conserved or protected areas, targeted intensive management for vulnerable species and protecting refugial areas where species can survive locally (medium confidence). {2.3, Figure 2.1, 2,6, Table 2.6, 2.6, 3.6, Box 3.4, 4.6, Box 11.2, 12.3, 12.5, 3.3, 13.4, 14.7, Box 4.6, CCP5.4, CCB FEASIB} SPM.C.2.5 Effective Ecosystem-based Adaptation44 reduces a range of climate change risks to people, biodiversity and ecosystem services with multiple co-benefits (high confidence). Ecosystem-based Adaptation 43 In this report, the term natural forests describes those which are subject to little or no direct human intervention, whereas the term managed forests describes those where planting or other management activities take place, including those managed for commodity production. 44 Ecosystem based Adaptation (EbA) is recognised internationally under the Convention on Biological Diversity (CBD14/5). A related concept is Nature-based Solutions (NbS), which includes a broader range of approaches with safeguards, including those that contribute to adaptation and mitigation. The term 'Nature-based Solutions' is widely but not universally used in the scientific literature. The term is the subject of ongoing debate, with concerns that it may lead to the misunderstanding that NbS on its own can provide a global solution to climate change. APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-25 Total pages: 35 is vulnerable to climate change impacts, with effectiveness declining with increasing global warming (high confidence). Urban greening using trees and other vegetation can provide local cooling (very high confidence). Natural river systems, wetlands and upstream forest ecosystems reduce flood risk by storing water and slowing water flow, in most circumstances (high confidence). Coastal wetlands protect against coastal erosion and flooding associated with storms and sea level rise where sufficient space and adequate habitats are available until rates of sea level rise exceeds natural adaptive capacity to build sediment (very high confidence). {2.4, 2.5, 2.6, Table 2.7, 3.4, 3.5, 3.6, Figure 3.26, 4.6, Box 4.6, Box 4.7, 5.5, 5.14, Box 5.11, 6.3, 6.4, Figure 6.6, 7.4, 8.5, 8.6, 9.6, 9.8, 9.9, 10.2, 11.3, 12.5, 13.3, 13.4, 13.5, 14.5, Box 14.7, 16.3, 18.3, CCB HEALTH, CCB NATURAL, CCB MOVING PLATE, CCB FEASIB.3, CWGB BIOECONOMY, CCP5.4} Urban, Rural and Infrastructure Transition SPM.C.2.6 Considering climate change impacts and risks in the design and planning of urban and rural settlements and infrastructure is critical for resilience and enhancing human well-being (high confidence). The urgent provision of basic services, infrastructure, livelihood diversification and employment, strengthening of local and regional food systems and community-based adaptation enhance lives and livelihoods, particularly of low-income and marginalised groups (high confidence). Inclusive, integrated and long-term planning at local, municipal, sub-national and national scales, together with effective regulation and monitoring systems and financial and technological resources and capabilities foster urban and rural system transition (high confidence). Effective partnerships between governments, civil society, and private sector organizations, across scales provide infrastructure and services in ways that enhance the adaptive capacity of vulnerable people (medium to high confidence). {5.12, 5.13, 5.14, Box 6.3, 6.3, 6.4, Box 6.6, Table 6.6, 7.4, 12.5, 13.6, 14.5, Box14.4, Box17.4, CCB FEASIB, CCP2.3, CCP2.4, CCP5.4} SPM.C.2.7 An increasing number of adaptation responses exist for urban systems, but their feasibility and effectiveness is constrained by institutional, financial, and technological access and capacity, and depends on coordinated and contextually appropriate responses across physical, natural and social infrastructure (high confidence). Globally, more financing is directed at physical infrastructure than natural and social infrastructure (medium confidence) and there is limited evidence of investment in the informal settlements hosting the most vulnerable urban residents (medium to high confidence). Ecosystem-based adaptation (e.g., urban agriculture and forestry, river restoration) has increasingly been applied in urban areas (high confidence). Combined ecosystem-based and structural adaptation responses are being developed, and there is growing evidence of their potential to reduce adaptation costs and contribute to flood control, sanitation, water resources management, landslide prevention and coastal protection (medium confidence). {3.6, Box 4.6, 5.12, 6.3, 6.4, Table 6.8, 7.4, 9.7, 9.9, 10.4, Table 10.3, 11.3, 11.7, Box 11.6, 12.5, 13.2, 13.3, 13.6, 14.5, 15.5, 17.2, Box 17.4, CCB FEASIB, CCP2.3, CCP 3.2, CCP5.4, CCB SLR, SROCC ES} SPM C.2.8: Sea level rise poses a distinctive and severe adaptation challenge as it implies dealing with slow onset changes and increased frequency and magnitude of extreme sea level events which will escalate in the coming decades (high confidence). Such adaptation challenges would occur much earlier under high rates of sea level rise, in particular if low-likelihood, high impact outcomes associated with collapsing ice sheets occur (high confidence). Responses to ongoing sea level rise and land subsidence in low-lying coastal cities and settlements and small islands include protection, accommodation, advance and planned relocation (high confidence) 45. These responses are more effective if combined and/or sequenced, planned well ahead, aligned with sociocultural values and development priorities, and underpinned by inclusive community engagement processes (high confidence). {CCB SLR, CCP2.3, 6.2, 10.4, 11.7, Box 11.6, 13.2.2, 14.5.9.2, 15.5, SROCC ES: C3.2, WGI SPM B5, C3} SPM.C.2.9 Approximately 3.4 billion people globally live in rural areas around the world, and many are highly vulnerable to climate change. Integrating climate adaptation into social protection programs, including cash transfers and public works programmes, is highly feasible and increases resilience to climate change, especially when supported by basic services and infrastructure. Social safety nets are increasingly being reconfigured to build adaptive capacities of the most vulnerable in rural and also urban communities. Social 45 The term 'response' is used here instead of adaptation because some responses, such as retreat, may or may not be considered to be adaptation. APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-26 Total pages: 35 safety nets that support climate change adaptation have strong co-benefits with development goals such as education, poverty alleviation, gender inclusion and food security. (high confidence) {5.14, 9.4, 9.10, 9.11, 12.5, 14.5, CCB GENDER, CCB FEASIB, CCP5.4} Energy System Transition SPM.C.2.10 Within energy system transitions, the most feasible adaptation options support infrastructure resilience, reliable power systems and efficient water use for existing and new energy generation systems (very high confidence). Energy generation diversification, including with renewable energy resources and generation that can be decentralised depending on context (e.g., wind, solar, small scale hydroelectric) and demand side management (e.g., storage, and energy efficiency improvements) can reduce vulnerabilities to climate change, especially in rural populations (high confidence). Adaptations for hydropower and thermo-electric power generation are effective in most regions up to 1.5°C to 2°C, with decreasing effectiveness at higher levels of warming (medium confidence). Climate responsive energy markets, updated design standards on energy assets according to current and projected climate change, smart-grid technologies, robust transmission systems and improved capacity to respond to supply deficits have high feasibility in the medium- to long-term, with mitigation co-benefits (very high confidence). {4.6, 4.7, Figure 4.28, Figure 4.29, 10.4, Table 11.8, Figure 13.19, Figure 13.16, 13.6, 18.3, CCB FEASIB, CWGB BIOECONOMY, CCP5.2, CCP5.4} Cross-cutting Options SPM.C.2.11 Strengthening the climate resiliency of health systems will protect and promote human health and wellbeing (high confidence). There are multiple opportunities for targeted investments and finance to protect against exposure to climate hazards, particularly for those at highest risk. Heat Health Action Plans that include early warning and response systems are effective adaptation options for extreme heat (high confidence). Effective adaptation options for water-borne and food-borne diseases include improving access to potable water, reducing exposure of water and sanitation systems to flooding and extreme weather events, and improved early warning systems (very high confidence). For vector-borne diseases, effective adaptation options include surveillance, early warning systems, and vaccine development (very high confidence). Effective adaptation options for reducing mental health risks under climate change include improving surveillance, access to mental health care, and monitoring of psychosocial impacts from extreme weather events (high confidence). Health and well-being would benefit from integrated adaptation approaches that mainstream health into food, livelihoods, social protection, infrastructure, water and sanitation policies requiring collaboration and coordination at all scales of governance (very high confidence). {5.12, 6.3, 7.4, 9.10, Box 9.7, 11.3, 12.5, 13.7, 14.5, CCB FEASIB, CCB ILLNESS, CCB COVID}. SPM.C.2.12 Increasing adaptive capacities minimises the negative impacts of climate-related displacement and involuntary migration for migrants and sending and receiving areas (high confidence). This improves the degree of choice under which migration decisions are made, ensuring safe and orderly movements of people within and between countries (high confidence). Some development reduces underlying vulnerabilities associated with conflict, and adaptation contributes by reducing the impacts of climate change on climate sensitive drivers of conflict (high confidence). Risks to peace are reduced, for example, by supporting people in climate-sensitive economic activities (medium confidence) and advancing women's empowerment (high confidence). {7.4, 12.5, CCB MIGRATE, Box 9.8, Box 10.2, CCB FEASIB} SPM.C.2.13 There are a range of adaptation options, such as disaster risk management, early warning systems, climate services and risk spreading and sharing that have broad applicability across sectors and provide greater benefits to other adaptation options when combined (high confidence). For example, climate services that are inclusive of different users and providers can improve agricultural practices, inform better water use and efficiency, and enable resilient infrastructure planning (high confidence). {2.6, 3.6, 4.7, 5.4, 5.5, 5.6, 5.8, 5.9, 5.12, 5.14, 9.4, 9.8, 10.4, 12.5, 13.11, CCB MOVING PLATE, CCB FEASIB, CCP5.4} Limits to Adaptation SPM.C.3 Soft limits to some human adaptation have been reached, but can be overcome by addressing a range of constraints, primarily financial, governance, institutional and policy constraints (high confidence). Hard APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-27 Total pages: 35 limits to adaptation have been reached in some ecosystems (high confidence). With increasing global warming, losses and damages will increase and additional human and natural systems will reach adaptation limits (high confidence). {Figure TS.7, 1.4, 2.4, 2.5, 2.6, CCB SLR, 3.4, 3.6, 4.7, Figure 4.30, 5.5, Table 8.6, Box 10.7, 11.7, Table 11.16, 12.5 13.2, 13.5, 13.6, 13.10, 13.11, Figure 13.21, 14.5, 15.6, 16.4, Figure 16.8, Table 16.3, Table 16.4, CCP1.2, CCP1.3, CCP2.3, CCP3.3, CCP5.2, CCP5.4, CCP6.3, CCP7.3} SPM.C.3.1 Soft limits to some human adaptation have been reached, but can be overcome by addressing a range of constraints, which primarily consist of financial, governance, institutional and policy constraints (high confidence). For example, individuals and households in low lying coastal areas in Australasia and Small Islands and smallholder farmers in Central and South America, Africa, Europe and Asia have reached soft limits (medium confidence). Inequity and poverty also constrain adaptation, leading to soft limits and resulting in disproportionate exposure and impacts for most vulnerable groups (high confidence). Lack of climate literacy46 at all levels and limited availability of information and data pose further constraints to adaptation planning and implementation (medium confidence). {1.4, 4.7, 5.4, Table 8.6, 8.4, 9.1, 9.4, 9.5, 9.8, 11.7, 12.5 13.5, 15.3, 15.5, 15.6, 16.4, Figure 16.8, 16.4, Box 16.1, CCP5.2, CCP5.4, CCP6.3} SPM.C.3.2 Financial constraints are important determinants of soft limits to adaptation across sectors and all regions (high confidence). Although global tracked climate finance has shown an upward trend since AR5, current global financial flows for adaptation, including from public and private finance sources, are insufficient for and constrain implementation of adaptation options especially in developing countries (high confidence). The overwhelming majority of global tracked climate finance was targeted to mitigation while a small proportion was targeted to adaptation (very high confidence). Adaptation finance has come predominantly from public sources (very high confidence). Adverse climate impacts can reduce the availability of financial resources by incurring losses and damages and through impeding national economic growth, thereby further increasing financial constraints for adaptation, particularly for developing and least developed countries (medium confidence). {1.4, 2.6, 3.6, 4.7, Figure 4.30, 5.14, 7.4, Table 8.6, 8.4, 9.4, 9.9, 9.11, 10.5, 12.5, 13.3, 13.11, Box 14.4, 15.6, 16.2, 16.4, Figure 16.8, Table 16.4, 17.4, 18.1, CCB FINANCE, CCP2.4, CCP5.4, CCP6.3, Figure TS 7} SPM.C.3.3 Many natural systems are near the hard limits of their natural adaptation capacity and additional systems will reach limits with increasing global warming (high confidence). Ecosystems already reaching or surpassing hard adaptation limits include some warm water coral reefs, some coastal wetlands, some rainforests, and some polar and mountain ecosystems (high confidence). Above 1.5°C global warming level, some ecosystem-based adaptation measures will lose their effectiveness in providing benefits to people as these ecosystems will reach hard adaptation limits (high confidence). {1.4, 2.4, 2.6, 3.4, 3.6, CCB SLR, 9.6, Box11.2, 13.4, 14.5, 15.5, 16.4, 16.6, 17.2, CCP1.2, CCP5.2, CCP6.3, CCP7.3, Figure SPM.4} SPM.3.4 In human systems, some coastal settlements face soft adaptation limits due to technical and financial difficulties of implementing coastal protection (high confidence). Above 1.5°C global warming level, limited freshwater resources pose potential hard limits for Small Islands and for regions dependent on glacier and snow-melt (medium confidence). By 2°C global warming level, soft limits are projected for multiple staple crops in many growing areas, particularly in tropical regions (high confidence). By 3°C global warming level, soft limits are projected for some water management measures for many regions, with hard limits projected for parts of Europe (medium confidence). Transitioning from incremental to transformational adaptation can help overcome soft adaptation limits (high confidence). {1.4, 4.7, 5.4, 5.8, 7.2, 7.3, 8.4, Table 8.6, 9.8, 10.4, 12.5, 13.2, 13.6, 16.4, 17.2, CCB SLR, CCP1.3. Box CCP1.1, CCP2.3, CCP3.3, CCP4.4, CCP5.3} SPM.C.3.5 Adaptation does not prevent all losses and damages, even with effective adaptation and before reaching soft and hard limits. Losses and damages are unequally distributed across systems, regions and sectors and are not comprehensively addressed by current financial, governance and institutional arrangements, particularly in vulnerable developing countries. With increasing global warming, losses and damages increase and become increasingly difficult to avoid, while strongly concentrated among the poorest vulnerable 46 Climate literacy encompasses being aware of climate change, its anthropogenic causes and implications. APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-28 Total pages: 35 populations. (high confidence) {1.4, 2.6, 3.4, 3.6, 6.3, Figure 6.4, 8.4, 13.7, 13.2, 13.10, 17.2, CCB LOSS, CCB SLR, CCP2.3, CCP4.4, CWGB ECONOMIC} Avoiding Maladaptation SPM.C.4 There is increased evidence of maladaptation15 across many sectors and regions since the AR5. Maladaptive responses to climate change can create lock-ins of vulnerability, exposure and risks that are difficult and expensive to change and exacerbate existing inequalities. Maladaptation can be avoided by flexible, multi-sectoral, inclusive and long-term planning and implementation of adaptation actions with benefits to many sectors and systems. (high confidence) {1.3, 1.4, 2.6., Box 2.2, 3.2, 3.6, Box 4.3, Box 4.5, 4.6, 4.7, Figure 4.29, 5.6, 5.13, 8.2, 8.3, 8.4, 8.6, 9.6, 9.7, 9.8, 9.9, 9.10, 9.11, Box 9.5, Box 9.8, Box 9.9, Box 11.6, 13.11, 13.3, 13.4, 13.5, 14.5, 15.5, 15.6, 16.3, 17.3, 17.4, 17.6, 17.2, 17.5, CCP5.4, CCB NATURAL, CCB SLR, CCB DEEP, CWGB BIOECONOMY, CCP2.3, CCP2.3} SPM.C.4.1 Actions that focus on sectors and risks in isolation and on short-term gains often lead to maladaptation if long-term impacts of the adaptation option and long-term adaptation commitment are not taken into account (high confidence). The implementation of these maladaptive actions can result in infrastructure and institutions that are inflexible and/or expensive to change (high confidence). For example, seawalls effectively reduce impacts to people and assets in the short-term but can also result in lock-ins and increase exposure to climate risks in the long-term unless they are integrated into a long-term adaptive plan (high confidence). Adaptation integrated with development reduces lock-ins and creates opportunities (e.g., infrastructure upgrading) (medium confidence). {1.4, 3.4, 3.6, 10.4, 11.7, Box 11.6, 13.2, 17.2, 17.5, 17.6, CCP 2.3, CCB SLR, CCB DEEP} SPM.C.4.2 Biodiversity and ecosystem resilience to climate change are decreased by maladaptive actions, which also constrain ecosystem services. Examples of these maladaptive actions for ecosystems include fire suppression in naturally fire-adapted ecosystems or hard defences against flooding. These actions reduce space for natural processes and represent a severe form of maladaptation for the ecosystems they degrade, replace or fragment, thereby reducing their resilience to climate change and the ability to provide ecosystem services for adaptation. Considering biodiversity and autonomous adaptation in long-term planning processes reduces the risk of maladaptation. (high confidence) {2.4, 2.6, Table 2.7, 3.4, 3.6, 4.7, 5.6, 5.13, Table 5.21, 5.13, Box 13.2, 17.2, 17.5, Table 5.23, Box 11.2, 13.2, CCP5.4} SPM.C.4.3 Maladaptation especially affects marginalised and vulnerable groups adversely (e.g., Indigenous

Peoples, ethnic minorities, low-income households, informal settlements), reinforcing and entrenching existing inequities. Adaptation planning and implementation that do not consider adverse outcomes for different groups can lead to maladaptation, increasing exposure to risks, marginalising people from certain socio-economic or livelihood groups, and exacerbating inequity. Inclusive planning initiatives informed by cultural values, Indigenous knowledge, local knowledge, and scientific knowledge can help prevent maladaptation. (high confidence) (Figure SPM.4) {2.6, 3.6, 4.3, 4.6, 4.8, 5.12, 5.13, 5.14, 6.1, Box 7.1, 8.4, 11.4, 12.5, Box 13.2, 14.4, Box 14.1, 17.2, 17.5, 18.2, 17.2., CCP2.4} SPM.C.4.4 To minimize maladaptation, multi-sectoral, multi-actor and inclusive planning with flexible pathways encourages low-regret47 and timely actions that keep options open, ensure benefits in multiple sectors and systems and indicate the available solution space for adapting to long-term climate change (very high confidence). Maladaptation is also minimized by planning that accounts for the time it takes to adapt (high confidence), the uncertainty about the rate and magnitude of climate risk (medium confidence) and a wide range of potentially adverse consequences of adaptation actions (high confidence). {1.4, 3.6, 5.12, 5.13, 5.14, 11.6, 11.7, 17.3, 17.6, CCP2.3, CCP2.4, CCB SLR, CCB DEEP; CCP5.4} 47 From AR5, an option that would generate net social and/or economic benefits under current climate change and a range of future climate change scenarios, and represent one example of robust strategies. APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-29 Total pages: 35 Enabling Conditions SPM.C.5 Enabling conditions are key for implementing, accelerating and sustaining adaptation in human systems and ecosystems. These include political commitment and follow-through, institutional frameworks, policies and instruments with clear goals and priorities, enhanced knowledge on impacts and solutions, mobilization of and access to adequate financial resources, monitoring and evaluation, and inclusive governance processes. (high confidence) {1.4, 2.6, 3.6, 4.8, 6.4, 7.4, 8.5, 9.4, 10.5, 11.4, 11.7, 12.5, 13.11, 14.7, 15.6, 17.4, 18.4, CCB INDIG, CCB FINANCE, CCP2.4, CCP5.4} SPM.C.5.1 Political commitment and follow-through across all levels of government accelerate the implementation of adaptation actions (high confidence). Implementing actions can require large upfront investments of human, financial and technological resources (high confidence), whilst some benefits could only become visible in the next decade or beyond (medium confidence). Accelerating commitment and followthrough is promoted by rising public awareness, building business cases for adaptation, accountability and transparency mechanisms, monitoring and evaluation of adaptation progress, social movements, and climaterelated litigation in some regions (medium confidence). {3.6, 4.8, 5.8, 6.4, 8.5, 9.4, 11.7, 12.5, 13.11, 17.4, 17.5, 18.4, CCB COVID, CCP2.4} SPM.C.5.2 Institutional frameworks, policies and instruments that set clear adaptation goals and define responsibilities and commitments and that are coordinated amongst actors and governance levels, strengthen and sustain adaptation actions (very high confidence). Sustained adaptation actions are strengthened by mainstreaming adaptation into institutional budget and policy planning cycles, statutory planning, monitoring and evaluation frameworks and into recovery efforts from disaster events (high confidence). Instruments that incorporate adaptation such as policy and legal frameworks, behavioural incentives, and economic instruments that address market failures, such as climate risk disclosure, inclusive and deliberative processes strengthen adaptation actions by public and private actors (medium confidence). {1.4, 3.6, 4.8, 5.14, 6.3, 6.4, 7.4, 9.4, 10.4, 11.7, Box 11.6, Table 11.17, 13.10, 13.11, 14.7, 15.6, 17.3, 17.4, 17.5, 17.6, 18.4, CCB DEEP, CCP2.4, CCP5.4, CCP6.3} SPM.C.5.3 Enhancing knowledge on risks, impacts, and their consequences, and available adaptation options promotes societal and policy responses (high confidence). A wide range of top-down, bottom-up and coproduced processes and sources can deepen climate knowledge and sharing, including capacity building at all scales, educational and information programmes, using the arts, participatory modelling and climate services, Indigenous knowledge and local knowledge and citizen science (high confidence). These measures can facilitate awareness, heighten risk perception and influence behaviours (high confidence). {1.3, 3.6, 4.8, 5.9, 5.14, 6.4, Table 6.8, 7.4, 9.4, 10.5, 11.1, 11.7, 12.5, 13.9, 13.11, 14.3, 15.6, 15.6, 17.4, 18.4, CCB INDIG, CCP2.4.1}. SPMC.5.4 With adaptation finance needs estimated to be higher than those presented in AR5, enhanced mobilization of and access to financial resources are essential for implementation of adaptation and to reduce adaptation gaps (high confidence). Building capacity and removing some barriers to accessing finance is fundamental to accelerate adaptation, especially for vulnerable groups, regions and sectors (high confidence). Public and private finance instruments include inter alia grants, guarantee, equity, concessional debt, market debt, and internal budget allocation as well as savings in households and insurance. Public finance is an important enabler of adaptation (high confidence). Public mechanisms and finance can leverage private sector finance for adaptation by addressing real and perceived regulatory, cost and market barriers, for example via public-private partnerships (high confidence). Financial and technological resources enable effective and ongoing implementation of adaptation, especially when supported by institutions with a strong understanding of adaptation needs and capacity (high confidence). {4.8, 5.14, 6.4, Table 6.10, 7.4, 9.4, Table 11.17, 12.5, 13.11, 15.6, 17.4, 18.4, BOX 18.9, CCP5.4, CCB FINANCE}. SPM.C.5.5 Monitoring and evaluation (M&E) of adaptation are critical for tracking progress and enabling effective adaptation (high confidence). M&E implementation is currently limited (high confidence) but has increased since AR5 at local and national levels. Although most of the monitoring of adaptation is focused towards planning and implementation, the monitoring of outcomes is critical for tracking the effectiveness and APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-30 Total pages: 35 progress of adaptation (high confidence). M&E facilitates learning on successful and effective adaptation measures, and signals when and where additional action may be needed. M&E systems are most effective when supported by capacities and resources and embedded in enabling governance systems (high confidence). {1.4, 2.6, 6.4, 7.4, 11.7, 11.8, 13.2, 13.11, 17.5, 18.4, CCB PROGRESS, CCB NATURAL, CCB ILLNESS, CCB DEEP, CCP2.4}. SPM.C.5.6 Inclusive governance that prioritises equity and justice in adaptation planning and implementation leads to more effective and sustainable adaptation outcomes (high confidence). Vulnerabilities and climate risks are often reduced through carefully designed and implemented laws, policies, processes, and interventions that address context specific inequities such as based on gender, ethnicity, disability, age, location and income (high confidence). These approaches, which include multi-stakeholder co-learning platforms, transboundary collaborations, community-based adaptation and participatory scenario planning, focus on capacity-building, and meaningful participation of the most vulnerable and marginalised groups, and their access to key resources to adapt (high confidence). {1.4, 2.6, 3.6, 4.8, 5.4, 5.8, 5.9, 5.13, 6.4, 7.4, 8.5, 11.8, 12.5, 13.11, 14.7, 15.5, 15.7, 17.3, 17.5, 18.4, CCB HEALTH, CCB GENDER, CCB INDIG, CCP2.4, CCP5.4, CCP6.4} SPM.D: Climate Resilient Development Climate Resilient Development integrates adaptation measures and their enabling conditions (Section C) with mitigation to advance sustainable development for all. Climate resilient development involves questions of equity and system transitions in land, ocean and ecosystems; urban and infrastructure; energy; industry; and society and includes adaptations for human, ecosystem and planetary health. Pursuing climate resilient development focuses on both where people and ecosystems are co-located as well as the protection and maintenance of ecosystem function at the planetary scale. Pathways for advancing climate resilient development are development trajectories that successfully integrate mitigation and adaptation actions to advance sustainable development. Climate resilient development pathways may be temporarily coincident with any RCP and SSP scenario used throughout AR6, but do not follow any particular scenario in all places and over all time. Conditions for Climate Resilient Development SPM.D.1 Evidence of observed impacts, projected risks, levels and trends in vulnerability, and adaptation limits, demonstrate that worldwide climate resilient development action is more urgent than previously assessed in AR5. Comprehensive, effective, and innovative responses can harness synergies and reduce tradeoffs between adaptation and mitigation to advance sustainable development. (very high confidence) {2.6, 3.4, 3.6, 4.2, 4.6, 7.2, 7.4, 8.3, 8.4, 9.3, 10.6, 13.3, 13.8, 13.10, 14.7, 17.2, 18.3, Figure 18.1, Table 18.5, Box 18.1} SPM.D.1.1 There is a rapidly narrowing window of opportunity to enable climate resilient development. Multiple climate resilient development pathways are still possible by which communities, the private sector, governments, nations and the world can pursue climate resilient development – each involving and resulting from different societal choices influenced by different contexts and opportunities and constraints on system transitions. Climate resilient development pathways are progressively constrained by every increment of warming, in particular beyond 1.5°C, social and economic inequalities, the balance between adaptation and mitigation varying by national, regional and local circumstances and geographies, according to capabilities including resources, vulnerability, culture and values, past development choices leading to past emissions and future warming scenarios, bounding the climate resilient development pathways remaining, and the ways in which development trajectories are shaped by equity, and social and climate justice. (very high confidence) {2.6, 4.7, 4.8, 5.14, 6.4, 7.4, 8.3, 9.4, 9.3, 9.4, 9.5, 10.6, 11.8, 12.5, 13.10, 14.7, 15.3, 18.5, CCP2.3, CCP3.4, CCP4.4, CCP5.3, CCP5.4, Table CCP5.2, CCP6.3, CCP7.5, Figure TS14.d} SPM.D.1.2 Opportunities for climate resilient development are not equitably distributed around the world (very high confidence). Climate impacts and risks exacerbate vulnerability and social and economic inequities and consequently increase persistent and acute development challenges, especially in developing regions and sub-regions, and in particularly exposed sites, including coasts, small islands, deserts, mountains and polar regions. This in turn undermines efforts to achieve sustainable development, particularly for vulnerable and marginalized communities (very high confidence). {2.5, 4.4, 4.7, 6.3, 9.4, Box 6.4, Figure 6.5, Table 18.5, CWGB URBAN, CCB HEALTH, CCP2.2, CCP3.2, CCP3.3, CCP5.4, CCP6.2} SPM.D.1.3 Embedding effective and equitable adaptation and mitigation in development planning can reduce vulnerability, conserve and restore ecosystems, and enable climate resilient development. This is especially challenging in localities with persistent development gaps and limited resources (high confidence). Dynamic trade-offs and competing priorities exist between mitigation, adaptation, and development. Integrated and inclusive system-oriented solutions based on equity and social and climate justice reduce risks and enable climate resilient development (high confidence). {1.4, 2.6, 3.6, 4.7, 4.8, Box 4.5, Box 4.8, 5.13, 7.4, 8.5, 9.4, 10.6, Box 9.3, Box 2.2, 12.5, 12.6, 13.3, 13.4, 13.10, 13.11, 14.7, 18.4, CCB HEALTH, SRCCL, CCB DEEP, CCP2, CCP5.4} Figure SPM.5: Climate resilient development (CRD) is the process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development. This figure builds on Figure SPM.9 in AR5 WGII (depicting climate resilient pathways) by describing how CRD pathways are the result of cumulative societal choices and actions within multiple arenas. Panel (a): Societal choices towards higher CRD (green cog) or lower CRD (red cog) result from interacting decisions and actions by diverse government, private sector and civil society actors, in the context of climate risks, adaptation limits and development gaps. These actors engage with adaptation, mitigation and development actions in political, economic and financial, ecological, socio-cultural, knowledge and technology, and community arenas from local to international levels. Opportunities for climate resilient development are not equitably distributed around the world. Panel (b): Cumulatively, societal choices, which are made continuously, shift global development pathways towards higher (green) or lower (red) climate resilient development. Past conditions (past emissions, climate change and development) have already eliminated some development pathways towards higher CRD (dashed green line). Panel (c): Higher CRD is characterised by outcomes that advance sustainable development for all. Climate resilient development is progressively harder to achieve with global warming levels beyond 1.5°C. Inadequate progress towards the Sustainable Development Goals (SDGs) by 2030 reduces climate resilient development prospects. There is a narrowing window of opportunity to shift pathways towards more climate resilient development futures as reflected by the adaptation limits and increasing climate risks, considering the remaining carbon budgets. (Figure SPM.2, Figure SPM.3) {2.6, 3.6, 7.2, 7.3, 7.4, 8.3, 8.4, 8.5, 16.4, 16.5, 17.3, 17.4, 17.5, 18.1, 18.2, 18.3, 18.4, Figure 18.1, Figure 18.2, Figure 18.3, Box 18.1, CCB COVID, CCB GENDER, CCB HEALTH, CCB INDIG, CCB SLR, AR6 WGI Table SPM.1 and Table SPM.2, SR1.5 Figure SPM.1, Figure TS.14b} Enabling Climate Resilient Development SPM.D.2 Climate resilient development is enabled when governments, civil society and the private sector make inclusive development choices that prioritise risk reduction, equity and justice, and when decision-making processes, finance and actions are integrated across governance levels, sectors and timeframes (very high confidence). Climate resilient development is facilitated by international cooperation and by governments at all levels working with communities, civil society, educational bodies, scientific and other institutions, media, investors and businesses; and by developing partnerships with traditionally marginalised groups, including women, youth, Indigenous Peoples, local communities and ethnic minorities (high confidence). These partnerships are most effective when supported by enabling political leadership, institutions, resources, including finance, as well as climate services, information and decision support tools (high confidence). (Figure SPM.5) {1.3, 1.4, 1.5, 2.7, 3.6, 4.8, 5.14, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.4, 17.6, 18.4, 18.5, CCP2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB HEALTH, CCB GENDER, CCB INDIG, CCB DEEP, CCB NATURAL, CCB SLR} SPM.D.2.1 Climate resilient development is advanced when actors work in equitable, just and enabling ways to reconcile divergent interests, values and worldviews, toward equitable and just outcomes (high confidence). These practices build on diverse knowledges about climate risk and chosen development pathways account for local, regional and global climate impacts, risks, barriers and opportunities (high confidence). Structural vulnerabilities to climate change can be reduced through carefully designed and implemented legal, policy, and process interventions from the local to global that address inequities based on gender, ethnicity, disability, age, location and income (very high confidence). This includes rights-based approaches that focus on capacitybuilding, meaningful participation of the most vulnerable groups, and their access to key resources, including financing, to reduce risk and adapt (high confidence). Evidence shows that climate resilient development processes link scientific, Indigenous, local, practitioner and other forms of knowledge, and are more effective and sustainable because they are locally appropriate and lead to more legitimate, relevant and effective actions (high confidence). Pathways towards climate resilient development overcome jurisdictional and organizational barriers, and are founded on societal choices that accelerate and deepen key system transitions (very high confidence). Planning processes and decision analysis tools can help identify 'low regrets' options47 that enable mitigation and adaptation in the face of change, complexity, deep uncertainty and divergent views (medium confidence). {1.3, 1.4, 1.5, 2.7, 3.6, 4.8, 5.14, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.2-17.6, 18.2-18.4, CCP2.3-2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, Box 8.7, Box 9.2, CCB HEALTH, CCB INDIG, CCB DEEP, CCB NATURAL, CCB SLR} SPM.D.2.2 Inclusive governance contributes to more effective and enduring adaptation outcomes and enables climate resilient development (high confidence). Inclusive processes strengthen the ability of governments and other stakeholders to jointly consider factors such as the rate and magnitude of change and uncertainties, associated impacts, and timescales of different climate resilient development pathways given past development choices leading to past emissions and scenarios of future global warming (high confidence). Associated societal choices are made continuously through interactions in arenas of engagement from local to international levels. The quality and outcome of these interactions helps determine whether development pathways shift towards or away from climate resilient development (medium confidence). (Figure SPM.5) {2.7, 3.6, 4.8, 5.14, APPROVED Summary for Policymakers IPCC WGII Sixth Assessment Report Subject to Copyedit SPM-33 Total pages: 35 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.2-17.6, 18.2, 18.4, CCP2.3-2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB HEALTH, CCB GENDER, CCB INDIG} SPM.D.2.3 Governance for climate resilient development is most effective when supported by formal and informal institutions and practices that are well-aligned across scales, sectors, policy domains and timeframes. Governance efforts that advance climate resilient development account for the dynamic, uncertain and contextspecific nature of climate-related risk, and its interconnections with non-climate risks. Institutions48 that enable climate resilient development are flexible and responsive to emergent risks and facilitate sustained and timely action. Governance for climate resilient development is enabled by adequate and appropriate human and technological resources, information, capacities and finance. (high confidence) {2.7, 3.6, 4.8, 5.14, 6.3, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.2-17.6, 18.2, 18.4, CCP2.3-2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB HEALTH, CCB GENDER, CCB INDIG, CCB DEEP, CCB NATURAL, CCB SLR} Climate Resilient Development for Natural and Human Systems SPM.D.3 Interactions between changing urban form, exposure and vulnerability can create climate changeinduced risks and losses for cities and settlements. However, the global trend of urbanisation also offers a critical opportunity in the near-term, to advance climate resilient development (high confidence). Integrated, inclusive planning and investment in everyday decision-making about urban infrastructure, including social, ecological and grey/physical infrastructures, can significantly increase the adaptive capacity of urban and rural settlements. Equitable outcomes contributes to multiple benefits for health and well-being and ecosystem services, including for Indigenous Peoples, marginalised and vulnerable communities (high confidence). Climate resilient development in urban areas also supports adaptive capacity in more rural places through maintaining peri-urban supply chains of goods and services and financial flows (medium confidence). Coastal cities and settlements play an especially important role in advancing climate resilient development (high confidence). {6.2, 6.3, 18.3, Table 6.6, Box 9.8, CCP6.2, CCP2.1. CCP2.2, CWGB URBAN} SPM.D.3.1 Taking integrated action for climate resilience to avoid climate risk requires urgent decision making for the new built environment and retrofitting existing urban design, infrastructure and land use. Based on socioeconomic circumstances, adaptation and sustainable development actions will provide multiple benefits including for health and well-being, particularly when supported by national governments, nongovernmental organisations and international agencies that work across sectors in partnerships with local communities. Equitable partnerships between local and municipal governments, the private sector, Indigenous Peoples, local communities, and civil society can, including through international cooperation, advance climate resilient development by addressing structural inequalities, insufficient financial resources, cross-city risks and the integration of Indigenous knowledge and Local knowledge. (high confidence) {6.2, 6.3, 6.4, 7.4, 8.5, 9.4, 10.5. 12.5, 17.4, 18.2, Table 6.6, Table 17.8, Box 18.1, CCP2.4, CCB GENDER, CCB INDIG, CCB FINANCE, CWGB URBAN} SPM.D.3.2 Rapid global urbanisation offers opportunities for climate resilient development in diverse contexts from rural and informal settlements to large metropolitan areas (high confidence). Dominant models of energy intensive and market-led urbanisation, insufficient and misaligned finance and a predominant focus on grey infrastructure in the absence of integration with ecological and social approaches, risks missing opportunities for adaptation and locking in maladaptation (high confidence). Poor land use planning and siloed approaches to health, ecological and social planning also exacerbates, vulnerability in already marginalised 48 Institutions: Rules, norms and conventions that guide, constrain or enable human behaviours and practices. Institutions can be formally established, for instance through laws and regulations, or informally established, for instance by traditions or customs. Institutions may spur, hinder, strengthen, weaken or distort the emergence, adoption and implementation of climate action and climate governance. communities (medium confidence). Urban climate resilient development is observed to be more effective if it is responsive to regional and local land use development and adaptation gaps, and addresses the underlying drivers of vulnerability (high confidence). The greatest gains in well-being can be achieved by prioritizing finance to reduce climate risk for low-income and marginalized residents including people living in informal settlements (high confidence). {5.14, 6.1, 6.2, 6.3, 6.4, 6.5, 7.4, 8.5, 8.6, 9.8, 9.9, 10.4, 18.2, Table 17.8, Table 6.6, Figure 6.5, CCB HEALTH, CCP2.2, CCP5.4, CWGB URBAN} SPM.D.3.3 Urban systems are critical, interconnected sites for enabling climate resilient development, especially at the coast. Coastal cities and settlements play a key role in moving toward higher climate resilient development given firstly, almost 11% of the global population – 896 million people – lived within the Low Elevation Coastal Zone49 in 2020, potentially increasing to beyond 1 billion people by 2050, and these people, and associated development and coastal ecosystems, face escalating climate compounded risks, including sea level rise. Secondly, these coastal cities and settlements make key contributions to climate resilient development through their vital role in national economies and inland communities, global trade supply chains, cultural exchange, and centres of innovation. (high confidence) {6.2, Box 15.2, CCP2.1, CCP2.2, Table CCP2.4, CCB SLR} SPM.D.4 Safeguarding biodiversity and ecosystems is fundamental to climate resilient development, in light of the threats climate change poses to them and their roles in adaptation and mitigation (very high confidence). Recent analyses, drawing on a range of lines of evidence, suggest that maintaining the resilience of biodiversity and ecosystem services at a global scale depends on effective and equitable conservation of approximately 30% to 50% of Earth's land, freshwater and ocean areas, including currently near-natural ecosystems (high confidence). {2.4, 2.5, 2.6, 3.4, Box 3.4, 3.5, 3.6, 12.5, 13.3, 13.4, 13.5, 13.10, CCB NATURAL, CCB INDIG} SPM.D.4.1 Building the resilience of biodiversity and supporting ecosystem integrity50 can maintain benefits for people, including livelihoods, human health and well-being and the provision of food, fibre and water, as well as contributing to disaster risk reduction and climate change adaptation and mitigation.{2.2, 2.5, 2.6, Table 2.6, Table 2.7, 3.5, 3.6, 5.8, 5.13, 5.14, 12.5, Box 5.11 CCP5.4, CCB NATURAL, CCB ILLNESS, CCB COVID, CCB GENDER, CCB INDIG, CCB MIGRATE} SPM.D.4.2 Protecting and restoring ecosystems is essential for maintaining and enhancing the resilience of the biosphere (very high confidence). Degradation and loss of ecosystems is also a cause of greenhouse gas emissions and is at increasing risk of being exacerbated by climate change impacts, including droughts and wildfire (high confidence). Climate resilient development avoids adaptation and mitigation measures that damage ecosystems (high confidence). Documented examples of adverse impacts of land-based measures intended as mitigation, when poorly implemented, include afforestation of grasslands, savannas and peatlands, and risks from bioenergy crops at large scale to water supply, food security and biodiversity (high confidence). {2.4, 2.5, Box 2.2, 3.4, 3.5, Box 3.4, Box 9.3, CCP7.3, CCB NATURAL, CWGB BIOECONOMY} SPM.D.4.3 Biodiversity and ecosystem services have limited capacity to adapt to increasing global warming levels, which will make climate resilient development progressively harder to achieve beyond 1.5°C warming (very high confidence). Consequences of current and future global warming for climate resilient development include reduced effectiveness of EbA and approaches to climate change mitigation based on ecosystems and amplifying feedbacks to the climate system (high confidence). {2.4, 2.5, 2.6, 3.4, 3.5, 3.6, 12.5, 13.2, 13.3, 13.10, 14.5, 14.5, 15.3, 17.3, 17.6, Box 14.3, Box 3.4, Table 5.2, CCP5.3, CCP5.4, Figure TS.14d, CCB EXTREMES, CCB ILLNESS, CCB NATURAL, CCB SLR, SR1.5, SRCCL, SROCC} 49 LECZ, coastal areas below 10 m of elevation above sea level that are hydrologically connected to the sea 50 Ecosystem integrity refers to the ability of ecosystems to maintain key ecological processes, recover from disturbance, and adapt to new conditions.

Subject to Copyedit SPM-35 Total pages: 35 Achieving Climate Resilient Development SPM.D.5 It is unequivocal that climate change has already disrupted human and natural systems. Past and current development trends (past emissions, development and climate change) have not advanced global climate resilient development (very high confidence). Societal choices and actions implemented in the next decade determine the extent to which medium- and long-term pathways will deliver higher or lower climate resilient development (high confidence). Importantly climate resilient development prospects are increasingly limited if current greenhouse gas emissions do not rapidly decline, especially if 1.5°C global warming is exceeded in the near term (high confidence). These prospects are constrained by past development, emissions and climate change, and enabled by inclusive governance, adequate and appropriate human and technological resources, information, capacities and finance (high confidence). {1.2, 1.4, 1.5, 2.6, 2.7, 3.6, 4.7, 4.8, 5.14, 6.4, 7.4, 8.3, 8.5, 8.6, 9.3, 9.4, 9.5, 10.6, 11.8, 12.5, 13.10, 13.11, 14.7, 15.3, 15.6, 15.7, 16.2, 16.4, 16.5, 16.6, 17.2-17.6, 18.2-18.5, CCP2.3-2.4, CCP3.4, CCP4.4, Table CCP5.2, CCP5.3, CCP5.4, CCP6.3, CCP6.4, CCP7.5, CCP7.6, Figure TS.14d, CCB DEEP, CCB HEALTH, CCB INDIG, CCB DEEP, CCB NATURAL, CCB SLR} SPM.D.5.1 Climate resilient development is already challenging at current global warming levels (high confidence). The prospects for climate resilient development will be further limited if global warming levels exceeds 1.5°C (high confidence) and not be possible in some regions and sub-regions if the global warming level exceeds 2°C (medium confidence). Climate resilient development is most constrained in regions/subregions in which climate impacts and risks are already advanced, including low-lying coastal cities and settlements, small islands, deserts, mountains and polar regions (high confidence). Regions and subregions with high levels of poverty, water, food and energy insecurity, vulnerable urban environments, degraded ecosystems and rural environments, and/or few enabling conditions, face many non-climate challenges that inhibit climate resilient development which are further exacerbated by climate change (high confidence). {1.2, 9.3, 9.4, 9.5, 10.6, 11.8, 12.5, 13.10, 14.7, 15.3, CCP2.3, CCP3.4, CCP4.4, Box 6.6. CCP5.3, Table CCP5.2, CCP6.3, CCP7.5, Figure TS.14d} SPM.D.5.2 Inclusive governance, investment aligned with climate resilient development, access to appropriate technology and rapidly scaled-up finance, and capacity building of governments at all levels, the private sector and civil society enable climate resilient development. Experience shows that climate resilient development processes are timely, anticipatory, integrative, flexible and action focused. Common goals and social learning build adaptive capacity for climate resilient development. When implementing adaptation and mitigation together, and taking trade-offs into account, multiple benefits and synergies for human well-being as well as ecosystem and planetary health can be realised. Prospects for climate resilient development are increased by inclusive processes involving local knowledge and Indigenous Knowledge as well as processes that coordinate across risks and institutions. Climate resilient development is enabled by increased international cooperation including mobilising and enhancing access to finance, particularly for vulnerable regions, sectors and groups. (high confidence) (Figure SPM.5) {2.7, 3.6, 4.8, 5.14, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.2-17.6, 18.2-18.5, CCP2.3-2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB HEALTH, CCB INDIG, CCB DEEP, CCB NATURAL, CCB SLR} SPM.D.5.3 The cumulative scientific evidence is unequivocal: Climate change is a threat to human well-being and planetary health. Any further delay in concerted anticipatory global action on adaptation and mitigation will miss a brief and rapidly closing window of opportunity to secure a liveable and sustainable future for all. (very high confidence) {1.2, 1.4, 1.5, 16.2, 16.4, 16.5, 16.6, 17.4, 17.5, 17.6, 18.3, 18.4, 18.5, CWGB URBAN, CCB DEEP, Table SM16.24, WGI SPM, SROCC SPM, SRCCL SPM}