Acta Polytechnica CTU Proceedings **36**:6–14, 2022
https://doi.org/10.14311/APP.2022.36.0006

ASSESSMENT OF EXISTING STRUCTURES UNDER CLIMATE CHANGE

Johan V. Retief

Stellenbosch University, Department of Civil Engineering, Private Bag X1, Stellenbosch, 7600, South Africa
correspondence: jvr@sun.ac.za

Abstract. Assessment of the influence of human activities on recent, current, and future global and regional climate conditions and extremes has advanced sufficiently to provide a reasonable measure of its impact across the globe. The lack of concurrent adaptation of the design base for load bearing structures results mainly from the absence of a clear signal that climate change will have a significant effect on the climate actions that are accounted for in the structural design basis. The recent IPCC assessment of the physical science basis of climate change reports significant advances in observing and projecting changes in weather and climate extremes due to human influences. This provides an opportunity to reassess projections of future climate action conditions. Whilst the IPCC assessment confirms previous indications that, for example extreme wind will respond moderately globally, improvements in understanding and projecting changes show that trends will be overshadowed by uncertainties. The implication is that the design base will need to account for increasing uncertainties as climate actions are projected into the future, over the service life of existing structures, as well as those designed to current standards. The design base consequently in advance need to reflect continuous changes of existing structures.

Keywords: Climate actions, climate change, design base, existing structures, projection skills, structures, uncertainties.

1. Introduction

Since early hypotheses that the use of fossil fuels will lead to global warming due to increased atmospheric concentration of CO_2 as a greenhouse gas, the more general version of global warming due to changes in various greenhouse gases caused by human activities is now considered to be proven [1], [2]. Furthermore, the subsequent impact of the additional heat load on global systems is now investigated extensively, with an emphasis on the climate, because of the wide exposure of both human and natural systems, although related systems such as the ocean and the cryosphere also play an integral role in the response to human caused warming [3]. The extensive body of information on climate change compiled by the IPCC Series of assessment reports on climate change [3] provides an opportunity to consider the potential impact of anthropogenic climate change on any system or activity exposed to climate and weather conditions.

One such case, considered in this review, is the role of extreme climate actions, such as wind and snow loads, or thermal actions, in the design base for load bearing structures, such as buildings, industrial structures, and civil engineering infrastructure. Although this class of human systems have a low profile in the assessment of the impact of climate change, it represents vast capital investment and play a fundamental role in the socioeconomic environment. The low profile could be ascribed to the level of specification of climate actions with return periods of the order of millennia for levels of reliability associated with safety, depending on the reliability class of the structure. Such specifications are much more severe than the level of event likelihoods considered in climate change investigations. There is nevertheless a realisation that extreme events represent an important component of the impact of human induced climate change on the natural and socioeconomic environment [4, 5]. This has led to extensive consideration of climate and weather extremes in climate change [6–8].

The design base for load bearing structures evolved concurrently with the growing attention being paid to human induced climate change, running in parallel since around the mid-twentieth century. Notably the inherent variability of climate actions on structures made a significant contribution to the application of risk and reliability in deriving operational semi-probabilistic design, expressed in limit states format. Ironically, the potential impact of climate change has yet to be implemented in general standardized design practice, as reflected for instance as an explicit class of risk [9] or as a prominent design situation [10]. This situation could be the result of climate actions that are specified at several standard deviations from annual extremes. Furthermore, pioneering efforts to account for climate change observe limited trends from either historic data or projected values, even under severe scenarios of human caused radiative forcing of global warming [11, 12]. When the difficulties of extracting reliable extreme value models from historic data is considered, such as for wind load in South Africa [13–15], the opportunity to benefit from the extended assessment of climate extremes [7] should be utilised.

Less obvious in the somewhat surprising state of matters is the acceptance that climate change will have a relatively mild effect on structural loads, given the growing body of information on substantial changes in future conditions coming out of the IPCC assessment of climate change. Some scrutiny of the relevance of climate change to structural loads indicate a lack of credible information on future extreme climate and weather conditions [16].

The objective of this paper is to review the advances in developing the physical sciences basis of climate change as reflected in the latest IPCC assessment [1] as source of information on climate actions on structures, specifically considering climate extremes [7]. Assessment of climate extremes rests on information from observations and paleoclimatic histories, which is applied to the identification of human drivers of changes, within processes of natural variability, towards sufficient understanding for attribution to human influences, to changes in the climate and in extremes [6, 16], observed changes, and the application of change indicators and uncertainties [17], projection of future conditions, and their various sources of uncertainty [18], finally input required for risk assessment [8].

The review is done at three levels: Firstly, confirmation of climate change, its attribution to human origins, and the current rate of change, provide the background information for decision-making on the necessity, even urgency to implement adaptation measures for the climate action design basis. At the second level the state of knowledge on changing of climate extremes relevant to structural actions provides the background to what information could be extracted from the climate change knowledge base currently available for possible decisions on immediate implementation. Thirdly the ultimate check is to review the available skills for projection of climate actions to determine the required resolution of projecting future trends, and the relative dominance of natural variability and projection uncertainties, as determined by projection model resolution. Each of these objectives could require an exposition on its own, so this review can only be done at strategic level within the scope of this paper. A secondary objective is to raise the issue of the impact of climate change on the design base for structures and provide an overview of the state of information. The perspective taken in this review is significantly biased towards extracting information to be used in decision-making, see for example [19–21].

2. Climate State And Pathways Towards Extreme Climate

Based on robust understanding of climate system fundamentals, the systematic scientific assessment of climate change has evolved from theory since the 1970s, to now be regarded as an established fact. Recent advancements are based on the integration of multiple lines of evidence consisting of observations that include the emergence of a climate change signal, paleoclimatic evidence, the identification of natural and human drivers of the climate, understanding and attributing climate change, and implementation of this information in model development [1]. This provides the platform for projecting possible future climate conditions for representative pathways that depend on mitigation measures taken on a global scale. Characterization of the current state of the climate, representative climate futures, with specific reference to climate and weather extremes, serve as background information currently available to inform decisions on future trajectories for climate actions on structures.

2.1. Current Climate State

Whilst the complexity of climate change emerges from each successive version of the IPCC series of Assessment Reports, the progression of the process is concisely represented by the metric of global warming since preindustrial conditions: The observed temperature increase ΔT of 1.09 [0.95 to 1.20] °C above the 1850-1900 baseline for the decade ending 2020 can be related to CO_2 atmospheric concentration, as most important greenhouse gas, reaching 410 ppm, compared to the 270 ppm baseline, with changes over land of 1.59 [1.34 to 1.83] °C and the ocean of 0.88 [0.68 to 1.01] °C respectively [1].

The trend since 1850 is displayed graphically in Figure 1, reflecting significant achievements in simulation of the climate change [1], [3]. The range of natural variability of about 0.5 °C is evident, including episodic perturbations due to natural causes. The overall trend is to show a steep incline starting at around the 1970's towards the ΔT-region of 1 °C. Climate simulation including natural and human drivers follow the trend remarkably well, though with some lag in the initial increase. The smoother simulated average (brown line) can be ascribed to the multi-model averaging process, however the uncertainty range (shading) that exceeds natural variability, suggests that the observation is just one 'worldline' of many possible outcomes of a highly complex system. Simulation of a counterfactual world without human influence provides a clear indication of emergence of climate change above natural variability at around the 1970s and attribution of the global temperature rise to human causes as indicated by the differences between simulations. Attribution is resolved further to indicate the contribution of all greenhouse gases [+1.5 °C] and other human causes [−0.4 °C], with CO_2 as the dominant gas [+0.8 °C] and SO_2 as the dominant other cause [−0.5 °C].

Scaling global temperature change across the global climate and down to its regional impact due to climate extremes is demonstrated by Figure 2, confirming human influences on extremes in temperature and precipitation, as representation of different modes of climate extremes. This overview of pervasive impact of human

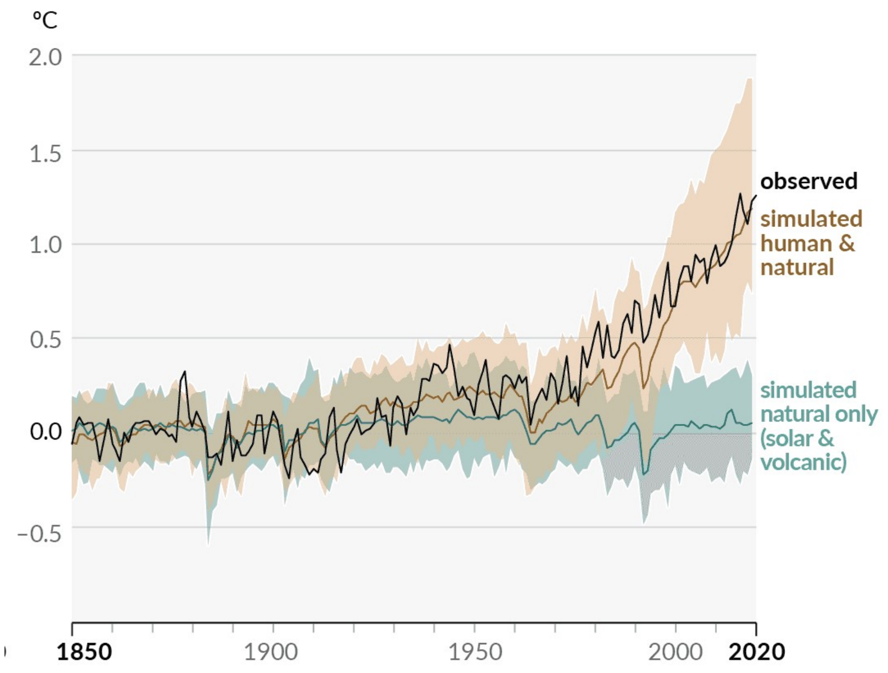

FIGURE 1. Observed and simulated history of global surface temperature changes (annual average) and causes of recent warming, demonstrating model skills [1].

activities on the environment is based on the systematic implementation of methodologies that apply also to resolving the climate extremes central to this paper, consisting of (i) understanding the climatological processes and drivers of change, (ii) to be able to observe historic trends, (iii) which are applied to validate simulation models, (iv) using the identification of emergence and attribution of the phenomenon under investigation, (v) as basis for establishing confidence in projection of future changes and conditions. This methodology is also used to assess climate extremes [7] and applied here to take measure of extremes relevant to climate actions on structures.

2.2. FUTURE CLIMATE PATHWAYS

The main future climate drivers caused by human activities are represented by five scenarios of combined shared socioeconomic pathways (SSP) that is combined with the level of radiative forcing by the end of the century (in W/m^2) with trajectories for CO_2 as the most significant greenhouse gas. Global warming scales almost linearly with accumulated atmospheric CO_2 concentrations (Figure 3(a)), resulting in alternative projections of observed warming up to the year 2100 (Figure 3(b)). The range of outcomes depending on mitigation policies [SSP1-1.9 to SSP5-8.5] can be compared to the *very likely* range for simulated pathways (coloured shading) shown for SSP1-2.6 and SSP3-7.0. A significant implication of the relationship between accumulated carbon release and temperature rise is that every tonne of carbon released contributes to global warming.

An indication of the geographic distribution of these changes is provided in Figure 4, showing the comparison between observed and simulated changes in surface temperature at 1 °C, and for projected ΔT-values of $\{1.5, 2.0.4.0\}$ °C. An indication of the regional distribution of climate change extremes is compiled in Figure 5, indicating the number of regions for which climate impact drivers (CID) for the set of climate extremes are relevant, where a CID is a measure of a physical climate system condition (mean, event, extreme) that will affect society or an ecosystem, by either increasing or decreasing. Confidence levels are indicated by shading. Mixed signals and *low confidence* levels are notable for severe wind and snowstorms.

3. CHANGING WEATHER AND CLIMATE EXTREMES

The occurrence of climate and weather extreme events have a high profile in public interest: it is often connected with climate change and its attribution to human activities. Information on such a relationship is therefore of interest to policy decision-making, as a prime objective of IPCC assessment of human induced climate change [1]. Differentiation of human related radiative forcing of changes from natural variability, however, poses stringent challenges to climate science skills, particularly to determine attribution for individual events. Successful simulation of climate extremes provides confidence in its projection skills. Furthermore, extreme weather and climate events evidently make a significant contribution to the impact of climate change. Against this background, recent

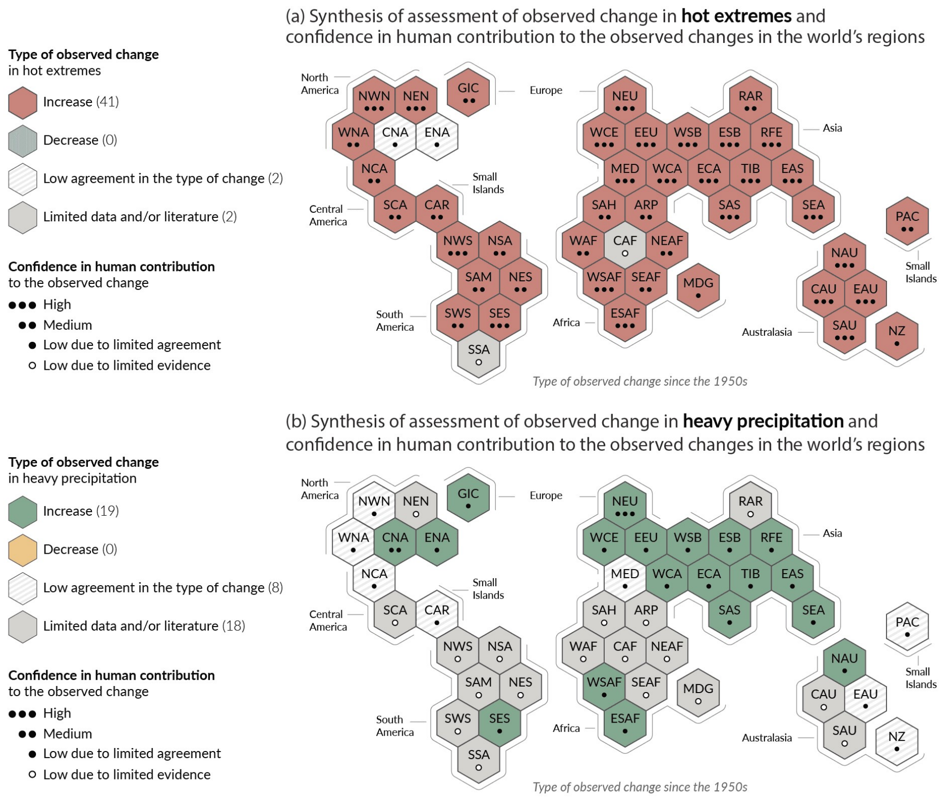

Figure 2. Synthesis of assessed observed and attributable regional changes for hot extremes and heavy precipitation, demonstrating the diversity of regional and modal changes [1].

advancement in the assessment of changes in extremes is regarded as one of the significant achievements of climate sciences [3].

Climate extremes provide a logical point of entry for climate actions on structures. This could be done in two steps: Projection of climate extremes in general, and extreme classes associated with extreme wind as assessed in [7] and [8] are reviewed in this section. The mode of presentation of the assessment is to aggregate results to inform general observations on the relevance of extremes to climate change. Application of this information to the adaptation of the design base for wind load is discussed in the next section, based on extracted information on trends in climate actions as it is demonstrated by considering wind load from [7, 8].

This section explores the challenges in observing and modelling of climate extremes, with the intrinsic properties of being rare, short-lived, dependent on local conditions, and inherently highly variable. This is aggravated by the extensive extrapolation into the future from an uncertain observation base, particularly for more extreme events.

3.1. Assessment Methodology for Extremes

A systematic methodology is employed to relate human influences to changes in extreme weather and climate from historic observation to the prediction of future conditions through validated models [7]. The first step consists of the identification of mechanisms and drivers of extreme events, to reflect the knowledge base of the process. Observed trends provide the baseline against which changes are measured. Model evaluation considers both the match between models and observation, and an assessment of projection uncertainties. Detection of human influences beyond natural variability is used as measure of the level of attribution; considered across the dimensions of the situation under investigation, such as extreme class, global, regional, or local scale; demonstrated for the class of extreme climate. Projections ultimately provide trends and uncertainties in changes to extremes as climate change progresses.

Assessment of the results is expressed in the customary levels of confidence and likelihood { *low, medium, high* }; in case of *high confidence*, a likelihood may be assigned as { *likely, very likely, extremely likely, virtually certain* }; based on skills to simulate observed trends, a measure of model uncertainty based on inter-model comparisons, and judgement on the scientific basis for dominating processes [6]. Detection and attribution of human influences are applied at global warming of ΔT of 2 °C; with projected changes at $\{1.5, 2.0, 4.0\}$ °C [7].

The success of the process is confirmed by the finding that changes in extremes for temperature, precipitation, droughts, tropical cyclones, and compound fire

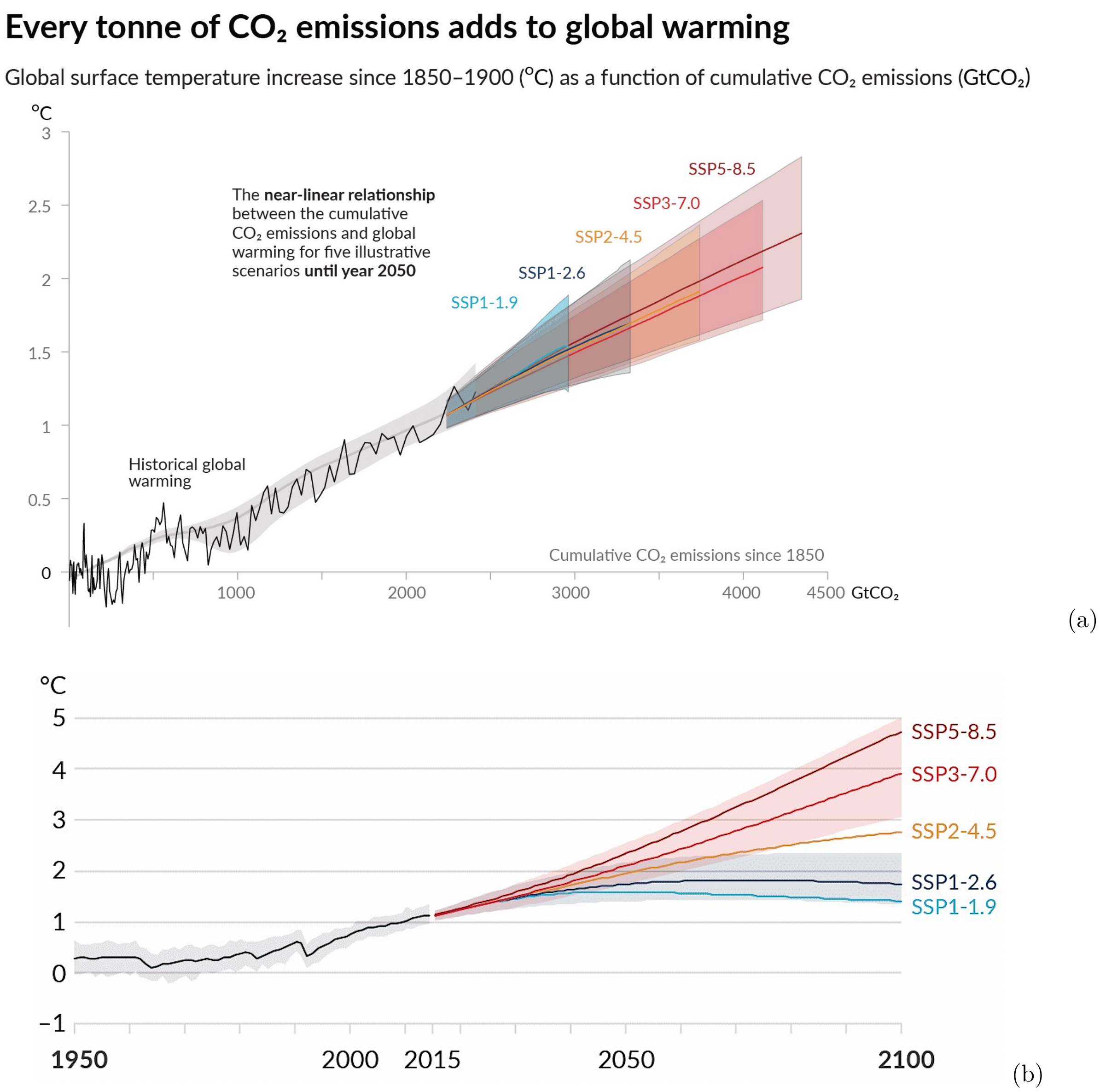

FIGURE 3. Pathway dependent global climate futures: (a) Near-linear linear relationship between cumulative emissions and global surface temperature (b) Global surface temperature changes in °C relative to 1850-1900 [1].

weather, would have been *extremely unlikely* without human causes [1]. Recent advances include resolving human influences on individual extreme events, regional scales, and at different warming levels. This is based on improved knowledge, complementary sources of evidence, improved models, and accumulating historic data.

3.2. EXTREME CLIMATE CLASSES

The assessment is concerned with occurrence over land, consisting broadly of temperature related extremes, the water cycle, storms, and compound events that are classified as low-likelihood high-impact (LL-HI) situations. Temperature extremes provide the yardstick for observing changes in extremes and their sensitivity to human influences. This results from the good standing of the state of knowledge, observation, modelling, attribution, and projection skills. Heavy precipitation, generally and as associated with extreme storms, demonstrates the implications of more complex extremes with interacting and feedback processes, yet advancing in projection and attribution skills. Extreme storms, subdivided into tropical cyclones (TC), extratropical cyclones (ETC), and severe convective storms (SCS), include extreme wind as a component. An extreme climate class dedicated to extreme wind was introduced recently [7, 8], allowing for the aggregation of common characteristics from storm classes; providing for better alignment between climatology and wind engineering application.

Extension of climate change assessment to extreme climate provides an additional line of scientific proof of the process: It is regarded as an integral component of climate change, manifested by the increased frequency of climate extremes, particularly hot extremes, on global and regional scales, on most continents, even

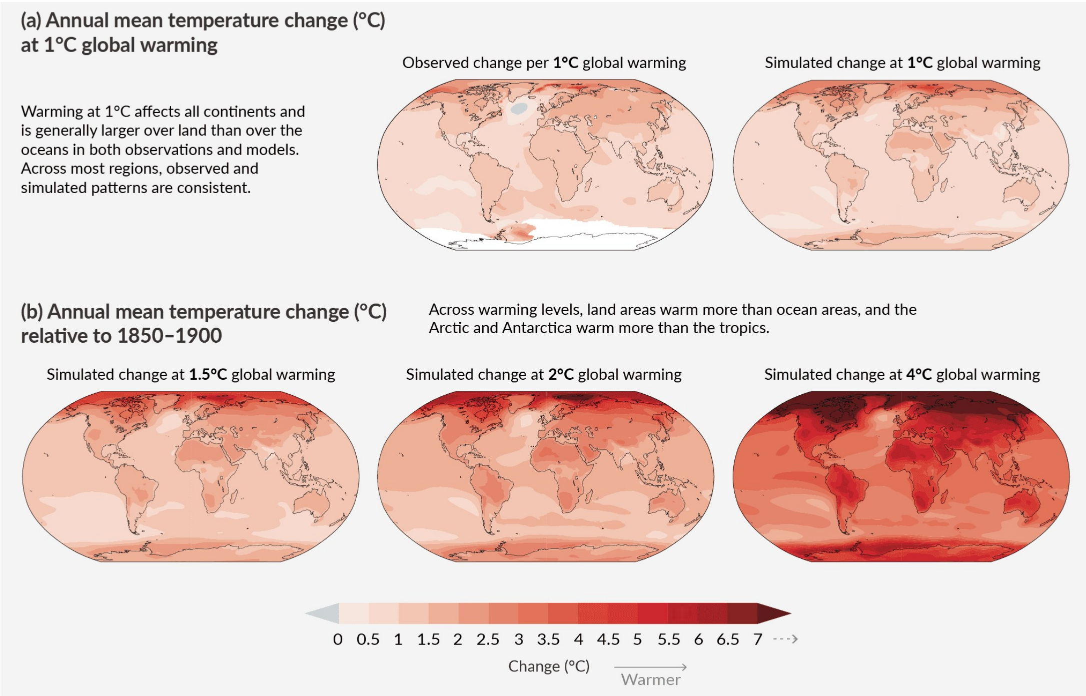

Figure 4. Geographical distribution of the global climate (a) comparing observation with simulation (b) for simulated changes in global warming at representative levels [1].

for individual events based on case studies [1], [7]. Observations made on extreme storms range from *high confidence* of increases in precipitation rates, average and peak wind for tropical cyclones globally and severe convective storms regionally, but *low confidence* in past changes of maximum wind speed for extratropical cyclones [7]. Low-likelihood high-impact events are assessed primarily from the perspective of concurrent events. Notably *high likelihood* is assigned to the generic observation that historically unprecedented events and surprises can be caused by the rate of global warming.

As a general observation on the outcome of the IPCC review, extreme weather and climate events are predominantly characterised by precipitation extremes, (occasionally complemented by wind) as a measure of frequency, intensity, or by implication by the impact of human origins on changing conditions. This approach is used extensively for assessing tropical cyclones. A significant deviation is the conclusion that an increase in the proportion of high intensity tropical cyclones will *very likely* lead to an increase in average peak wind speed, as well as an increase in rain-rates, despite a decrease in global frequencies of such events [7].

A similar low profile for strong wind can be observed for SCS, as opposed to using precipitation as indicator. It is concluded for example with *high confidence* that average and maximum rain rates associated with such storms will increase with global warming in some regions [7]. Yet, wind and tornadoes are included as an outcome of projecting an increase in frequency and intensity of severe thunderstorms with *high confidence*.

An exception to the subdued role of severe wind in extreme storms is the use of near-surface wind speed, together with precipitation, as extreme value indicator of the severity of ETCs. Still, extreme precipitation events are well established in the identification of extratropical storm conditions. Indication of past changes in maximum wind speed associated with ETCs is regarded to be observed with *low confidence*, with *medium confidence* that projected changes will be small, and with *high confidence* that precipitation rates will increase with warming. Notably, there is *medium confidence* that the projection of wind speed and precipitation associated with ETCs depend on the resolution and formulation of climate models.

The aggregated conclusion, made with *low confidence*, is that the intensity of observed extreme winds is becoming less severe in the lower to mid-latitudes, while becoming more severe in poleward latitudes beyond 60 degrees. There is *medium confidence* that the frequency and intensity of extreme winds will be associated with the projected changes in the frequency and intensity of associated tropical and extratropical cyclones. Although no explicit mention is made of SCSs in the summary, *high confidence* is indicated that convective available potential energy increases in response to global warming in the tropics and subtropics, suggesting more favourable environment for SCSs; though with *high confidence* that limited application of convection-permitting models lead to significant uncertainty about projected regional changes.

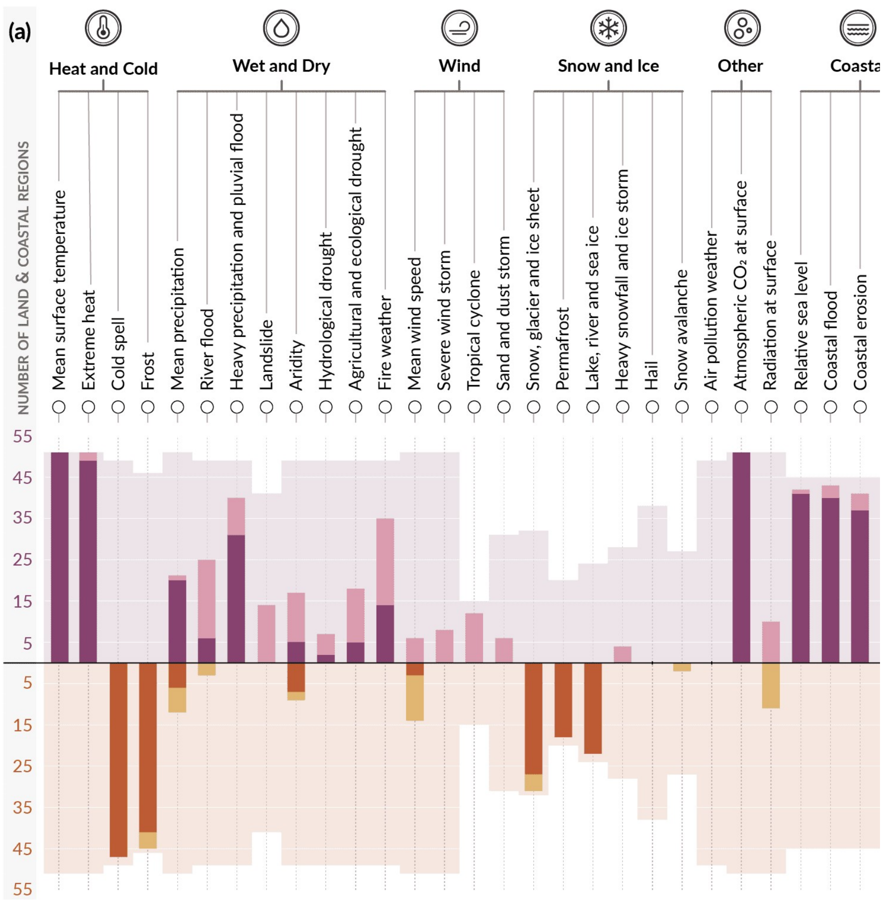

Figure 5. Synthesis of the number of regions where climate impact drivers (CID) are projected to change, increasing (top) and decreasing (bottom) with high/medium confidence levels (shading) [1].

4. Adaptation Of Design Base For Wind Actions

The difference between the scientific approach followed in the IPCC assessment of climate change to provide best estimates of the process, even including climate extremes, and the information required for risk-based decision-making that includes the consequences of tail-end events, is appreciated by assessors and researchers [22, 23]. Conversion of the information on extreme wind, as summarised above, to information serving as background to the adaptation of the design base for wind load, requires best estimates of both trends and their uncertainties.

4.1. Assessment of Projected Wind Actions

In the absence of any reported observation related to extreme wind changes in [7], expressed at likelihood levels as indicated in the previous section, confidence levels are applied in an inverse manner to reflect uncertainty in the projection qualitatively, as opposed to its intended scientific qualifier, as applied in [7]. Climate systems associated with extreme wind for South Africa are synoptic scale frontal systems and mesoscale convective storms [24], which are related to ETCs and SCSs respectively. Confidence levels for the components of assessment (see Section 3.1) for these two extreme storm classes are therefore utilised as basis for qualifying changes in trend and uncertainty of wind load projections.

Significantly, there is no review of the mechanisms and drivers used for the identification, modelling, and projection of changes due to human causes for ETC's (compare Section 2.1). Accordingly, it is not surprising that there is *low confidence* in observed changes recently, and over the past century. This is due to large interannual and decadal variability. Ironically, *high confidence* is assigned to model underestimation of dynamical intensity of events (related to surface wind speed), similarly for linking systematic bias between ETC events and rainfall intensity to model limitations. Furthermore, there is *low confidence* in attribution of events to human influence resulting from limited observations. Projections of dynamic intensity depend, with *medium confidence*, to the resolution and formulation of the representation of convection in climate models. Given the limited information on trends in ETC intensity, also for extreme wind projections, the poor rating obtained for all components of the assessment methodology leads to the conclusion that the current state of information does not provide any guidance on future changes, rather than to indicate small changes. This situation arises from limitations in observation, attribution to human influences, and modelling that reflects drivers of change in ETC wind extremes.

A rather complex situation emerges from the assessment of SCS, or mesoscale convective systems (MCS), with highly skewed information provided across all elements of the assessment steps, ranging from noticeable advances in mesoscale observation networks, complemented by high resolution modelling, mainly in the USA, versus *low confidence* in resolving regional scale impacts across the balance of regions due to limits in observation and simulation modelling. The specific advances in resolving mesoscale extremes could therefore serve as benchmark to estimate uncertainties in other regions, mostly outside the USA. Such comparisons should include the identification of regional climate impact drivers, limits to observed trends due to insufficient coverage and long-term records, model deficiencies of resolution and provision for convection processes, the influence of the fine balance between opposing environmental factors that affect severe storm development.

4.2. Integrated Basis for Design and Assessment

The adaptation of the design base for wind load on structures is evidently dominated by uncertainties of the changes to the extreme wind climate caused by future climate conditions. An expedient use of the current design base to enhance the robustness of structures against such uncertainties, consists of applying the stipulated wind load in a sensitivity analysis as an accidental design situation for climate change [25]. The extension of such an approach to incorporate methodologies for the assessment of existing structures [26] provides the opportunity to reflect the trajectory of changing wind loads over the service life of the structure. At the fundamental level, such an approach explicitly accounts for the significant conversion from treating climate actions under assumptions of stationarity to transitionary. At an operational level, the progression of assessment methodologies from design value, through reliability- and risk-based approaches, enables more advanced estimates of reserve capacity of the structure to changing wind loads. Strategically, planning for future assessments of the structure as the changing climate pathways evolve can be incorporated into the design process. In addition, performing the first assessment upon completion of the structure would not only ensure that pertinent information for subsequent assessments is captured, but should contribute to proper integration of the bases for design and assessment of structures in general.

5. Observations And Conclusions

The paper reviews the latest set of assessments on the physical science basis for climate change due to human influences from the perspective of its relevance to climate actions on load bearing structures. Of particular interest is the advances made in determining the impact of changing climate extremes on human and ecological systems. Characterisation of climate change in general provides the context for decisions on timing of any adaptation of the design base, whilst climate extremes inform decisions on climate actions, which are specified at extreme value fractiles to achieve required levels of reliability for structures. Both topics are therefore reviewed in the paper.

It is notable that initial suppositions and pioneering observations on both climate and extreme changes are substantiated with advancement of its scientific bases, with growth of the information base, arguably over orders of magnitude, predominantly realised as confirmation, but with an appreciation of the complexity of the process, if not its pervasive nature. This is demonstrated by the observation that the initial identification of human caused global warming has progressed not only to measurable global and regional warming, but also to the attribution of human influences on an increasing set of extreme events, and an extension of the set of human influences.

The main conclusions of this review are thus related to both the changing climate and extremes. Human induced climate change has demonstrably advanced to such an extent that any system that would be impacted over multidecadal scales, need to implement adaptation measures, irrespective of the outcomes of mitigation scenarios. On the question of whether this includes structures exposed to climate actions, the conclusion is that such exposure results not so much from the mild trends observed and projected for climate actions, but predominantly from uncertainties of future changes which might be several standard deviations from expected trend conditions.

Two main lines of action follows: Whilst advances in climate extreme projections should be followed up, sufficient robustness and adaptability should in the meantime (now) be incorporated in design decisions. The methodologies for the assessment and adaptation of existing structures provide useful instruments for the transition from the context of stationarity of the current design base.

As a final disclaimer, the review considers an issue which evidently falls within the domain of climate sciences, rather than engineering sciences. However, it is essential for engineering considerations to appreciate the impending conversion of climate actions on structures from an empirical base under stationary conditions, to one requiring at least a reflection of the transient future climate and its impact on an adapted design base that is intimately related to climate sciences. The review therefore also demonstrates an engineer's perspective of climate change, in preparing to engage with climatologists in divining the future.

List of symbols

CID Climate Impact Driver

ETC Extratropical cyclons

IPCC Intergovernmental Panel on Climate Change

LL-HI Low-Likelihood High-Impact situations

MCS Mesoscale convective systems

SCS Severe convective storms

SSP Share Socioeconomic Pathways

TC Tropical cyclones

References

[1] IPCC. *Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. et al. (eds.)]. Cambridge University Press. In Press, 2021.

[2] M. Hulme. Concept of Climate Change. *The International Encyclopaedia of Geography.* Wiley-Blackwell/Association of American Geographers (AAG), 2016.

[3] P. A. Arias, N. Bellouin, E. Coppola et al. Technical Summary. In: *Climate Change 2021: The Physical Science Basis*. Cambridge University Press. In Press, 2021.

[4] IPCC. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation.* A Special Report of Working Groups I and II of IPCC. Cambridge University Press, Cambridge, UK and New York, NY, USA, p. 582, 2012.

[5] D. L. Swain, D. Singh, D. Touma, et al. Attributing Extreme Events to Climate Change: A New Frontier in a Warming World. *One Earth* **2**(6):522-7, 2020. https://doi.org/10.1016/j.oneear.2020.05.011.

[6] D. Chen, M. Rojas, B. H. Samset, K. Cobb et al. Framing, Context, and Methods. In: *Climate Change 2021: The Physical Science Basis.* Cambridge University Press. In Press, 2021.

[7] S. I. Seneviratne, X. Zhang, M. Adnan et al. Weather and Climate Extreme Events in a Changing Climate. In: *Climate Change 2021: The Physical Science Basis.* Cambridge University Press. In Press, 2021.

[8] R. Ranasinghe, A. C. Ruane, R. Vautard et al. Climate Change Information for Regional Impact and for Risk Assessment. In: *Climate Change 2021: The Physical Science Basis.* Cambridge University Press. In Press, 2021.

[9] ISO 2394:2015. *General principles on reliability for structures.* International Organisation for Standardization, 2015.

[10] ISO 22111:2019. *Basis for design of structures - General requirements.* International Organisation for Standardization, 2019.

[11] P. Croce, P. Formichi, F. Landi. Climate Change: Impacts on Climatic Actions and Structural Reliability. *Applied Sciences* **9**(24), 2019. https://doi.org/10.3390/app9245416.

[12] H. P. Hong, Q. Tang, S. C. Yang, et al. Calibration of the design wind load and snow load considering the historical climate statistics and climate change effects. *Structural Safety* **93**, 2021. https://doi.org/10.1016/j.strusafe.2021.102135.

[13] J. V. Retief, A. M. Goliger. Development of an updated fundamental basic wind speed map for SANS 10160-3. *Journal of the South African Institution of Civil Engineering* **59**(4):12-25, 2017. https://doi.org/10.17159/2309-8775/2017/v59n4a2.

[14] J. Botha, J. V. Retief, C. Viljoen. Uncertainties in the South African wind load design formulation. *Journal of the South African Institution of Civil Engineering* **60**(3), 2018. https://doi.org/10.17159/2309-8775/2018/v60n3a2.

[15] F. P. Bakker. *Characterisation of the South African Extreme Wind Environment Relevant to Standardisation.* PhD Dissertation, Stellenbosch University. 2021.

[16] V. Eyring, N. P. Gillett, K. M. Achuta et al. Human Influence on the Climate System. In: *Climate Change 2021: The Physical Science Basis.* Cambridge University Press. In Press, 2021.

[17] S. K. Gulev, P. W. Thorne, J. Ahn J et al. Changing State of the Climate System. In: *Climate Change 2021: The Physical Science Basis.* Cambridge University Press. In Press, 2021.

[18] J. Y. Lee, J. Marotzke, G. Bala, et al. Future Global Climate: Scenario-Based Projections and Near-Term Information. In: *Climate Change 2021: The Physical Science Basis*, 2021.

[19] H. E. Auld. Adaptation by design: The impact of changing climate on infrastructure. J Public Works & Infrastructure. 1(3), 276-288, 2008.

[20] S. Hallegatte. Strategies to adapt to an uncertain climate change. *Global Environmental Change* **19**(2):240-7, 2009. https://doi.org/10.1016/j.gloenvcha.2008.12.003.

[21] C. Helgeson. Structuring Decisions Under Deep Uncertainty. *Topoi* **39**(2):257-69, 2018. https://doi.org/10.1007/s11245-018-9584-y.

[22] R. T. Sutton. Climate Science Needs to Take Risk Assessment Much More Seriously. *Bulletin of the American Meteorological Society* **100**(9):1637-42, 2019. https://doi.org/10.1175/bams-d-18-0280.1.

[23] C. P. Weaver, R. H. Moss, K. L. Ebi, et al. Reframing climate change assessments around risk: recommendations for the US National Climate Assessment. *Environmental Research Letters* **12**(8), 2017. https://doi.org/10.1088/1748-9326/aa7494.

[24] A. C. Kruger, A. M. Goliger, J. V. Retief et al. Strong wind climatic zones in South Africa. *Wind and Structures Journal* **13**(1):37-55, 2010.

[25] J. Retief, C. Viljoen. Provisions for Climate Change in Structural Design Standards. In *Engineering for Extremes*, Springer Tracts in Civil Engineering, p. 429-46. 2022. https://doi.org/10.1007/978-3-030-85018-0_21.

[26] M. Holický, J. V. Retief, C. Viljoen. Reliability basis for assessment of existing building structures with reference to SANS 10160. *Journal of the South African Institution of Civil Engineering* **63**(1), 2021. https://doi.org/10.17159/2309-8775/2021/v63n1a1.