**What is the evidence for the impact of ocean warming on subtropical and temperate corals and coral reefs? A systematic map.**

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**Abstract**

Background.

Subtropical coral reefs are important, yet comparatively understudied ecosystems, which host diverse and abundant array of marine life and provide substantial socio-economic benefit to communities. Research into the impacts of climate change on subtropical coral reef ecosystems has increased over the past 2 decades as severe, extreme, and increasingly frequent degradation events have been recorded in the systems. Understanding the extent of research effort and type of evidence assessing the response of subtropical corals and coral reefs to climate change can provide a valuable insight into global patterns in research effort and identify critical knowledge gaps that will impact our ability to predict and respond to change in subtropical coral reefs. Here a systematic map protocol is applied to identity research effort from 2010 to 2023 and highlight patterns in the type, scale, and location of research conducted and availability of data reported.

Methods.

Primary literature within Scopus and Web of Science databases are identified and extracted. The methodologies outlined in previously published systematic map protocol was applied from which a total of 91 primary research publications were identified for data extraction. Data extraction included bibliometric data, discipline and type of research, type of data reported and how it was recorded, and data availability.

Findings. The identified literature consisted primarily of experimental studies (46%) and observational studies (38%). The major cluster in knowledge was identified by using Marine Ecoregion of the World (MEOW); majority of the primary literature investigated the corals in the ecoregion of Southern China (13%), followed by the ecoregion of Western Mediterranean (10%). A total of 7 ecoregions with primary literature identified are in within the Oceania continent, which takes up a majority (29%) when compared to Southern China and Western Mediterranean. Stressors reported as drivers of ocean warming are identified, and an increase in use of standardised metrices such as degree heating week (DHW) and marine heatwave (MHW) particularly in Australia for both metrices is reported. The continued use of both standardised metrices (DHW and MHW) to allow for effective communication between researcher and readers is recommended. Finally, the need for research in regions such as the Western Indian Ocean are also highlighted, where studies on the systems are lagging behind their counterparts in other subtropical ecoregions.

Conclusions. Increasing ocean temperature and its effects on subtropical and temperate coral reefs is of increasing concern to policy makers and researchers. A systematic map provides a broad overview of research efforts and topics and identifies areas where research efforts should be focused on. This systematic map identified the major research clusters in Asia, Australia, Mediterranean, and North America, gaps of research are identified in regions such as East Indian Oceans, and research efforts on the topic since 2010 around the globe.

Keywords: Coral; Coral Reefs; Scleractinian; High Latitude; Marginal; Climate Change; DHW; MHW

**Background**

Coral reefs ecosystems are amongst the most important ecosystems in the world, providing suitable environment for marine biodiversity and socio-economic benefits to communities that rely on the resources of coral reefs [1]. However, the conditions of coral reefs are declining under the effects of climate change [2, 3], threatening the biodiversity of marine environments, and even leading to local extinction of specialist species [4]. In tropical coral reefs, records of climate change have shown that declination in number of species and subsequently the degradation of the coral reef will be catastrophic [5]. These issues are pressing and researchers around the world have put in significant efforts to identify the issues and address the public about the topic [6]. Despite these efforts, tropical coral reef conditions around the world continue to decline [7, 8]. The continuation in increase of ocean temperature causes bleaching and mortality in tropical reefs and expansion of tropical coral species into subtropical regions [9, 10]. In 2010, record of subtropical coral reefs bleaching [11, 12] indicated that ocean warming is also affecting subtropical marine ecosystems. These bleaching events in the recent decades reflect the need to assess the conditions of subtropical coral reefs to conserve them. The subtropical coral reefs are different from tropical coral reefs in terms of reef dynamics [13], and they house a variety of marine organisms with some species of marine organisms are endemic on these reefs [14]. Moreover, studies also reviewed the capability of these coral reefs in subtropical regions to become refugia for tropical species in the marginal areas [15]. This leads to a new influx of research into the topic and more resources and efforts are put into conservation of subtropical coral reefs.

Despite the efforts of research on the conservation of subtropical coral reefs, there are contradictions between studies on the hypotheses for the future role and impacts to these ecosystems, from refuge from climate change [16, 17], poleward expansion of tropical species [17, 18], and decline and loss of endemism of regions [19]. In terms of refugia, the conditions for a site to become a refugia depends largely on the oceanographic properties of its surrounding water. Studies reported the importance of upwelling in the water columns to the long-term stable state of domination by thermally susceptible coral genera on the forereef of subtropical atoll by decreasing the temperature of water [15, 16]. However, the upwelling of water column will only provide a refuge if there is synchrony between ocean warming and upwelling [16]. For poleward expansion of tropical species, studies have shown under climate change, herbivory marine organisms and tropical corals from tropical regions are expanding into subtropical and temperate region, and these expansions have the potential to alter the community structures of subtropical and temperate regions [17, 20], this influx of tropical poleward expansion could pose a threat on the subtropical and temperate coral communities, as some key tropical coral species such as *Acropora hyacinthus* and *Acropora muricata* have higher growth rates than other species, endemic species in these regions [21] may face a declination as the result of competition with invasion of tropical species [17]. Thus, there is a need to compile the evidence currently available to provide a summary of the current state of knowledge on different aspects of the topic. With the current number of primary literatures available, it is now the time where existing literature can be comprehended into a report for easy communication of current state of knowledge.

Systematic map acts as an overview of distribution and abundance of evidence in relation to a broad research topic [22]. Systematic maps enable the identification of gaps in research, knowledge clusters, study themes and methodologies in studies. Additionally, analysis of bibliometric data such as citation numbers, publishing information and author collaboration details from published studies provides details of authors collaboration networks, which can be used to identify the trend of study, research groups and impact of studies. The insights provided by a systematic map help direct future research effort more accurately and effectively.

To determine the research question for this systematic map, several major aspects are considered, including the location of study, year of publication, study types, and metric used for identifying ocean warming events. Marine Ecoregions of the World (MEOW) was introduced as a hierarchical biogeoregionalisation of coastal and shelf areas based on biogeographic assessments, ecoregional assessments, government-derived or supported systems and input from different researchers and assessments [23]. Using MEOW as a standardised reference for location enables a systematic approach for recording locational data in marine conservation planning and research, enabling a more robust referencing between studies to identify biogeographical data. In early 2010s, more publications begin to record the effects of ocean warming and extreme weather events on subtropical coral reefs [24-26], therefore, assessing studies from as far as 2010 will allow a good understanding of existing relevant literature on the topic. Methods of recording extreme temperature events are available in a variety of ways; most common methods of recording include degree heating weeks [27-29] and marine heatwaves [30]. Using standardised event recording methods allows direct comparison between study, and the use of DHW and MHW is also reproducible using openly available NOAA’s remote sensing data. Identifying the literature that utilised these standardised methods will provide insights into the commonality of using DHW and MHW in study of subtropical coral reefs.

**Objective of the Review**

The following questions are the aim of this systematic map as outlined in the published protocol [31]:

What is the evidence, since 2010, within scientific literature on the impact of ocean warming to subtropical and temperate corals and coral reefs?

How has sea surface temperature data been recorded in subtropical and temperate coral reef locations?

Are the studies using MHW (Marine heatwaves) and/or DHW (degree heating weeks) as their metrics of evaluation of climate events?

How are the levels of mortality and bleaching defined in the research locations?

Where, and how, has coral biological response and coral reef ecological impacts been recorded in subtropical and temperate coral reef locations?

The questions listed above concerns the recording methods of existing literature as well as the distribution of researchers around the world working on the topic. Through answering these questions, the trend of using different temperature data, reporting metrices and publication timeline are identified, providing a summary of recent publications to the users of this report.

**Terminology.**

**Ocean warming.** Ocean warming refers to increase of temperature in oceanic waters by the means of raising SSTs and thereafter the increase in temperature of sea water in various depths.

**Ocean Acidification (OA) and warming interaction.** Drop in pH value of ocean due to accumulation of carbon dioxide gases in atmosphere [32-34]. Some 30% of the atmospheric CO2 were absorbed by the ocean [33, 35] and it led to chemical reactions which reduced the amount of carbonate ions available in the water. This makes it difficult for marine calcifying organisms to form their biogenic calcium carbonate skeletons [36]. Ecological changes due to ocean warming combined with ocean acidification could compound and led to further damage to the calcifying organisms in the ocean.

**Biological responses.** Intrinsic response of an individual species or organism due to change of their environment.

**CEESAT.** Acronym for Collaboration of Environmental Evidence Synthesis Assessment Tool. [37]

**Coral.** Members of the Anthozoa orders; Scleractinia, Corallimorpharia, Alcyonacea and Antipatharia which include the true stony corals, soft corals, black corals, etc.

**Coral bleaching.** Coral bleaching occurs when the water that the coral system lives in becomes warmer than the temperature threshold of the coral, causing coral to expel the symbiont zooxanthellae, leaving a white coral skeleton. Corals at this stage are likely still alive.

**Coral populations.** Mixed and single species populations of coral within an ecosystem.

**Coral reef ecosystem.** coral dominated ecosystem.

**Coral reef refugia.** Coral reef refugia are areas where the physical, biological, and ecological characteristics allow for a potential habitat for corals in the rising tide of climate change [38].

**Degree Heating Weeks.** Degree heating weeks (DHWs) is a measure of accumulated thermal stress experienced by corals. It is calculated by adding up days where temperatures exceed the usual summertime maximum by at least 1 degree Celsius over a 12-week period [39].

**Ecological responses.** Response of an individual species or a group to the change in environment.

**High latitude reef.** Reefs that are in regions above and below 28°N and 28°S respectively [40]. As referred in Beger et al. [41] work and the henceforth figure and table. (Figure S1. And Table. S4, see appendix)

**Marine Heat Wave.** Marine heat wave (MHW) is calculated from SST data obtained by satellite, in-situ instruments, or other means of observed data collection. It is defined as thermal events where SST exceeds the 90th percentile of the climatological dataset for at least 5 consecutive days [30].

**Marginal reef.** Marginal reefs are where the environmental conditions are marginal or close to threshold for the survival of the coral species, meaning that the living conditions are less than ideal but still feasible for coral species to survive.

**PECO.** (P)opulation, IxposurI©omparator and (O)bjective. It is a metric used to define a problem statement in environmental studies, originally used in medicinal studies.

**Primary literature.** These are literatures where original results from the authors were reported in the form of a report of their findings.

**Secondary literature.** These are literatures that the authors integrate information of primary literature into a separate document, such as a review.

**Subtropical.** The region surrounding the tropical regions. However, in this work the subtropical ecoregions are defined as in Figure 1 and Table S1 (See appendix).

**Systematic map.** Methodical overviews of the quantity and quality of evidence in relation to an open question of policy or management relevance [37].

**Temperate.** The region surrounding the subtropical regions. However, in this work the temperate ecoregions are defined as in Figure 3.

**Thermal limit.** The threshold in degree Celsius when the temperature reaches above 4 degrees when using degree heating weeks (DHW) or when the temperature is above the 90th percentile of the temperature recorded when using marine heatwaves (MHW) as the measuring metric.

**Tropicalisation.** Tropicalisation refers to a region outside the tropical latitudes increasing in number of warm-affinity species and decreasing in number of cool-water species [20].

**Methods**

**Protocol**

The systematic followed the Collaboration for Environmental Evidence Guidelines and Standards for Evidence Synthesis in Environmental Management [37] and conforms to the reporting standards for systematic evidence synthesis (ROSES) [42]. The systematic map is based on a previously published protocol registered in PROCEED, the global database of prospectively registered evidence reviews and syntheses in the environmental sector [31].

**Deviation from the protocol**

Data coding strategy

Data extracting was done collaboratively by six reviewers using the same questionnaire. The data extracting progress followed the consistency checking outlined in the protocol. No other deviation or additions were made to the protocol.

**Search strategy**

10 benchmark articles were selected for the development of the search string. These 10 articles were selected based on their relevance to the topic, covering both climatology, and subtropical and temperate coral systems under the influence of ocean warming. A series of search string were trialled to test their capability on capturing the benchmark articles. The Boolean operator search string was developed on Scopus and translated to Web of Science database after it successfully captured all 10 benchmark articles on Scopus. To capture recent studies, the search results are limited to publication on and after 2010 and limited to English only. There are four main areas the search string is designed to capture according to the PECO criteria.

**Search strings**

**Bibliographic databases**

Scopus: TITLE-ABS-KEY ( ( coral\* OR “coral reef\*” ) ) AND TITLE-ABS-KEY ( ( “ocean warming” OR “marine heatwave\*” OR “marine heat wave\*” OR mhw\* OR “degree heating week\*” OR dhw\* OR “heat stress\*” OR stress OR tropicali?ation OR temperature\* OR “climate change” ) ) AND TITLEABS- KEY ( ( mortal\* OR surviv\* OR health\* OR diseas\* OR grow\* OR reprodu\* OR cover\* OR tropicali?\* OR shift\* OR habitat\* OR increase\* OR declin\* OR decreas\* OR impact\* OR threat\* OR bleach\* OR acclimati?\* OR respons\* ) ) AND TITLE-ABS-KEY ( ( marginal OR “high latitude” OR temperate OR subtropic\* OR extratropic\* ) ) Followed by a removal of articles published prior to 2010.

Web of Science: (All Fields) ( ( coral\* OR “coral reef\*” ) ) AND (All Fields) ( ( “ocean warming” OR “marine heatwave\*” OR “marine heat wave\*” OR mhw\* OR “degree heating week\*” OR dhw\* OR “heat stress\*” OR stress OR tropicali?ation OR temperature\* OR “climate change” ) ) AND (All Fields) ( ( mortal\* OR surviv\* OR health\* OR diseas\* OR grow\* OR reprodu\* OR cover\* OR tropicali?\* OR shift\* OR habitat\* OR increase\* OR declin\* OR decreas\* OR impact\* OR threat\* OR bleach\* OR acclimati?\* OR respons\* ) ) AND (All Fields) ( ( marginal OR “high latitude” OR temperate OR subtropic\* OR extratropic\* ) ) Followed by removal of articles published prior to 2010.

**Web-based search engines**

Grey literature was searched on Open Access Theses and Dissertations (OATD) database, with the following search string used, which in pilot testing has yielded 8 results: coral AND (subtropical OR temperate) AND "ocean warming" The included results will be limited to articles and reports published since 2010 to cohere with the rest of the searches. Grey literature included was limited to research theses, pre-review reports, and open access scientific studies (herein defined as grey literature selected for inclusion in systematic mapping) while government reports were excluded due to the inconsistency in availability of these reports between regions.

**Comprehensiveness of the search**

We have selected 10 benchmark articles for developing the search string, all 10 manually collected benchmark articles were returned in the Scopus search, ensuring the search string to be sensitive enough for this systematic mapping study.

**Screening strategy**

The first screening was conducted including and excluding articles by titles and abstracts using Rayyan and was undertaken by two reviewers independently. Articles included in the first round of screening were screened again in the second phase of the screening by full text. Where full text did not meet the selection criteria, they were excluded from the data extraction. A pilot screening was performed by two of the authors to assess the coherence of articles screening agreement by Cohen’s Kappa coefficients [43, 44]. Articles on Rayyan were selected at random for reviewers to quickly screen through the titles and abstracts (30/1218, 24.6%). Articles with uncertainty in decisions are flagged for a third independent reviewer (TDA) for final decision. Consistency checks were performed for both stages, first on 30 titles and abstracts (Kappa = 0.61). Full text data inclusion and exclusion were cross checked by the author (MLH) to ensure that all meta-data extracted are coherent to the inclusion criteria.

**Eligibility criteria**

Articles from the databases were screened manually according to the following PECO criteria:

Population: Subtropical and Temperate Coral Systems and Coral Reefs

* All subtropical and temperate coral systems and coral reefs will be included; this includes marginal, high latitude coral systems.
* Studies focused solely on tropical, polar and/or deep sea corals, kelp forests and fishes will be excluded.

Exposure: Ocean Warming

* We will include studies focused on the effects of exposure to ocean warming, specifically empirical ocean warming studies that utilise degree heating weeks and the definition of marine heatwaves as defined by Hobday et al. (2016) [30], meaning cases where:
  + SST exceeds the bleaching threshold of 4 degrees Celsius.
  + SST exceeds the 90th percentile of the ongoing and continuous 30 years climatological data, subjected to 30 days moving window [30].
* Ocean acidification and its interaction with ocean warming will be excluded from this systematic map.

Comparator: Effects before and after recorded event/exposure.

Outcome: Mortality and bleaching, habitat changes, threats, acclimatisation of subtropical and temperate coral systems.

* We will include all literatures that address the physiological effects and ecological effects ocean warming have on the coral systems and reefs – this includes mortality, bleaching, changes in habitats (E.g., destruction of reef structures), threats (E.g., increase in species that pose threats to corals and coral reefs). Topics addressing the acclimatisation of species will also be considered.

**Reporting screening outcomes**

During the full-text screening, studies that are rejected from the process will be recorded with the respective reasons recorded. A ROSES flow diagram will be used to record and visualise the number of studies assessed and rejected at each stage. It will be uploaded, and all supplementary materials will be provided. If deviations from the ROSES flow diagram exist, they will be discussed in the systematic map.

**Study validity assessment.**

No study validity assessment of studies has been performed for this systematic map.

**Data coding strategy**

Data extraction was done collaboratively by 6 reviewers using a questionnaire from the articles included in the full text screening. The following categories of variables were extracted and described in a spreadsheet (Additional file 1):

* Bibliographic map (Title, DOI, number of citations, authors’ information, year of publication, journal, keywords)
* Location of research (Research ecoregions, type of location, development status, species)
* Research data recorded (Temperature data recording methods, study type, study timeline, environmental parameters, availability of temperature data)
* Ocean warming evidence (Extreme weather events recorded, stressors, severity, extreme weather events timeline, study outcome or prediction)

**Type of mapping**

A written report will be produced to accompany the systematic map to document all methodology, results, discussion, and other supplementary details during this mapping exercise. Details and information regarding the literature search, screening and data extraction will also be provided to facilitate the reproducibility of this study.

**Narrative synthesis methods**

The data from the review will be presented in the form of narrative review, descriptive tables, and graphical presentations. Data-generated figures will be created in R [45].

**Demonstrating procedural independence**

As some of the authors of this proposed review may have been authors of some of the studies to be reviewed in this work, their studies will be independently assessed by other reviewers without discussion with the study authors to ensure the independence of the review.

**Reporting**. Methods outlined in previously published protocol are followed, apart from minor additions and deviations described in the section “Deviation, additions and justifications”.

The ROSES Reporting Standard for the reports of findings from the systematic map was applied [42]. MLH used the search strings proposed in the published protocol for Scopus and Web of Science respectively, 877 results returned from Scopus, 1042 results returned from Web of Science, and 9 results from Open Access Theses and Dissertations. MLH and PS independently screened 1227 unique papers by title, abstract and keywords. The screening resulted in 187 unique papers for full-text screening. MLH, PS, CP, SV, JW and SE coordinated on screening by text, and yielded 91 unique papers for data extraction (Figure 1). Included articles must be primary literature, and the topic of study must be dominantly on subtropical coral. Examples of excluded articles are provided in Supplementary Table S1.

Here 51 separate parameters are identified for data extraction based on the primary and secondary questions from the published protocol [31]. These parameters include bibliometric information, methodology, reporting, etc. For the ease of reporting, the sections of reporting are divided into two groups: the first group systematic map consists of drivers of ocean warming, severity of ocean warming, location, and method of research, and the second group is bibliometric map. During the data extraction from full text, further parameters were added to the extraction to identify the availability of temperature data of studies, and bibliometric parameters such as number of citations, number of co-authors and journal of publications were added to the data collection.

All figures on this systematic map were created using R version 4.2.2 [45] on R Studio version 2023.06.0 [46], as well as RAWGraphs [47]. Several packages in R were used in the creation of figures, including ggplot2 [48], wordcloud [49], wordcloud2 [50], tidyverse [51], dplyr [52], reshape2 [53], viridis [54], RColorBrewer [55], leaflet [56], htmlwidgets [57], webshot [58], and tm [59] Organisation of figures into infographics were done with the use of Adobe Illustrator.

**Review findings**

**Data characteristics**. From the 1236 initially identified studies, 91 studies met the inclusion criteria for the purpose of this systematic map (Figure 1), the inclusion and exclusion criteria are listed in the protocol [31]. All 91 studies provided data for the formulation of the systematic map and bibliometric map. 44 studies are identified (48.4%) that are observational based, 3 studies (3.3%) are observational, and modelling based. 35 studies (38.5%) identified as experimental, with 7 studies (7.7%) being experimental and observational based and 1 study (1.1%) identifying as experimental and modelling based. 1 study (1.1%) identified as solely modelling based. The keywords used for each study are extracted. The top three used keywords for included studies are “coral”, “change coral” and “bleaching coral” respectively and provide a word cloud of all key words (Figure 2a).

**Bibliometric map**. Increasing research effort from 2013 to 2015 is reported (a total of 19 publications during 2013- 2015) following by a drop to 4 publications 2016 and increase to 9 publications in 2017 (Figure 2b) and has reached a peak of now 10 publications per year in each of 2022 and Mid-2023. In terms of number of citations, 2 studies stood out, having 510 citations (study by Yamano et al., 2011 [17]) and 159 citations (study by Le Nohaïc et al., 2017 [60]), overall publications included in this systematic map are less cited (Median = 20) (Figure 4a). Authors with more than one publication are associated with institutions in Hong Kong (3 authors), Australia (1 author), United States of America (1 author), United Kingdom (1 author), Italy (1 author), Taiwan (1 author), Spain (1 author), New Zealand (1 author), and Monaco (1 author). Most authors publishing only intermittently (Figure 5). The number of journals for publications are reported, the largest number of studies included come from Coral Reefs (17 studies), followed by Frontiers in Marine Science (7 studies), Scientific Reports (6 studies) (Figure 4b). Other journals include Science of the Total Environment (4 studies), Diversity (3 studies), Global Change Biology (3 studies), Marine Ecology Progress Series (3 studies), Marine Pollution Bulletin (3 studies), PloS One (3 studies), Proceedings of the Royal Society B: Biological Sciences (3 studies), Bulletin of Marine Science (2 studies), Ecology and Evolution (2 studies), Journal of Experimental Marine Biology and Ecology (2 studies), Limnology and Oceanography (2 studies), Molecular Ecology (2 studies) (Table 1 with all included articles freely/openly available).

**Location of research.**

The provinces are identified (Defined by Spalding et al. (2007) [23] as large areas with presence of distinct biotas, that hold some level of endemism.), and subsequently the ecoregion (Defined by Spalding et al. (2007) [23] as areas of relatively homogeneous species composition and clearly distinct from adjacent systems. Ecoregions are nested within Provinces.) where the included studies were conducted (Figure 7). Majority of studies were conducted in the province of South China Sea (20 occurrences), this includes the ecoregions of Southern China (15 studies), South China Sea Oceanic Islands (1 study), and Gulf of Tonkin (4 studies). The second highest province is Mediterranean Sea, consisting of 15 occurrences, including the ecoregions of Western Mediterranean (11 studies), Adriatic Sea (2 studies), Levantine Sea (1 study), and Ionian Sea (1 study). The province of Warm Temperate Northwest Pacific is the third highest occurring province, with 12 occurrences with studies identified in the ecoregions of East China Sea (6 studies), Central Kuroshio Current (6 studies) (Figure 7b).

When examining the provinces recorded from the included studies, 7 provinces that are on the Australian continent are identified, including Lord Howe and Norfolk Islands (9 occurrences), Southwest Australian Shelf (6 occurrences), West Central Australian Shelf (5 occurrences), East Central Australian Shelf (4 occurrences), Northeast Australian Shelf (3 occurrences), Southeast Australian Shelf (2 occurrences) and Northwest Australian Shelf (1 occurrence). These provinces include the ecoregions of Lord Howe and Norfolk Island (9 studies), Leeuwin (6 studies), Houtman (5 studies), Tweed-Moreton (3 studies), Manning-Hawkesbury (1 study), Central and Southern Great Barrier Reef (2 studies), Torres Strait Northern Great Barrier Reef (1 study), Cape Howe (2 studies), and Ningaloo (1 study) (Figure 7b and Table 2).

6 occurrences are identified for the province of Cold Temperate Northwest Atlantic. The ecoregion included is Gulf of Maine/Bay of Fundy (6 studies). Tropical Southwestern Atlantic and Warm Temperate Northwest Atlantic record 4 occurrences each, within the ecoregions of Eastern Brazil (2 studies), North-eastern Brazil (2 studies), Carolinian (3 studies), and Northern Gulf of Mexico (1 study). Tropical North-western Atlantic and Warm Temperate Southwestern Atlantic each has 2 occurrences. The ecoregions under these two provinces, Floridian and South-eastern Brazil, respectively, have 2 studies each recorded.

The province of Somali/Arabian has 3 occurrences, the included ecoregion is Arabian (Persian) Gulf (3 studies). Similarly, the province of Lusitanian also recorded 3 occurrences, in the ecoregion of Azores Canaries Madeira (2 studies) and South European Atlantic Shelf (1 study). Remaining recorded provinces are Western Indian Ocean (2 occurrences) with the ecoregions of Mascarene Islands (1 study) and Delagoa (1 study); Agulhas (1 occurrence) with the ecoregion Natal (1 study), and South Kuroshio (1 occurrence), with 1 study in the ecoregion South Kuroshio.

Within the included studies, majority (58 studies) of the study were conducted in developed economies (United Nations Country Classification, accessed 2024), with Australia (23 studies) having the highest number of studies published within the category. This is followed by United States of America (12 studies) and Japan (7 studies). Within the category of developed economies, 1 study has also included an economy in transition (defined as industrialised countries that are undergoing process of transition to a market economy. These include some former Soviet Union republics [61].). Another study also encompasses a developed economy and developing economy (defined as countries with less developed industrial base and lower human development index in relative to other countries [62]). For developing economies (31 studies), Hong Kong has the highest number of published studies (11 studies), followed by China (5 studies) and Brazil (5 studies).

For proximity of the research site to the mainland (Figure 8a), most studies involve close/territorial sea (69 studies). Studies in middle/contiguous zone are recorded in 7 studies. Far/exclusive economic zone are recorded in 15 studies. Of all the studies involving close/territorial sea, 4 studies also involve middle/contiguous zone, 2 studies involve far/exclusive economic zone, and 2 studies involve both middle/contiguous and far/exclusive economic zone. 10 studies did not specify their proximity to the mainland (Figure 8a) and 21 of the studies took place in protected areas (Figure 8b). A list of the protected areas can be found in Table 3.

**Research data recorded.**

***Temperature Data Record*.** When examining the methods reported for ocean temperature records, 50 publications were found to have obtained their temperature data *in-situ* (deployment of loggers), 28 studies used remote sensing data (herein referred to satellite derived and SST, sea surface temperature) for temperature data. 26 studies used other methods of obtaining temperature data, these are *ex-situ* conservation (where temperature was set to match the experimental criteria) (24 studies) or not identified (2 studies) in the literature (Figure 9a). For *in-situ* collected data were collected using temperature logger (26 studies), dive computers (2 studies), NOAA National Buoy Center (2 studies), remotely operated vehicles (ROV) (2 studies), digital thermometer (1 study), mercury thermometer (1 study), local monitoring sites (1 study), and T-MEDNet as a temperature data sharing site (1 study) (Figure 9b). 13 studies did not specify the method of recording temperature data. For temperature data availability, 51 of the 91 studies did not provide raw temperature data for access, with the remaining 40 studies providing full access to raw temperature data (see Supplementary Table S2).

***Study depth*.** For study depth and/or depth of data collection, majority of temperature data were obtained at depth of above 20m (Figure 9c), with 1 temperature data recording at a depth of 40m (T-MEDNet). The highest occurrence of depth for temperature collection is 3m (8 occurrences), followed by 4m (7 occurrences) and 2m (5 occurrences).

***Type of study*.** 17 studies of the 91 studies included are reported to have taken place during extreme weather or climate events (Figure 10a and Table 4) and focused on reporting evidence associated with the specific event occurring, while 2 further studies report extreme weather events but were not conducted concurrently with the events. Majority of studies (72 studies) were not describing any specific extreme weather events.

***Other environmental data*.** From the included studies, most observed environmental parameters (Figure 10b) are light (13 studies), salinity (12 studies) and pH values (9 studies), while other parameters include nutrients (8 studies), ocean current (6 studies), chlorophyll a concentration (5 studies), wind speed (1 study), water quality (1 study), mean-sea bottom temperature (1 study), CO2 concentration (1 study), chlorophyll c concentration (1 study), boron isotopic composition of sea water (1 study), and bathymetry (1 study).

***Study species.*** For species studied, Scleractinian is reported to be the most dominant studied order (124 species studied), followed by Alcyonacea (7 species), Zoantharia (5 species), Actiniaria (3 species), Anthoathecata (2 species), Axinellida (2 species), Laminariales (2 species), Agelasida (1 species), Aplousobranchia (1 species), Dictyoceratida (1 species), Haplosclerida (1 species), Pennatulacea (1 species), Poecilosclerida (1 species), and Suessiales (1 species) (Figure 4a). Within the order Scleractinian, *Murilinidae* (48 occurrences) was found to be the most studied family, followed by *Acroporidae* (42 occurrences) (Figure 11). Species level information can be found in Supplementary Table S3,

**Ocean Warming Evidence**

69 studies provided an outcome (defined here as studies presenting results and conclusion based on the processes of research efforts) associated with the study conclusion, while 13 studies provided prediction (defined here as studies providing a prediction of future scenarios based on results presented in their research) in their conclusion, and the remaining 9 studies provided both outcome and prediction (Figure 12a). From the outcomes and predictions, most studies focus on reporting on physiology of coral systems under thermal stress (34 studies), followed by investigations into adaptation of coral species into marginal reefs (16 studies), changes in coral populations (12 studies), calcification of reefs (8 studies), assessment of potential refugia (6 studies), recovery of population (5 studies), climate change projections (2 studies), impact of cold stress on coral (2 studies), seasonal changes (2 studies), and ENSO interactions (1 study) (Figure 12b).

***Drivers*.** Most studies included involve using long-term climate change as a driver of ocean warming (47 papers, 51.6%). This is followed by use of experimental stressors such as artificially heightening temperature and acute thermal stress treatments (20 papers, 22.0%). Degree heating weeks made up the third most recorded stressor (11 papers, 12.1%) of ocean warming and marine heatwaves (Hobday et al., 2016) being the fourth (8 papers, 8.8%). The other stressors include seasonal variation (4 papers, 4.4%), localised hotspots (2 papers, 2.2%), cold stress (2 papers, 2.2%), El Nino Southern Oscillation (1 paper, 1.1%), tidal temperature change (1 paper, 1.1%), and temperature difference along latitudes (1 paper, 1.1%). 2 papers (2.2%) did not specify the stressor used when describing bleaching events (Figure 13a).

***Severity*.** 17 papers (18.7%) that reported degree heating weeks, marine heatwaves, or both as identifier of severity of ocean warming (Figure 13b), 6 papers did not specify the intensity of marine heatwaves, 1 paper recorded a moderate and a strong marine heatwave event, and 1 paper recorded a severe marine heatwave event. For studies reporting degree heating weeks as recording matrix, 5 papers did not specify the level of bleaching alert. 2 separate papers recorded bleaching events exceeding bleaching alert level 5 (>20 DHW), another two papers recorded bleaching events exceeding bleaching alert level 4 (>16 DHW). Bleaching alert level 3 (>12 DHW) was reported in 1 paper, while bleaching alert level 2 (>8 DHW) was not reported in the papers. 3 bleaching alert level 1 (>4 DHW) were reported in 2 separate papers, and 3 bleaching warning (1 to 4 DHW) was reported in 1 paper (Figure 13b).

**Discussion**

Here research effort was found for climate change in subtropical ecosystems has increased over the past 2 decades, with most evidence now available from the period 2020-2024. Research has focused in 3 main provinces in Asia Pacific and Mediterranean Sea, and 7 provinces in Australia. Studies have predominately been led by researchers associated with developed nation institutions (61.5% of studies). Research has predominantly investigated the impact of climate change to corals within the orders Scleractinian and Alcyonacea. 12.1 % of researchers were found to have reported on climate events using the DHW (degree heating weeks metric) with 8.8% reporting on events applying the MHW metric (marine heat wave). While research effort for the impacts of climate change on subtropical corals and coral reefs has lagged behind that of tropical regions, evidence on impact and responses of subtropical systems is increasingly rapidly. There is also an apparent increase in evidence-base for the subtropics is likely be aligned with records of severe (or extreme) climate and weather events now impacting these regions, with 18.7% of the identified research here coming from studies reporting during events associated with ecological scale events such as coral bleaching, kelp losses, seagrass losses and anomalously high sea surface temperatures.

***Study type and timeline of evidence.*** More of the studies identified here are observational or have components of observational (defined here as studies that collect data by observing the subjects in their natural settings) (59.3% of studies) associated with recorded extreme/severe climate events, and experimental studies as the second most prevalent study type (47.3%). Throughout the years of publications, there is no apparent shift in dominance of experimental (29 out of 61, 47.5% of studies between 2010-2020) or observational (39 out of 61, 62.9% of studies between 2010-2020) studies reported before 2020, with both types of study being published at a similar rate throughout those years. However, from 2020 onwards, the number of observational studies (17 out of 30, 56.7% after 2020) began to level out with experimental studies (12 out of 30, 40% of studies) for evidence reports.

In early 2010s, the number of publications identified investigating climate change impacts on subtropical reefs (or corals) was relatively low, ranging from 1 to 2 studies a year until 2014. A drastic increase in number of publications by 50% was then apparent from 2015 as research efforts begin to increase. Beger et al., (2014) published a review highlighting the need for preserving high latitude coral reef systems and the potential impacts of climate change. Additionally, 2014 to 2017 saw an unprecedented period of severe sea surface temperature, and the longest recorded bleaching events for coral reef ecosystems which was associated high mortality in coral reefs [63]. Increasing awareness of, and observations of, climate change impact on subtropical coral reefs likely contributed significantly to the increase in research efforts into the subtropical reefs post 2014. The number of publications continued over the past 5 years showing a steady research effort being undertaken in the subtropical coral reefs, with now a near annual publication rate of 10 publications per year (2022, 2023).

***Ecoregions, provinces and sources of climate change impacts evidence.*** Marine Ecoregions Of the World (MEOW) were defined by Spalding et al., 2007 [23], with the ecoregions categorised as areas of relatively homogenous species composition with distinction from adjacent systems, the dominant biogeographic drivers defining the ecoregions are diverse and may vary from site to site [23]. Search effort for subtropical coral research and subsequently evidence for the impact of climate change in these ecosystems has to-date was found predominantly focused on ecoregions in the Asian Pacific region. Specifically, the ecoregions of the provinces South China Sea, Andaman, Warm Temperate Northwest Pacific, and South Kuroshio are sites where research effort has been intensive (a total of 27 publications). Research in these sites are primarily published on and after 2015, associated with coral bleaching events reported in 2014 in Hong Kong [11], 2016 in Andaman Sea [64] and 2016 in Japan [65]. Therefore, ecoregions are also identified within which there are research gaps and evidence for the impact of climate change has remined low, such as Delagoa, Mascarene Islands, Arabian Gulf, Natal, etc. While these ecoregions are directly exposed to the Western Indian Ocean, there are evidence of bleaching events in the area [66]. Here, studies where research effort has been associated with recorded marine protected areas (MPAs) are identified, herein MPAs are defined as areas with a clearly defined geographical space, recognised, dedicated, and managed through legal or other means to maintain the long-term conservation of ecosystems and cultural values associated with the location [67]. Most marine park/reserve literature is reported from Australia. Only 23.1% (21 out of 91) of the studies reported having conducted research in protected or associated with marine protected areas and 35.2% of studies (32 out of 91) did not clearly indicate if their published studies took place in or within the region of a marine protected area. Given the recent increases in areas designated MPAs or marine parks internationally [68], future research identifying patterns of research effort, knowledge gaps and evidence synthesis for coral reef ecosystems should consider further investigating the location and establishment of marine protected areas to build evidence-base for park management.

***Drivers and Severity of Ocean Warming****.* Prior to 2016, most studies report long-term climate change as an environmental driver for ocean warming, use of long-time monitoring data was common for studies, and the research using this as an approach to driver of ocean warming generally are on the study of coral calcification and adaptation to marginal reefs. The introduction of a hierarchical approach on defining marine heatwaves [30] sees the increase in use of marine heatwaves as a tool on identifying potential bleaching event [69, 70]. Use of degree heating weeks for subtropical corals was uncommon until 2017, when an increased number of publications used degree heating week as a reporting mechanism on bleaching of subtropical coral [60, 71, 72] was observed. This allowed the authors of respective studies to use standardised metrics to compare the severity of bleaching on subtropical reefs to tropical reefs. A combined use of both marine heatwave and degree heating week as reporting mechanisms may benefit future studies in quantitatively comparing data between sites and events.

The use of marine heatwave and degree heating weeks provide researchers with the quantitative sense of severity of an ocean warming event and/or bleaching event. This is a quality where studies utilizing the mechanisms could quickly communicate the severity of events to readers. However, a concerning increase in the degree heating weeks and severity of marine heatwaves reporting, with publications in recent years highlighting the high levels of bleaching alerts [73-75], strong [76] and severe [77] marine heatwaves was found.

**Conclusion and Future Direction.** This systematic map provides a summary of research effort directed at understanding the impacts of climate change to subtropical corals and coral reefs. In doing so a trend of increasing research effort in subtropical coral reefs globally is evident, with this increase in knowledge likely driven by and in conjunction with increasing climate driven degradation events affecting subtropical regions, including increasingly severe marine heatwave events. Major research clusters globally are identified in regions of Asia-Pacific, Mediterranean Sea, and Australia, which together have provided the vast majority of evidence to suggest climate change is having ongoing impacts to subtropical coral reefs. Similarly, identification of major knowledge clusters here has also revealed research gaps in areas such as the Western Indian Ocean where research effort has been substantially lower than in other ecoregions. By identifying the current state of knowledge, networks of researchers, and advocation on use of standardised metrics when describing driver of ocean warming, future research efforts can become more precise and efficient. Research globally has primary focused on reporting ecological responses to climate change associated events however substantial effort has also been directed to experimental studies. Interestingly physiological data is one of the most common forms of impact and data reported in the studies, with 30% of the identified literature reporting on the physiological state of corals associated with climate impacts in subtropical regions. Future research in this area should consider meta-analysis of the evidence identified in the current study. In particular, the assessment of severity of bleaching impacts within subtropical studies with research effort shows severe bleaching events recorded from 2010-2023 predominantly report events occurring within mortality scale of impact (degree heating week of 8 or above). Understanding the severity of bleaching reports across subtropical regions will aid managers in predicting and responding to the impact of bleaching on these reefs. Ongoing systematic assessment of research effort and evidence provided will also provide managers with reliable, transparent and comparable assessment of evidence as it continues to develop, and allow for development of evidence-based management practices specific to these unique and valuable ecosystems

**Declarations**

**Ethics approval and consent to participate**

Not applicable.

**Consent for publication**

Not applicable.

**Availability of data and materials**

The datasets generated and/or analysed during the current study are available in the GitHub repository, <https://github.com/MLH95/Ho-et-al-2024_Systematic-Map>

**Competing interests**

The authors declare that they have no competing interests.

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**Authors’ contributions**

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MLH and TDA conceptualised the idea for this study. MLH, TDA, PS and CP designed the data extraction methods, as well as validating the design. MLH and PS screened the original database of articles by title and abstract, and later screening was done collaboratively by MLH, PS, CP, SV, JW and SE. Data analysis was performed by MLH. MLH led the writing of the report with crucial contribution from TDA. All authors give their permission for publication of this systematic map in its final form.

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**Tables**

Table 1 Number of publications by journals across literature included for this systematic map.

|  |  |
| --- | --- |
| Journal Name | Number of Publications |
| Coral Reefs | 17 |
| Frontiers in Marine Science | 7 |
| Scientific Reports | 6 |
| Science of The Total Environment | 4 |
| Diversity | 3 |
| Global Change Biology | 3 |
| Marine Biology | 3 |
| Marine Ecology Progress Series | 3 |
| Marine Pollution Bulletin | 3 |
| PloS One | 3 |
| Proceedings of the Royal Society B | 3 |
| Bulletin of Marine Science | 2 |
| Ecology and Evolution | 2 |
| Journal of Experimental Marine Biology and Ecology | 2 |
| Limnology and oceanography | 2 |
| Molecular Ecology | 2 |
| Applied microbiology and biotechnology | 1 |
| Aquatic Conservation: Marine and Freshwater Ecosystems | 1 |
| Aquatic Ecosystem Health & Management | 1 |
| Biodiversity and Conservation | 1 |
| Biogeosciences | 1 |
| Cell Stress and Chaperones | 1 |
| Ecography | 1 |
| Environmental Science and Pollution Research | 1 |
| Estuarine, Coastal and Shelf Science | 1 |
| Frontiers in Physiology | 1 |
| Geophysical Research Letters | 1 |
| Helgoland Marine Research | 1 |
| Integrative Organismal Biology | 1 |
| Journal of Experimental Biology | 1 |
| Journal of Heredity | 1 |
| Journal of Marine Science and Engineering | 1 |
| Journal of phycology | 1 |
| Marine Chemistry | 1 |
| Marine Environmental Research | 1 |
| Microorganisms | 1 |
| Nature | 1 |
| Pakistan Journal of Biological Sciences | 1 |
| PeerJ | 1 |
| Progress in Oceanography | 1 |
| Regional Studies in Marine Science | 1 |
| The Biological Bulletin | 1 |

Table 2 Number of publications by ecoregions across this systematic map.

|  |  |  |
| --- | --- | --- |
| Ecoregions | Belongs to Province | Number of Publications Concerning the Ecoregion |
| Southern China | South China Sea | 15 |
| Western Mediterranean | Mediterranean Sea | 11 |
| Lord Howe and Norfolk Islands | Lord Howe and Norfolk Islands | 9 |
| Leeuwin | Southwest Australian Shelf | 6 |
| Gulf of Maine/Bay of Fundy | Cold Temperate Northwest Atlantic | 6 |
| Central Kuroshio Current | Warm Temperate Northwest Pacific | 6 |
| East China Sea | Warm Temperate Northwest Pacific | 6 |
| Houtman | West Central Australian Shelf | 5 |
| Gulf of Tonkin | South China Sea | 4 |
| Arabian (Persian) Gulf | Somali/Arabian | 3 |
| Tweed-Moreton | East Central Australian Shelf | 3 |
| Carolinian | Warm Temperate Northwest Atlantic | 3 |
| Central and Southern Great Barrier Reef | Northeast Australian Shelf | 2 |
| Azores Canaries Madeira | Lusitanian | 2 |
| Southeastern Brazil | Warm Temperate Southwestern Atlantic | 2 |
| Floridian | Tropical Northwestern Atlantic | 2 |
| Eastern Brazil | Tropical Southwestern Atlantic | 2 |
| Cape Howe | Southeast Australian Shelf | 2 |
| Northeastern Brazil | Tropical Southwestern Atlantic | 2 |
| Adriatic Sea | Mediterranean Sea | 2 |
| Torres Strait Northern Great Barrier Reef | Northeast Australian Shelf | 1 |
| Northern Gulf of Mexico | Warm Temperate Northwest Atlantic | 1 |
| Levantine Sea | Mediterranean Sea | 1 |
| Natal | Agulhas | 1 |
| Western India | West and South Indian Shelf | 1 |
| West Caroline Islands | Tropical Northwestern Pacific | 1 |
| Andaman Sea Coral Coast | Andaman | 1 |
| South Kuroshio | South Kuroshio | 1 |
| Ningaloo | Northwest Australian Shelf | 1 |
| Ionian Sea | Mediterranean Sea | 1 |
| Mascarene Islands | Western Indian Ocean | 1 |
| Manning-Hawkesbury | East Central Australian Shelf | 1 |
| South China Sea Oceanic Islands | South China Sea | 1 |
| South European Atlantic Shelf | Lusitanian | 1 |
| Delagoa | Western Indian Ocean | 1 |

Table 3 List of identified marine reserve, protected area, or marine park.

|  |  |  |
| --- | --- | --- |
| Name of Protected Area | Country | Reference |
| Abrolhos Marine National Park | Brazil | Ferreira et al., 2021 |
| Blue Bay Marine Park | Mauritius | McClanahan et al., 2021 |
| Columbretes Islands Marine Protected Area | Spain | Kersting et al., 2015 |
| Medes Island Marine Protected Area | Spain | Kersting et al., 2015; Gómez-Gras et al., 2019; Crisci et al., 2017 |
| Green Island Marine Research Station | Taiwan | Schutter et al., 2015 |
| Jurien Bay Marine Park | Australia | Ross et al., 2021 |
| Marmion Marine Park | Australia | Ross et al., 2021 |
| Rottnest Island Marine Reserve | Australia | Ross et al., 2021 |
| Shoalwater Islands Marine Park | Australia | Ross et al., 2021 |
| Ngari Capes Marine Park | Australia | Ross et al., 2021 |
| Lord Howe Island Marine Park | Australia | Steinberg et al., 2022; Davis et al., 2020; Oakley et al., 2022; Dalton et al., 2011 |
| Malvan Marine Santuary | India | De et al., 2023 |
| Scandola Nature Reserve | France | Crisci et al., 2017 |
| Mljet National Park | Croatia | Kružić et al., 2015 |
| Pedra da Risca do Meio | Brazil | Lucas et al., 2023 |
| Pedra Vermelha Restricted-Access Site | Brazil | Lima et al., 2016 |
| Solitary Islands Marine Park | Australia | Lachs et al., 2021; Dalton et al., 2011 |
| Tung Ping Chau Marine Park | Hong Kong | Chui et al., 2015; Chui et al., 2016; Chui et al., 2017; Chui et al., 2023 |
| Yan Chau Tong Marine Park | Hong Kong | Cai et al., 2018 |

Table 4 Studies that were conducted concurrently with extreme weather events.

|  |  |
| --- | --- |
| Period of Extreme Weather Events | Study |
| Beginning of Austral Summer 2010 to End of Austral Summer 2011 | Bridge et al., 2014 |
| January 2019 to March 2019 | Davis et al., 2020 |
| 2015 to 2016 | Le Nohaïc et al., 2017 |
| February 2016 to August 2016 | Goyen et al., 2019 |
| 2020 to 2021 | Mo et al., 2022 |
| March 2019 to May 2019 | Ferreira et al., 2021 |
| Multiple events over the years of 2004 to 2019 | McClanahan et al., 2021 |
| February 2019 to May 2019 | Banha et al., 2020 |
| June 2017 to August 2017 | Ip et al., 2022 |
| August 2014 to September 2014 | Xie et al., 2017 |
| Within 2020 | Bergman et al., 2023 |
| February 2011 to April 2011 | Giraldo-Ospina et al., 2020 |
| December 2018 to January 2019, January 2019 to February 2019, March 2019 to June 2019 | Steinberg et al., 2022 |
| 1997 to 1999, 2001 to 2004, 2006 to 2009, 2011 to 2012 | Kružić et al., 2014 |
| April 2016 to July 2016 | Lachs et al., 2021 |
| 2014 to 2017 | Porter et al., 2021 |
| January 2020 to February 2020, February 2020 to May 2020, May 2020 to June 2020 | Lucas et al., 2023 |