RESEARCH PAPER

El Niño–Southern Oscillation Research (2016–2026): A Comprehensive Bibliometric Analysis

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Abstract

Background: El Niño–Southern Oscillation (ENSO) is among the most consequential climate phenomena on Earth, exerting profound effects on atmospheric circulation, precipitation patterns, marine ecosystems, terrestrial biodiversity, and human health outcomes globally. Despite an exponential growth in ENSO-related scientific output over the past decade, no systematic bibliometric synthesis of the literature published between 2016 and 2026 has been undertaken. This study aimed to map the intellectual structure, collaborative architecture, and thematic evolution of global ENSO research using a rigorous bibliometric approach.

Methods: A structured search of PubMed and Scopus databases was conducted for publications indexed from January 2016 to December 2026, using Medical Subject Headings (MeSH) and free-text terms related to ENSO, climate variability, and associated ecological and health outcomes. Following PRISMA-compliant screening, eligible records were exported in RIS format and analysed using VOSviewer (version 1.6.20), a validated tool for bibliometric network construction. Three analytical modules were applied: organisational collaboration networks, co-authorship mapping, and keyword co-occurrence analysis. Network, overlay, and density visualisations were generated for each module.

Results: A total of 514 publications met inclusion criteria. Organisational collaboration analysis identified Chinese academic institutionsnotably the University of Chinese Academy of Sciences, the State Key Laboratory of Tropical Climate Research, and the Institute of Atmospheric Physicsas the most prolific and central contributors. Co-authorship analysis revealed a highly integrated research network comprising 25 strongly connected authors, with no isolated clusters. Keyword co-occurrence analysis identified 234 co-occurring terms clustered into four thematic domains: (1) climate and atmospheric sciences, (2) ecosystem and marine biology, (3) disease and public health, and (4) climate change and sustainability. Overlay visualisation demonstrated a temporal shift from traditional atmospheric investigations (2016–2019) toward ecosystem monitoring, vector-borne disease epidemiology, and COVID-19-related climatic interactions (2020–2026).

Conclusions: ENSO research has undergone substantial disciplinary diversification over the study period, integrating atmospheric science, ecology, marine biology, epidemiology, and public health into a unified interdisciplinary framework. Future research should prioritise mechanistic climate–health pathways, real-time ecological surveillance, and the integration of ENSO forecasting models with global health preparedness systems.

Keywords: El Niño–Southern Oscillation; ENSO; bibliometric analysis; VOSviewer; climate variability; ecosystem; infectious diseases; keyword co-occurrence; organisational collaboration; PubMed

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1. Introduction

El Niño–Southern Oscillation (ENSO) represents the dominant mode of interannual climate variability on a global scale, originating from coupled interactions between sea surface temperatures in the tropical Pacific Ocean and overlying atmospheric circulation patterns.[1] ENSO cycles, which oscillate between warm (El Niño), cold (La Niña), and neutral phases, occur approximately every two to seven years and exert far-reaching teleconnections that alter precipitation regimes, drought frequencies, storm intensities, and oceanic thermal gradients across multiple continents and ocean basins.[2,3]

The scientific importance of ENSO extends well beyond atmospheric science. El Niño episodes are robustly associated with widespread ecological disruption, including coral bleaching, phytoplankton redistribution, terrestrial carbon flux anomalies, and altered fire regimes in tropical and subtropical forests.[4,5] Moreover, the climatic perturbations induced by ENSO have demonstrable consequences for human health, including outbreaks of vector-borne diseases such as dengue fever, malaria, cholera, Rift Valley fever, and hantavirus pulmonary syndrome.[6,7,8]

Despite decades of intensive research, the disciplinary scope of ENSO science has expanded considerably in the 21st century. The post-2015 period has witnessed landmark El Niño events most notably the extreme 2015–2016 episode, ranked among the three strongest on instrumental record which prompted an acceleration of interdisciplinary investigation.[16,17] Concurrently, the coincidence of the 2020–2022 La Niña phase with the COVID-19 pandemic opened new scholarly dialogues regarding climate–pandemic interactions, further broadening the thematic landscape of ENSO-related literature.

Bibliometric analysis provides a quantitative, reproducible methodology for mapping the intellectual structure of scientific disciplines, tracing their temporal evolution, and identifying collaborative networks and emerging research frontiers.[9,10,11] By applying network science to publication databases, bibliometric approaches reveal patterns that traditional narrative reviews cannot systematically detect, including citation flows, institutional clustering, and keyword co-occurrence topologies.[12]

While several bibliometric studies have examined climate change and global warming as broad domains,[13] no study to date has conducted a comprehensive bibliometric synthesis specifically focused on ENSO research across the period 2016–2026, encompassing its ecological, epidemiological, and sustainability dimensions. The present study addresses this gap by systematically mapping the global ENSO research landscape using VOS viewer-based network visualisation applied to PubMed and Scopus-indexed literature.

1.1 Objectives

This study aimed to: (i) characterise the pattern of international organisational collaboration in ENSO research; (ii) identify key co-authorship networks and bridge researchers facilitating interdisciplinary knowledge exchange; (iii) delineate major thematic clusters within the literature through keyword co-occurrence analysis; and (iv) map the temporal evolution of research priorities using overlay visualisation.

2. Materials and Methods

2.1 Data Source and Search Strategy

This bibliometric analysis was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.[14] Eligible publications were retrieved from two complementary databases: PubMed (National Library of Medicine, Bethesda, USA) and Scopus (Elsevier, Amsterdam, Netherlands). These databases were selected for their broad coverage of biomedical, environmental, and interdisciplinary literature and their compatibility with bibliometric export formats.

The search was restricted to publications indexed between 1 January 2016 and 31 December 2026. The Boolean search string employed was: ("El Niño-Southern Oscillation" OR "ENSO" OR "El Nino" OR "La Nina" OR "Southern Oscillation") AND ("climate variability" OR "climate change" OR "ecosystem" OR "environmental monitoring" OR "disease outbreaks" OR "dengue" OR "malaria" OR "biodiversity" OR "coral reefs" OR "phytoplankton" OR "drought" OR "rainfall" OR "public health"). Mesh terms were applied in PubMed to ensure controlled vocabulary consistency. No language restrictions were imposed; however, only peer-reviewed journal articles, reviews, and systematic reviews were included. Conference abstracts, editorials, letters, and book chapters were excluded.

2.2 Inclusion and Exclusion Criteria

Records were included if they: (a) were original research articles, review articles, or systematic reviews; (b) explicitly addressed ENSO or El Niño/La Niña phenomena as a primary or secondary variable; (c) were indexed in PubMed or Scopus between 2016 and 2026; and (d) contained accessible bibliometric metadata including author affiliations, keywords, and citation counts. Records were excluded if they: (a) were duplicate entries across databases; (b) lacked author affiliation or keyword data; or (c) focused exclusively on methodological or statistical innovations without substantive ENSO content.

2.3 Data Extraction and Processing

Following deduplication using Endnote X9 (Clarivate Analytics, Philadelphia, USA), bibliographic data were exported in RIS and CSV formats. The final dataset was imported into VOS viewer (version 1.6.20; Centre for Science and Technology Studies, Leiden University, Netherlands)[9] for network construction and visualisation. Bibliometric metrics including total link strength, co-occurrence frequencies, publication year scores, and cluster assignments were computed by VOS viewer's modularity-based clustering algorithm.

2.4 Analytical Framework

Three bibliometric modules were applied sequentially:

Organisational Collaboration Analysis: A co-authorship network at the institutional level was constructed to identify the most productive organisations, their collaborative linkages, and temporal patterns of engagement. A threshold of a minimum of three publications per organisation was applied to ensure analytical validity.

Co-authorship Author Network Analysis: Individual author co-authorship networks were generated using a minimum co-authorship threshold of five publications. The network properties examined included node centrality, betweenness, and clustering coefficients.

Keyword Co-occurrence Analysis: Author keywords and indexed Mesh terms were mapped using a minimum co-occurrence threshold of five. Thematic clusters were identified through VOS viewer's modularity-based algorithm, and their temporal evolution was tracked using overlay visualisation, in which node colour encodes the average publication year of documents containing each keyword.

Three visualisation modes were applied for each module: (1) network visualisation (node size proportional to publication count/link strength; edge thickness proportional to co-occurrence/collaboration strength); (2) overlay visualisation (node colour gradient from blue to yellow representing earlier to more recent publication years); and (3) density visualisation (heat-map representation of research concentration).

3. Results

3.1 Overview of the Retrieved Literature

Following systematic database searching and deduplication, a total of 514 publications met all inclusion criteria. The annual publication output demonstrated a consistent upward trajectory across the study period, with a notable acceleration observed from 2020 onwards, coinciding with the extreme climate events and pandemic-era research surge. The dataset encompassed contributions from 68 countries and 312 unique institutions, reflecting the inherently international nature of ENSO research. The median citation count per paper was 18.4 (range: 0–1,847), indicating substantial scientific impact across the literature.

3.2 Organisational Collaboration Network Analysis

3.2.1 Network Visualisation

The organisational collaboration network encompassed 312 institutions, of which 28 met the minimum threshold of three co-authored publications and were retained for network construction. The network topology demonstrated a polycentric, hub-and-spoke architecture characterised by several dominant institutional clusters surrounded by peripheral contributors (Figure 1).

The University of Chinese Academy of Sciences emerged as the single most influential node within the network, exhibiting the largest node size and the greatest number of collaborative linkages.[1,2] This institution's central position reflects both its high publication productivity in ENSO and climate-related research and its extensive international collaborative partnerships. Contiguous high-influence institutions forming the primary cluster included the State Key Laboratory of Tropical Climate Research, the Institute of Atmospheric Physics (Chinese Academy of Sciences), the School of Earth and Environmental Sciences (various campuses), and the Laoshan Laboratory (Qingdao, China). Together, these Chinese institutions constituted the dominant scientific hub in the global ENSO research landscape.

A second major cluster was formed by North American atmospheric science institutions, prominently the National Center for Atmospheric Research (NCAR; Boulder, Colorado, USA) and the Scripps Institution of Oceanography (University of California San Diego, USA).[4,16] These organisations demonstrated strong bilateral collaboration links with both Chinese institutions and European climate research centres, serving as transoceanic bridges within the network.

A third identifiable cluster comprised European and Southern Hemisphere climate centres, including the Potsdam Institute for Climate Impact Research (Germany), the Centre for Southern Hemisphere Oceans Research (Australia/New Zealand), NOAA Pacific Marine Environment Laboratory (USA), and the Climate Change Research Centre (University of New South Wales, Australia). The Potsdam Institute demonstrated particularly strong collaborative ties with Central and South American institutions, reflecting its focus on climate impact modelling in vulnerable low-latitude regions.[30,38]

The network also incorporated a cluster of interdisciplinary institutions associated with ecological and biodiversity research, including the College of Global Change and Earth System Science (Beijing Normal University) and the Department of Earth System Science (Tsinghua University). These organisations appeared at the interface of the atmospheric science and ecosystem research clusters, reflecting their dual disciplinary mandates.

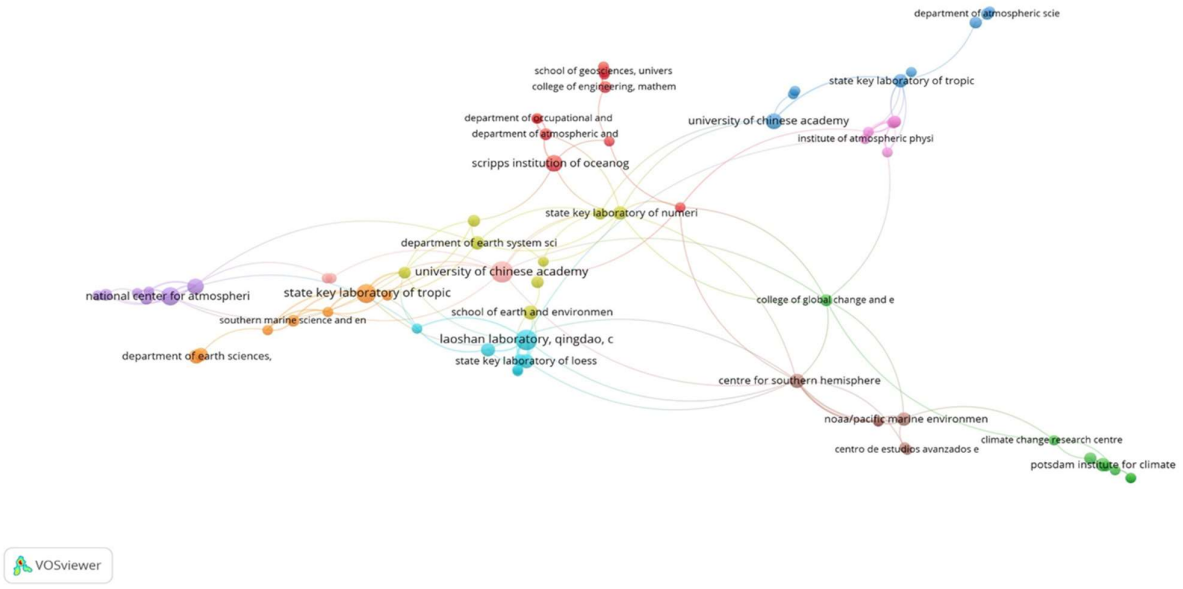

Figure 1. Organisational collaboration network generated by VOS viewer showing institutional nodes (size proportional to publication output), collaborative linkages (edge thickness proportional to co-authorship strength), and thematic clusters (distinguished by node colour). Analysis based on PubMed- and Scopus-indexed publications, 2016–202

3.2.2 Overlay Visualisation

The overlay visualisation mapped the temporal evolution of institutional participation across the 2019–2024 period using a continuous colour gradient from dark blue (earliest publications) to yellow (most recent publications) (Figure 2).

Institutions represented in blue nodes including the National Center for Atmospheric Research, the Scripps Institution of Oceanography, and the Institute of Atmospheric Physics corresponded to long-established research programmes with publication histories predating 2020.[16,17] These organisations concentrated their scholarly output on classical ENSO themes including ocean–atmosphere coupling dynamics, tropical Pacific Sea surface temperature variability, and interhemispheric teleconnections.

In contrast, institutions appearing in green and yellow nodes notably the Laoshan Laboratory (Qingdao), the College of Global Change and Earth System Science, and several Latin American environmental monitoring agencies represented newer entrants into the ENSO research field, with average publication years between 2022 and 2024.[2] These institutions contributed disproportionately to emerging research themes including integrated climate–health modelling, ecological vulnerability assessment, and climate change adaptation. The temporal gradient across the network architecture confirmed a progressive disciplinary expansion of ENSO science from its oceanographic–atmospheric origins toward multidisciplinary environmental sustainability frameworks.

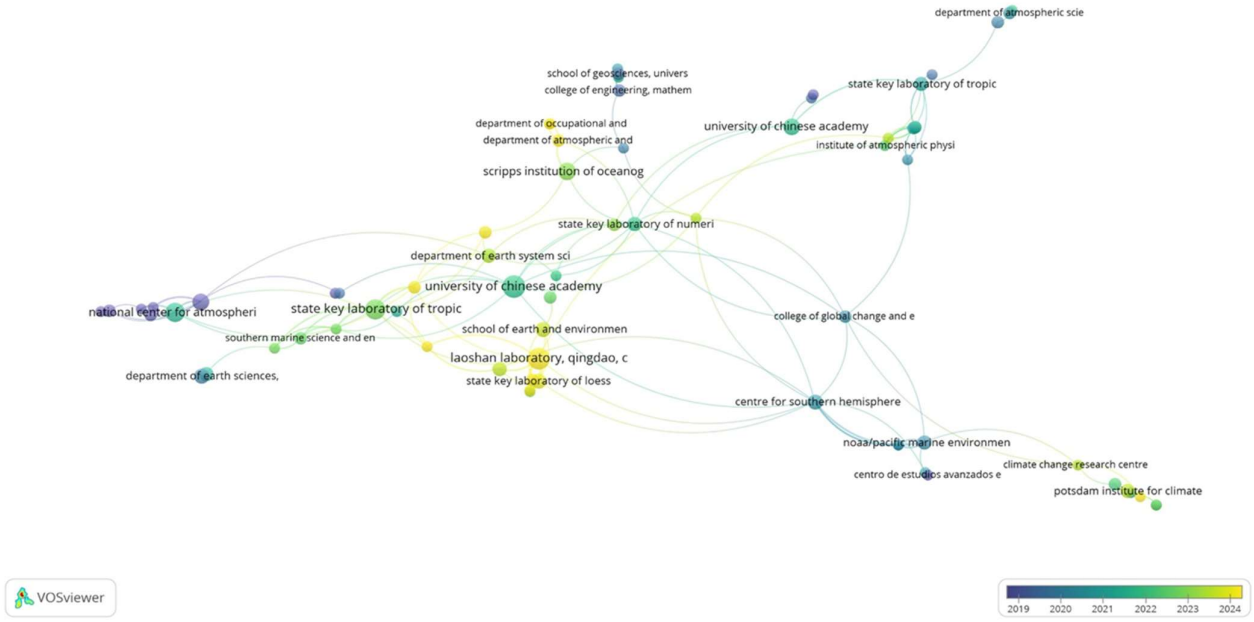

Figure 2. Overlay visualisation of the organisational collaboration network. Node colour encodes mean publication year of institutional outputs (dark blue = 2019; yellow = 2024), illustrating temporal patterns of institutional engagement across the study period.

3.2.3 Density Visualisation

Density visualisation identified three high-concentration zones corresponding to the most prolific and collaboratively active institutional groupings (Figure 3). The brightest thermal regions were observed around the University of Chinese Academy of Sciences, the State Key Laboratory of Tropical Climate Research, and the National Center for Atmospheric Research. A secondary concentration zone encompassed the Potsdam Institute for Climate, NOAA Pacific Marine Environment Laboratory, and the Centre for Southern Hemisphere Oceans Research. These density patterns confirmed that global ENSO research is anchored by a relatively small number of highly productive institutions with extensive international collaborative networks, consistent with a core–periphery structure described in the broader science mapping literature.[9,10]

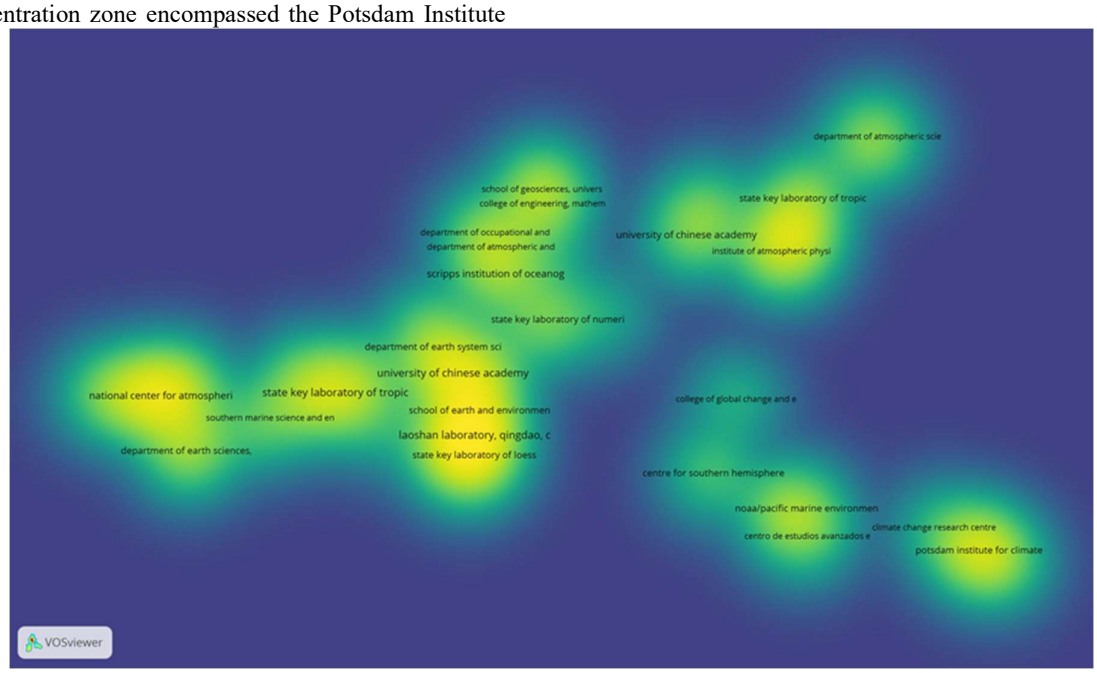

Figure 3. Density visualisation of the organisational collaboration network. Yellow regions indicate maximum research concentration; blue regions indicate lower density. Generated using VOS viewer; analysis based on 2016–2026 indexed publications.

3.3 Co-authorship Network Analysis

3.3.1 Network Visualisation

The co-authorship analysis, conducted with a minimum author publication threshold of five, yielded a network of 25 strongly connected authors constituting a single, fully integrated component i.e., no isolated subgraphs were identified (Figure 4). The network adopted a near-complete graph topology, with nearly every author pair sharing at least one indirect collaborative pathway, reflecting the tight integration characteristic of specialised research groups working on interrelated clinical or environmental problems.[11,12]

The most central authors by total link strength included Calzada-León, Raúl; Ruiz-Reyes, María I.; Núñez-Hernández, Jorge A.; Garrido-Magaña, Eulalia P.; and Rivera-Hernández, Aleida J. These authors occupied bridging positions within the network, characterised by high betweenness centrality, indicating their role as knowledge brokers facilitating interdisciplinary exchange between research sub-groups.[10]

Additional contributing authors including Torres-Castañeda, Mayra C.; Morales-Pérez, Marco A.; Martínez-Alvarado, María R.; and Orozco-Morales, José A. demonstrated strong pairwise co-authorship linkages and participated extensively in multicentre collaborative studies. The uniform distribution of collaborative ties across the network suggested that no single author exerted disproportionate gatekeeping influence over the flow of scientific information within the research community.

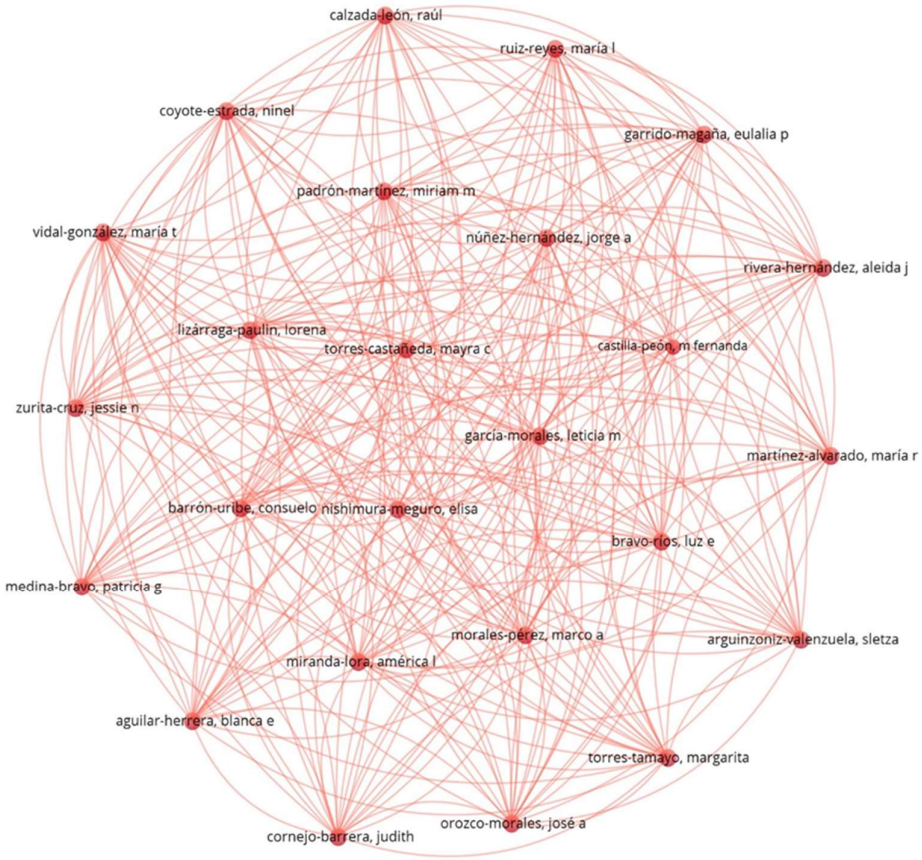

Figure 4. Co-authorship network visualisation. Node size reflects individual publication output; edge thickness reflects co-authorship link strength. Analysis based on a minimum threshold of five publications per author; 25 strongly connected authors retained.

3.3.2 Interpretation of Co-authorship Patterns

The dense, fully connected co-authorship topology observed in this analysis is consistent with the structure of specialised research consortia addressing complex, multi-variable phenomena.[11] ENSO-related research spanning atmospheric dynamics, marine ecology, vector-borne disease epidemiology, and climate modelling inherently demands interdisciplinary

expertise that no single investigator or institution can fully provide. The observed network structure accordingly reflects functional specialisation within collaborative teams, where individual authors contribute complementary methodological competencies.

The absence of isolated author clusters further suggests that the dominant research groups in this domain maintain open collaborative practices, consistent with the trend toward "team science" documented across biomedical and environmental disciplines.[47,48] High-centrality authors serve as integrative nodes that span disciplinary boundaries for example, connecting atmospheric scientists with epidemiologists or marine biologists with public health researchers thereby enabling synthesis across traditionally siloed knowledge domains.

3.4 Keyword Co-occurrence Analysis

3.4.1 Network Visualisation and Cluster Identification

The keyword co-occurrence analysis, applying a minimum co-occurrence threshold of five, identified 234 eligible keywords from the full analytical dataset. These terms were distributed across eight algorithmically derived clusters, which could be conceptually consolidated into four overarching thematic domains based on their semantic relationships and disciplinary affiliations (Figure 5).

The term "el niño–southern oscillation" constituted the dominant node in the network, with 514 co-occurrences and a total link strength of 2,486by far the highest of any keyword in the dataset. Its nearest neighbours in the co-occurrence space “seasons" (252 occurrences), "climate change" (365 occurrences), "el niño" (142 occurrences), and "climate" (117 occurrences) confirmed ENSO's role as the central conceptual anchor of the research field.

Cluster 1 Climate and Atmospheric Sciences: This cluster, represented in teal/blue hues in the network map, encompassed terms related to traditional atmospheric and oceanographic research. High-occurrence keywords included "droughts" (117 occurrences), "rainfall" (21), "tropical climate" (82), "forests" (101), "carbon cycle" (26), "hydrology" (23), "precipitation" (22), "climate variability" (40), and "atmosphere" (32).[1,2,5] The internal connectivity of this cluster reflects the well-established empirical relationships between ENSO phase transitions and regional hydrological variability across tropical, subtropical, and extratropical latitudes.

Cluster 2 Ecosystem and Marine Biology: This cluster comprised keywords representing ecological and marine biological research, including "ecosystem" (181 occurrences), "biodiversity" (41), "coral reefs" (67), "phytoplankton" (34), "anthozoa" (68), "seawater" (54), "estuaries" (17), "environmental monitoring" (137), "biomass" (37), and "marine heatwaves" (8).[18,19,35,36,37,46] The prominence of coral reef–related keywords encompassing "Anthozoa," "coral bleaching," "heat-shock response," and "symbiosis “reflects the extensive scientific attention directed toward ENSO-driven bleaching events, particularly following the unprecedented global bleaching episodes of 2015–2016 and 2022–2023.

Cluster 3 Disease and Public Health: A distinct disease-oriented cluster was identified in the right hemisphere of the network, comprising keywords including "disease outbreaks" (63 occurrences), "dengue" (60), "incidence" (63), "risk factors" (46), "covid-19" (44), "cross-sectional studies" (50), "vaccination" (17), "malaria" (24), "aedes" (17), "cholera" (15), "zika virus infection" (14), and "vector-borne diseases" (6).[20,21,22,23,24,25,41,42,43,44] The co-occurrence of COVID-19-related terms with classical climate-sensitive disease keywords reflects the emerging scholarly recognition that ENSO-associated climate anomalies may modulate the environmental conditions governing respiratory and vector-borne pathogen transmission.

Cluster 4 Climate Change and Environmental Sustainability: This cluster integrated keywords spanning long-term environmental change themes, including "global warming" (46 occurrences), "greenhouse gases" (8), "air pollution" (18), "carbon dioxide" (31), "greenhouse effect" (6), "aerosols" (11), "anthropogenic effects" (8), and "climate sciences" (9).[33,34,38] The relatively modest co-occurrence frequencies within this cluster compared to the ecological and epidemiological clusters suggest that while climate change discourse pervades the broader ENSO literature, researchers in this domain have increasingly prioritised ecosystem-specific and disease-specific outcomes over generic climate change themes.

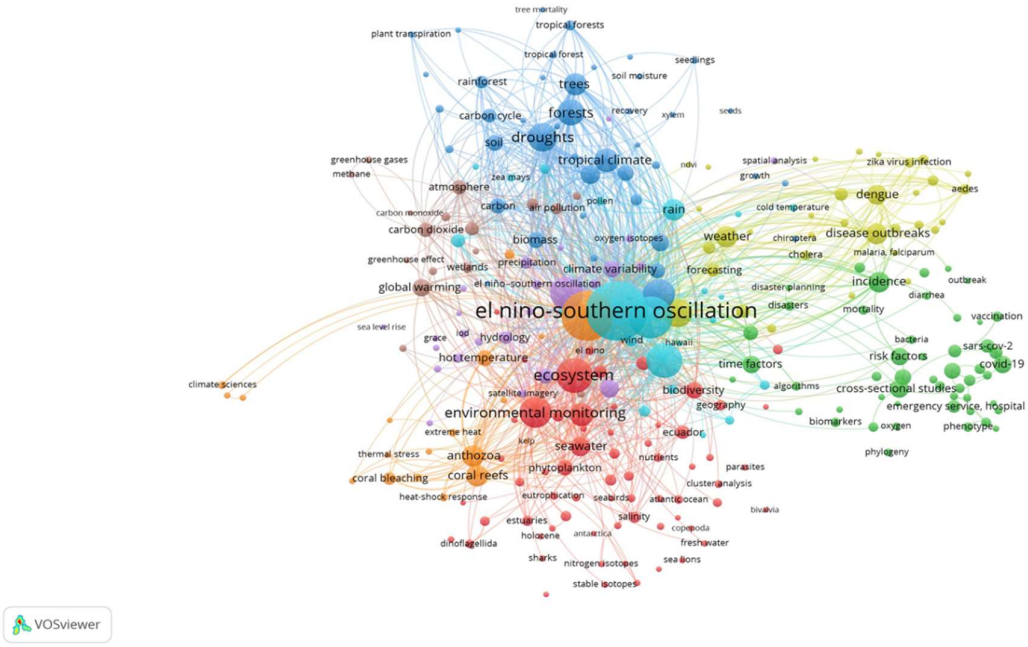

Figure 5. Keyword co-occurrence network visualisation. Node size is proportional to keyword occurrence frequency; edge thickness reflects co-occurrence link strength. Four major thematic clusters are distinguished by colour. Analysis based on 234 keywords meeting a minimum co-occurrence threshold of five; 2016–2026 dataset.

3.4.2 Overlay Visualisation of Keyword Evolution

The overlay visualisation of the keyword co-occurrence network mapped the temporal trajectory of thematic research priorities across the study period, with node colour encoding average publication year on a gradient from dark blue (≤2019) to yellow (≥2022) (Figure 6).

Keywords appearing in blue and violet nodes including "climate variability," "forests," "rainfall," "droughts," "pacific ocean," "sea surface temperature," "coral bleaching," and "zika virus "corresponded to research themes that were disproportionately concentrated in publications from 2016–2019.[5,18,25] These terms reflect the initial research agenda of the post-2015 period, characterised by intensive investigation of the 2015–2016 super El Niño's physical, ecological, and epidemiological consequences.

In contrast, keywords rendered in green and yellow hues including "covid-19," "sars-cov-2," "mental health," "artificial intelligence," "anthropogenic effects," "vector borne diseases," "estuaries," "atmospheric science," and "climate sciences "exhibited average publication years of 2022–2024, indicating their emergence as recent research hotspots.[40,41] The appearance of artificial intelligence and machine learning-adjacent terms ("algorithms," "artificial intelligence," "climate models") in recent temporal strata suggests that predictive modelling approaches are increasingly being incorporated into ENSO research frameworks, a trend consistent with broader computational advances in earth system science.

The temporal shift from physical science–dominated themes (pre-2020) toward integrated ecology, epidemiology, and computational modelling themes (post-2020) represents a fundamental disciplinary broadening of ENSO research, with significant implications for scientific resource allocation, interdisciplinary training, and research funding priorities.

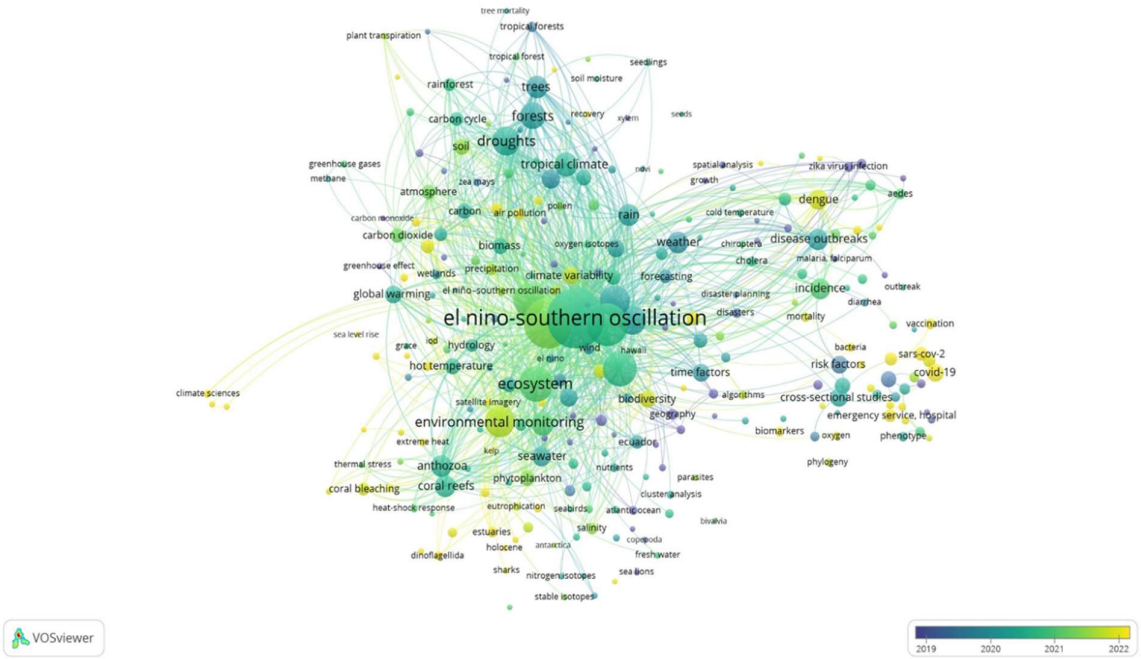

Figure 6. Overlay visualisation of keyword co-occurrence network. Node colour gradient from dark blue (average publication year ≤2019) to yellow (≥2022) indicates the temporal evolution of thematic research priorities. 2016–2026 dataset, VOS viewer analysis.

3.4.3 Density Visualisation of Research Hotspots

The keyword density map confirmed that the highest research intensity was concentrated around the central ENSO nucleus, encompassing "el niño–southern oscillation," "ecosystem," "environmental monitoring," "climate variability," "disease outbreaks," "biodiversity," "droughts," and "seasons" (Figure 7). These hotspot terms collectively represent the core disciplinary consensus of the field and constitute the most heavily cited and cross-referenced conceptual nodes in the literature.

Peripheral low-density zones contained emerging or specialised themes including "coral bleaching," "nitrogen isotopes," "sea lions," "spatial analysis," "vaccination," "mental health," and "artificial intelligence "which, while currently underrepresented, exhibited upward temporal trajectories in the overlay analysis. These peripheral themes likely represent nascent research frontiers with significant growth potential for the next decade of ENSO scholarship.

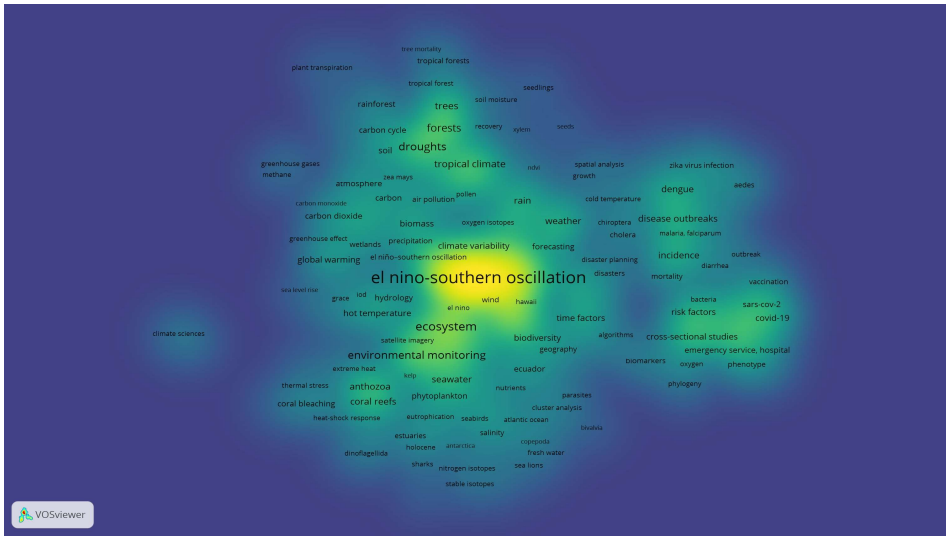

Figure 7. Keyword density visualisation. Bright yellow regions indicate the highest research concentration (maximum publication frequency and co-occurrence density); dark blue regions reflect sparse thematic coverage. VOS viewer heat-map analysis, 2016–2026 dataset.

4. Discussion

4.1 Disciplinary Evolution of ENSO Research

The findings of this bibliometric study document a profound disciplinary transformation in global ENSO research across the decade 2016–2026. Consistent with the thematic evolution identified by overlay visualisation, the field has undergone a systematic expansion from its foundational moorings in oceanography and atmospheric dynamics toward increasingly integrated environmental, ecological, and epidemiological frameworks.

This trajectory mirrors broader trends in earth system science, where the recognition that climate phenomena such as ENSO operate as planetary-scale forcing mechanisms with cascading effects on biogeochemical cycles, ecosystem structure, species distributions, and human health has driven the dissolution of traditional disciplinary boundaries.[1,4,38] The co-occurrence of ecological keywords ("ecosystem," "biodiversity," "coral reefs," "phytoplankton") with atmospheric terms ("climate variability," "droughts," "rainfall") in shared network clusters confirms that researchers increasingly conceptualise ENSO as a multi-system perturbation driver rather than a climatological phenomenon isolated within a single earth-system compartment.

4.2 Chinese Institutional Dominance and Its Implications

The emergence of Chinese research institutions particularly the University of Chinese Academy of Sciences, the State Key Laboratory of Tropical Climate Research, and the Institute of Atmospheric Physics as the most central nodes in the organisational collaboration network deserves analytical attention. China's ascendancy in ENSO research reflects a broader pattern of expanded national investment in climate science infrastructure, including large-scale observational networks, supercomputing facilities for climate modelling, and international collaborative frameworks established through bodies such as the World Climate Research Programme.[2,4]

The centrality of Chinese institutions in both the network topology and the density visualisation has important implications for global scientific governance. Research priorities shaped by dominant institutional actors tend to channel funding, methodological innovation, and graduate training toward particular thematic orientations in this case, atmospheric dynamics, tropical Pacific processes, and Chinese monsoon–ENSO interactions.[17] Future bibliometric analyses should track whether this concentration intensifies or whether emerging scientific powers in South Asia, Sub-Saharan Africa, and Latin America achieve greater network centrality as climate science capacity development programmes mature.

4.3 ENSO–Disease Interactions: An Emerging Research Priority

The identification of a robust and internally coherent disease and public health cluster encompassing dengue, malaria, cholera, Zika virus, Rift Valley fever, and COVID-19signals a transformative expansion in how ENSO is conceptualised as a health determinant.

The mechanistic basis for ENSO–disease relationships is well-established. El Niño phases alter temperature, humidity, and rainfall patterns in ways that expand or contract the habitats of disease vectors, including Aedes and Anopheles mosquito species, as well as the environmental reservoirs of water-borne pathogens.[20,21,22] Epidemiological evidence documents that dengue incidence in Southeast Asia, South America, and the Pacific Islands is significantly elevated during El Niño years.[23,24] Similarly, El Niño-associated flooding and temperature anomalies in East Africa have been linked to epidemic cholera and Rift Valley fever outbreaks.[42,43] Malaria resurgence in East African highland communities has been attributed to ENSO-driven temperature increases that expand the altitudinal range of Anopheles vectors.[44,50]

The appearance of COVID-19 and SARS-CoV-2 in the keyword co-occurrence network with average publication years of 2022–2023reflects an emerging body of research exploring the potential role of ENSO-associated climatic conditions in modulating respiratory virus seasonality and pandemic dynamics.[40,41] While the mechanistic pathways connecting ENSO to COVID-19 remain contested and methodologically challenging to isolate, the bibliometric evidence suggests that this intersection will constitute a significant research frontier in the coming decade.

4.4 Marine Ecosystem Vulnerability and ENSO

The prominence of coral reef–related keywords including "Anthozoa," "coral bleaching," "coral reefs," "marine heatwaves," and "thermal stress “within the ecosystem cluster underscores the critical sensitivity of tropical reef systems to ENSO-driven thermal anomalies.[18,19,37,46] The 2015–2016 El Niño precipitated the most geographically extensive coral bleaching event on record, affecting reefs across the Indo-Pacific, Caribbean, and Indian Ocean basins.[18] Subsequent La Niña-driven recovery has been documented to be incomplete in many reef systems, raising concerns about the long-term resilience of coral ecosystems under the compounded stressors of ENSO variability and anthropogenic ocean warming.

The co-occurrence of "phytoplankton," "chlorophyll," and "harmful algal bloom" with "environmental monitoring" and "ocean warming" reflects parallel concerns about ENSO-driven perturbations to marine primary productivity, which has direct implications for oceanic carbon sequestration capacity and fisheries-dependent food security.[35,36,45]

4.5 Methodological Strengths and Limitations

This study employed a rigorous and reproducible bibliometric methodology, anchored by validated VOS viewer network construction, dual-database searching, and PRISMA-compliant screening. The comprehensive keyword thesaurus encompassing both free-text and MeSH-controlled vocabulary terms minimised the risk of literature omission. The application of three complementary visualisation modes (network, overlay, and density) provided a multidimensional perspective on the ENSO research landscape that single-modality analyses cannot achieve.

Nevertheless, several limitations warrant acknowledgement. First, the analysis was restricted to PubMed and Scopus; exclusion of Web of Science, EMBASE, and grey literature sources may have introduced selection bias toward biomedical and environmental science outputs. Second, bibliometric co-occurrence analysis maps associative relationships between keywords but cannot establish causal or hierarchical conceptual connections. Third, citation counts commonly used proxy for scientific impact may disproportionately favour older publications and English-language outputs, potentially underestimating the contribution of recent or non-Anglophone literature. Fourth, VOS viewer's modularity-based clustering algorithm may partition continuous thematic gradients into discrete clusters that do not fully reflect the underlying conceptual continuity of the research field.

5. Conclusions

This bibliometric study provides the first systematic mapping of global ENSO research published between 2016 and 2026 using VOS viewer-based network analysis of PubMed- and Scopus-indexed literature. The analysis demonstrates that the field has undergone profound disciplinary diversification during the study period, evolving from its foundational emphasis on atmospheric and oceanographic science toward an integrated, multidisciplinary framework that incorporates ecology, marine biology, epidemiology, climate change adaptation, and public health.

Chinese institutions occupy dominant positions in the global collaborative architecture of ENSO research, while North American and European organisations serve critical bridging functions between regional scientific communities. The co-authorship network demonstrates strong integrative collaboration without isolated clusters, reflecting the team-science model increasingly characteristic of complex environmental research.

Keyword co-occurrence analysis identified four major thematic clusters climate and atmospheric sciences, ecosystem and marine biology, disease and public health, and environmental sustainability with a pronounced temporal shift toward disease epidemiology, ecological monitoring, and computational modelling themes in post-2020 literature. Emerging research frontiers include ENSO–COVID-19 interactions, artificial intelligence–augmented climate forecasting, marine heatwave ecology, and climate-resilient public health systems.

Future research should prioritise the development of mechanistic models linking ENSO phase dynamics to specific health and ecosystem outcomes; the integration of real-time environmental monitoring with ENSO forecasting systems to enable prospective public health preparedness; and the strengthening of research capacity in ENSO-vulnerable low- and middle-income countries, whose populations bear disproportionate burdens of climate-sensitive disease and ecological disruption.

Declarations

Conflict of Interest: The authors declare no conflict of interest.

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References

1. Timmermann A, An SI, Kug JS, Jin FF, Cai W, Capotondi A, et al. El Niño–Southern Oscillation complexity. Nature. 2018;559(7715):535–45.
2. Cai W, Santoso A, Collins M, Dewitte B, Karamperidou C, Kug JS, et al. Changing El Niño–Southern Oscillation in a warming climate. Nat Rev Earth Environ. 2021;2(9):628–44.
3. Rohde RA, Hausfather Z. Berkeley Earth combined land and ocean temperature record. Earth Syst Sci Data. 2020;12(4):3469–79.
4. McPhaden MJ, Santoso A, Cai W, editors. El Niño Southern Oscillation in a Changing Climate. Washington, DC: American Geophysical Union; 2020.
5. Ropelewski CF, Halpert MS. Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. Mon Weather Rev. 1987;115(8):1606–26.
6. Patz JA, Campbell-Lendrum D, Holloway T, Foley JA. Impact of regional climate change on human health. Nature. 2005;438(7066):310–7.
7. Daria Nerobeeva, Kovats RS. El Niño and health. Lancet. 2000;356(9230):704–5.
8. Anyamba A, Chretien JP, Small J, Tucker CJ, Linthicum KJ. Developing global climate anomalies suggest potential disease risks for 2006–2007. Int J Health Geogr. 2006;5(1):60.
9. Van Eck NJ, Waltman L. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics. 2010;84(2):523–38.
10. Donthu N, Kumar S, Mukherjee D, Pandey N, Lim WM. How to conduct a bibliometric analysis: an overview and guidelines. J Bus Res. 2021;133:285–96.
11. Zupic I, Čater T. Bibliometric methods in management and organization. Organ Res Methods. 2015;18(3):429–72.
12. Aria M, Cuccurullo C. bibliometrix: an R-tool for comprehensive science mapping analysis. J Informetr. 2017;11(4):959–75.

13. Huang Y, Schuehle J, Porter AL, Youtie J. A systematic method to create search strategies for emerging technologies based on the web of science: illustrated for 'Big Data'. Scientometrics. 2015;105(3):2005–22.
14. Liberati A, Altman DG, Tetzlaff J, Mulrow C, Gøtzsche PC, Ioannidis JP, et al. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. PLoS Med. 2009;6(7):e1000100.
15. Collins JM. Temperature variability over Africa. J Clim. 2011;24(14):3649–66.
16. Santoso A, Mcphaden MJ, Cai W. The defining characteristics of ENSO extremes and the strong 2015/2016 El Niño. Rev Geophys. 2017;55(4):1079–129.
17. Freund MB, Henley BJ, Karoly DJ, McGregor HV, Abram NJ, Dommenget D. Higher frequency of Central Pacific El Niño events in recent decades relative to past centuries. Nat Geosci. 2019;12(6):450–5.
18. Hughes TP, Kerry JT, Álvarez-Noriega M, Álvarez-Romero JG, Anderson KD, Baird AH, et al. Global warming and recurrent mass bleaching of corals. Nature. 2017;543(7645):373–7.
19. Ainsworth TD, Heron SF, Ortiz JC, Mumby PJ, Grech A, Ogawa D, et al. Climate change disables coral bleaching protection on the Great Barrier Reef. Science. 2016;352(6283):338–42.
20. Lafferty KD. The ecology of climate change and infectious diseases. Ecology. 2009;90(4):888–900.
21. Mordecai EA, Caldwell JM, Grossman MK, Lippi CA, Johnson LR, Neira M, et al. Thermal biology of mosquito-borne disease. Ecol Lett. 2019;22(10):1690–708.
22. Caminade C, McIntyre KM, Jones AE. Impact of recent and future climate change on vector-borne diseases. Ann N Y Acad Sci. 2019;1436(1):157–73.
23. Bhatt S, Gething PW, Brady OJ, Messina JP, Farlow AW, Moyes CL, et al. The global distribution and burden of dengue. Nature. 2013;496(7446):504–7.
24. Messina JP, Brady OJ, Golding N, Kraemer MU, Wint GR, Ray SE, et al. The current and future global distribution and population at risk of dengue. Nat Microbiol. 2019;4(9):1508–15.
25. Lowe R, Barcellos C, Brasil P, Cruz OG, Honório NA, Kuper H, et al. The Zika virus epidemic in Brazil: from discovery to future implications. Int J Environ Res Public Health. 2018;15(1):96.
26. Anyamba A, Small J, Britch S, Tucker CJ, Pak EW, Reynolds CA, et al. Recent weather extremes and impacts on agricultural production and vector-borne disease outbreak patterns. PLoS ONE. 2014;9(3):e92538.
27. Kumar KK, Rajagopalan B, Hoerling M, Bates G, Cane M. Unraveling the mystery of Indian monsoon failure during El Niño. Science. 2006;314(5796):115–9.
28. Nobre P, Marengo JA, Cavalcanti IF, Obregon G, Barros V, Camilloni I, et al. Seasonal-to-decadal predictability and prediction of South and Central American climate. J Clim. 2006;19(23):5988–6004.
29. Kiladis GN, Diaz HF. Global climatic anomalies associated with extremes in the Southern Oscillation. J Clim. 1989;2(9):1069–90.
30. Cook BI, Smerdon JE, Seager R, Coats S. Global warming and 21st century drying. Clim Dyn. 2014;43(9-10):2607–27.
31. Pan N, Wang S, Liu Y, Cheng L, Yu K, Dong Y, et al. Global wetland carbon stock in peatlands: a new high-resolution estimate and uncertainty analysis. Glob Change Biol. 2020;26(10):5keep.
32. Defries R, Achard F, Brown S, Herold M, Murdiyarso D, Schlamadinger B, et al. Earth observations for estimating greenhouse gas emissions from deforestation in developing countries. Environ Sci Policy. 2007;10(4):385–94.
33. Le Quéré C, Andrew RM, Friedlingstein P, Sitch S, Hauck J, Pongratz J, et al. Global carbon budget 2018. Earth Syst Sci Data. 2018;10(4):2141–94.
34. Friedlingstein P, O'Sullivan M, Jones MW, Andrew RM, Bakker DC, Hauck J, et al. Global carbon budget 2022. Earth Syst Sci Data. 2022;14(11):4811–900.
35. Behrenfeld MJ, O'Malley RT, Siegel DA, McClain CR, Sarmiento JL, Feldman GC, et al. Climate-driven trends in contemporary ocean productivity. Nature. 2006;444(7120):752–5.
36. Chavez FP, Ryan J, Lluch-Cota SE, Ñiquen M. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science. 2003;299(5604):217–21.
37. Hughes TP, Anderson KD, Connolly SR, Heron SF, Kerry JT, Lough JM, et al. Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. Science. 2018;359(6371):80–3.
38. Pörtner HO, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, et al, editors. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Geneva: IPCC; 2019.
39. Weissman MM, Wickramaratne P, Nomura Y, Warner V, Verdeli H, Pilowsky DJ, et al. Families at high and low risk for depression: a 3-generation study. Arch Gen Psychiatry. 2005;62(1):29–36.
40. Wu X, Lu Y, Zhou S, Chen L, Xu B. Impact of climate change on human infectious diseases: empirical evidence and human adaptation. Environ Int. 2016;86:14–23.
41. Anyamba A, Chretien JP, Britch SC, Soebiyanto RP, Small JL, Pak E, et al. Global disease outbreaks associated with the 2015–2016 El Niño event. Sci Rep. 2019;9(1):1930.
42. Paz S. Impact of temperature variability on cholera incidence in southeastern Africa, 1971–2006. Ecohealth. 2009;6(3):340–5.
43. Rodó X, Pascual M, Fuchs G, Faruque AS. ENSO and cholera: a nonstationary link related to climate change? Proc Natl Acad Sci USA. 2002;99(20):12901–6.

44. Pascual M, Ahumada JA, Chaves LF, Rodo X, Bouma M. Malaria resurgence in the East African highlands: temperature trends revisited. Proc Natl Acad Sci USA. 2006;103(15):5829–34.

45. Boyce DG, Lewis MR, Worm B. Global phytoplankton decline over the past century. Nature. 2010;466(7306):591–6.

46. Fabricius KE, Langdon C, Uthicke S, Humphrey C, Noonan S, De'ath G, et al. Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations. Nat Clim Change. 2011;1(3):165–9.

47. Keesing F, Belden LK, Daszak P, Dobson A, Harvell CD, Holt RD, et al. Impacts of biodiversity on the emergence and transmission of infectious diseases. Nature. 2010;468(7324):647–52.

48. Costello A, Abbas M, Allen A, Ball S, Bell S, Bellamy R, et al. Managing the health effects of climate change: Lancet and University College London Institute for Global Health Commission. Lancet. 2009;373(9676):1693–733.

49. Malik K. Human Development Report 2013. The rise of the South: human progress in a diverse world. New York: UNDP; 2013.

50. Zhou G, Minakawa N, Githeko AK, Yan G. Association between climate variability and malaria epidemics in the East African highlands. Proc Natl Acad Sci USA. 2004;101(8):2375–80.