A Bibliometric Analysis of Global Ocean Acidification Research (Postprint)

Authors: Chen Peng, Chen Xinjun, Chen Changsheng, Hu Feifei

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Abstract

Ocean acidification is currently a global issue of significant public concern. To objectively reveal the research trends in ocean acidification, this study employs bibliometric analysis, using all literature related to ocean acidification research in the ISI Web of Science Journal Citation Database since the concept was proposed (post-2004) as the sample. Descriptive statistics were conducted on the growth trends and journal distribution of the literature, and keyword-based knowledge mapping and burst detection analysis were used to explore the temporal evolution of hot research directions and research frontiers in ocean acidification. Descriptive statistics indicate that in the decade since the concept of ocean acidification was proposed, the number of research publications related to ocean acidification has surged, with obvious interdisciplinary characteristics, and the impact of ocean acidification on coral reefs has been a key research area during this period. Keyword-based knowledge mapping reveals that in the early stage of ocean acidification research (2004-2009), research content was mainly divided into two parts: first, the impact of ocean acidification on marine organisms (especially coral reef organisms and phytoplankton) and ecosystems; second, the understanding of the ocean acidification phenomenon itself. In the middle stage (2010-2015), research content was similar to the early stage, with the research focus shifting toward marine organisms, while new hot research regions and directions emerged. In the recent stage (post-2016), research on the impact of ocean acidification on marine organisms continues to occupy the mainstream research direction. Analysis of literature on current hot topics in ocean acidification research (as of February 2018) obtained through burst detection reveals that current ocean acidification research has the following five frontier directions: (1) When exploring the relationship between ocean acidification and organisms, multi-factor discussions must be integrated; (2) Exploring the intrinsic coping mechanisms of organisms under ocean acidification; (3) Comprehensive assessment and prediction of biological responses under ocean acidification impacts; (4) Exploring the impact of ocean acidification on marine

ecosystems; (5) A challenge to the concept of ocean acidification—exploring the causes of ocean acidification formation.

Full Text

Preamble

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Bibliometric Analysis of the Global Study on Ocean Acidification
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* **Bibliometric Analysis of the Global Study on Ocean Acidification**
Chen Peng[1],[2],[3], , ,*, Chen Xinjun[1], Chen Changsheng[1], , Hu Feifei[1],
[1] College of Marine Sciences, Shanghai Ocean University
[2] Laboratory for Marine Fisheries Science and Food Production Processes
[3] Qingdao National Laboratory for Marine Science and Technology
Key Laboratory of Sustainable Exploitation of Oceanic Fisheries Resources, Ministry of Education, Shanghai Ocean University
National Engineering Research Center for Oceanic Fisheries, Shanghai Ocean University
Key Laboratory of Oceanic Fisheries Exploration, Ministry of Agriculture
Department of Fisheries Oceanography, School for Marine Science and Technology, University of Massachusetts Dartmouth, New Bedford 02744, USA

Abstract

Ocean acidification is a well-known global issue. To objectively reveal research trends in ocean acidification, this study employs bibliometric analysis to review all literature related to ocean acidification published after the concept was introduced (i.e., after 2004) and indexed in the ISI Web of Science journal citation database. We first created descriptive statistics of annual publication numbers and journal distribution frequency, then used keyword-based knowledge mapping and burst analysis methods to explore evolving hotspots and research frontiers. Descriptive statistics show that over the past decade since the concept's introduction, literature on ocean acidification has surged dramatically, with obvious interdisciplinary characteristics. The impact of ocean acidification on coral reefs has been a major focus during this period. Keyword-based knowledge mapping reveals that most studies belong to the field of biology. During the initial stage of ocean acidification research (2004-2009), studies focused on two main areas: (1) impacts on marine organisms (especially coral reefs and phytoplankton) and ecosystems, and (2) understanding the ocean acidification phenomenon itself, with new hotspot regions and research directions emerging. During the middle stage (2010-2015), research content remained similar to the

initial stage but shifted focus toward marine organisms. In the recent stage (after 2016), studies on ocean acidification' s impact on marine organisms continue to dominate. Burst analysis of current hotspots (up to February 2018) identifies five research frontiers: (1) combining multiple factors with ocean acidification when exploring relationships with marine organisms; (2) exploring internal response mechanisms of marine organisms in acidic environments; (3) comprehensive assessment and prediction of biological responses under ocean acidification; (4) exploring impacts on marine ecosystems; and (5) challenges to the ocean acidification concept and exploration of other causes.

Keywords: ocean acidification; climate change; bibliometric analysis; keyword analysis; knowledge mapping

1. Sample Source

The literature sample was sourced from the Web of Science Core Collection in the ISI Web of Science database, using "Ocean acidification" as the search term. The search timeframe covered the period after the ocean acidification concept was proposed (2004-2018). Paper titles, keywords, and cited references were used as analytical samples.

2. Descriptive Statistics

Descriptive statistics were divided into analysis of literature growth patterns and journal distribution to grasp overall research trends and gain preliminary understanding of involved disciplines.

3. Keyword-Based Knowledge Mapping

Knowledge mapping is a graphical representation that describes the development process and structural relationships of scientific knowledge, showing connections between different knowledge domains. In ocean acidification research, scientists have different research focuses—some describe the phenomenon itself, while others examine impacts on shellfish and coral reefs. Additionally, hotspot knowledge varies across periods. Therefore, this study employs co-word analysis using keywords from ocean acidification literature as indicators to construct co-occurrence knowledge maps for different periods and explore temporal changes in research hotspots.

The basic principles and steps are as follows: Article keywords centrally summarize research content. When two or more keywords frequently co-occur across many papers, they represent a research hotspot. The basic principle of co-word analysis assumes that a group of keywords appearing together in one article indicates close relationships and content connections. In knowledge maps, keywords serve as nodes connected by lines, forming a co-occurrence network.

The timeframe was divided into three periods: initial stage (2004–2009), middle stage (2010–2015), and recent stage (after 2016). For each period, we first counted keyword frequencies, removed keywords directly related to ocean acidification itself (e.g., "ocean acidification," "seawater acidification"), and merged obviously synonymous keywords (e.g., "carbon dioxide" and "CO "). The top 30 most frequent keywords were selected as hotspot keywords for analysis.

Network drawing and optimization used the Kamada & Kawai algorithm and Pathfinder algorithm. Cluster analysis and keyword betweenness centrality were also employed. In bibliometrics, cluster analysis simplifies complex keyword networks into fewer groups based on co-occurrence frequencies. Modularity values between 0.4–0.8 indicate good clustering results—lower values suggest unclear boundaries, while higher values indicate insufficient inter-group connections. Betweenness centrality, calculated as a specific numerical value, reflects how many other keyword nodes a given keyword connects to, revealing research emphases within clusters.

4. Burst Detection

Kleinberg's burst theory suggests that when an article's citation frequency surges during a specific period, its content may represent a new research direction. We used Kleinberg' s burst detection algorithm to identify research frontiers in ocean acidification. This probabilistic automaton-based algorithm correlates an article' s attention with its citation frequency over time, identifying when citations significantly increase or decrease to determine if the literature was a focus of scholarly attention, providing start/end years and burst strength.

Burst detection was applied to the top 100 most-cited references in the sample to identify literature still receiving hotspot attention in 2018, thereby determining current research frontiers.

5. Analysis Software

All analyses were conducted using bibliometric software CiteSpace 5.1.R6.

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1. Literature Growth Pattern

A total of 3,752 articles on ocean acidification were retrieved. The number of publications shows a dramatic surge: only 4 articles in 2004, increasing to double digits by 2005; 105 articles in 2008; and peaking at 636 articles in 2017. Although data were only collected through February 2018, 105 articles were already published, indicating ocean acidification has been a hot topic in the scientific community for over a decade.

[Figure 1: see original paper] Annual numbers (from 2004 to February 2018) of literatures about ocean acidification studies

2. Journal Distribution Pattern Analysis

The top 20 journals publishing ocean acidification research account for 44.95% of all retrieved literature. The list includes not only traditional marine science journals (e.g., *ICES Journal of Marine Science*, *Oceanography*) but also interdisciplinary fields like biogeosciences (*Biogeosciences*) and biology (*Marine Biology*), demonstrating that ocean acidification research requires multidisciplinary participation. Notably, the list includes prestigious mainstream journals such as *Scientific Reports*, *Proceedings of the National Academy of Sciences of the United States of America*, and *Science*, indicating significant attention from the international academic community. The presence of the coral reef-specific journal *Coral Reefs* suggests that ocean acidification' s impact on coral reefs has been a key research area.

The top 20 journals of published literatures on ocean acidification (2016 impact factors shown)

3. Keyword Co-Occurrence Knowledge Mapping

[Figure 2: see original paper] Keywords-based co-occurrence knowledge mapping for different periods

Through cluster analysis, the knowledge mapping reveals distinct research clusters for each period. In the initial stage (2004–2009), four main clusters emerged with modularity values of 0.4625 and 0.3144, indicating good clustering. The middle stage (2010–2015) showed poor clustering effects (modularity 0.663), while the recent stage (after 2016) again showed good clustering.

Initial Stage Analysis:
Cluster 1 centered on "calcification" (betweenness centrality 0.79) with the most coral reef-related terms, representing research on ocean acidification' s impact on coral reefs and organisms. It also included basic terms like pH and calcite. Cluster 2 centered on "Emiliania huxleyi" (centrality 0.42), representing impacts on marine plankton. Cluster 3, centered on "CO " (centrality 0.32), represented studies on ocean acidification mechanisms. Cluster 4 contained too few keywords for clear interpretation but may represent model-based ocean acidification studies. Overlapping clusters indicate interdisciplinary connections.

Middle Stage Analysis:
Similar to the initial stage, coral reef terms remained abundant with "calcification" having the highest centrality (0.27). "CO " (centrality 0.34) represented mechanism studies. New elements included "sea urchin" and "temperature," showing expanded research objects and the emergence of multi-factor studies.

Recent Stage Analysis:
"Growth"showed the highest centrality (0.42) with biological terms like photosynthesis, representing phytoplankton impacts. "CO " remained central (centrality 0.6) for mechanism studies. "Climate change" had the highest centrality (0.87), indicating its dominance as a research context. Coral reef terms persisted but

expanded to include fish. The separate clusters with biological keywords confirm that marine organism impacts remain the mainstream research direction.

Cluster analysis results for top 30 highest-frequency keywords in different stages

4. Burst Analysis Results

Burst detection of cited references identified 20 articles still in hotspot status in 2018, which can be categorized into: ocean acidification impacts on marine organisms, ocean acidification phenomena and mechanisms, ecosystem impacts, biological evolution, and background/application literature (e.g., climate change studies).

Hotspot literatures of ocean acidification study at present time (up to February 2018) based on burst analysis

The analysis reveals five frontier directions: (1) multi-factor studies combining ocean acidification with other stressors; (2) internal response mechanisms of organisms; (3) comprehensive assessment and prediction of biological responses; (4) ecosystem-level impacts; and (5) challenges to the ocean acidification concept and exploration of alternative causes.

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1. Evaluation of Bibliometric Analysis Effectiveness

Compared with traditional literature reviews, bibliometric analysis avoids subjectivity in literature selection by objectively describing issues through inherent connections within the literature itself. In this study, descriptive statistics effectively captured the basic situation of ocean acidification research over the past decade: surging publication numbers, obvious interdisciplinary characteristics, and focused research on coral reefs and phytoplankton.

However, clustering based on keyword knowledge mapping showed limitations. The middle stage exhibited poor clustering effects, partly due to research characteristics and the inherent uncertainty of high-frequency keyword selection. Too few keywords may not cover all content, while too many create excessive clusters. Although hotspot directions were identifiable, burst analysis was added for supplementation. The top 100 most-cited references covered scholars' main concerns, and the lowest citation count among current hotspot literature was 18, corroborating that biological impact studies dominate the field and providing clear identification of research frontiers.

2. Frontier Issues in Ocean Acidification Research

Based on literature analysis, current ocean acidification research can be divided into five frontier directions across oceanography, biology, and ecosystems:

1. Multi-Factor Consideration in Organism Relationship Studies

Many studies treat ocean acidification as a single factor, but this may cause biased understanding. For example, Beniash et al. [22] found that elevated CO increased mortality and reduced shell hardness in Eastern oyster (*Crassostrea virginica*) larvae. However, when combined with other factors, results differ. Byrne et al. [23] reviewed warming and acidification impacts on marine invertebrates, finding effects can be additive, synergistic (e.g., *Acropora tenuis*), or antagonistic (e.g., *Tripneustes gratilla* where warming reduces acidification' s negative impact). McCulloch et al. [24] found that pH up-regulation mechanisms in some corals can improve calcification under warming despite acidification stress. Harvey et al. [25] noted that impacts vary across life stages, with mature/larger individuals generally more resistant than juvenile/smaller ones. These examples demonstrate that understanding ocean acidification' s biological impacts requires considering species life histories and interactions with other environmental factors.

2. Exploring Internal Response Mechanisms of Organisms

Temperature [24], food availability [26], and other conditions may mitigate ocean acidification' s adverse effects. For instance, some corals have up-regulation mechanisms for adaptation. Responses also show species specificity: most seagrasses and non-calcifying macroalgae may benefit from increased CO . Koch et al. [27] analyzed algae containing carbonic anhydrase that enhances photosynthesis with rising CO , yet acidic conditions hinder calcification in calcifying macroalgae. Understanding these internal processes (carbon cycling, acid-base balance) and their integration is crucial. Dupont et al. [28] demonstrated acclimation in the copepod *Pseudocalanus acuspes*, where fecundity loss was less severe in individuals from high-CO environments compared to those suddenly exposed. Transgenerational effects and genetic/epigenetic diversity suggest adaptation and evolution potential [29,30]. However, evolution is not a universal solution and its uncertainties must be incorporated into ecosystem predictions and management [29]. Priority should be given to studying key species with high evolutionary potential, such as fast-generation, large-population phytoplankton [31].

3. Comprehensive Assessment and Prediction of Biological Responses

Given varied responses, meta-analysis helps synthesize evidence. Chan and Connolly [32] meta-analyzed coral calcification rates, finding current rates should be -15% (range: -66% to +25%) and predicting a 22% decline by 2100. Wittmann and Pörtner [33] predicted negative impacts on echinoderms and mollusks under projected CO levels. However, meta-analysis depends on subjective study selection and may mask species specificity. Future approaches should combine physical oceanography and ecology using ecosystem dynamic models based on thorough understanding of species responses and interactions [25].

4. Exploring Impacts on Marine Ecosystems

Diverse organismal responses alter species relationships, potentially changing ecosystem structure and function. Although burst analysis detected few ecosystem-level studies (mostly theoretical reviews), this indicates scholars are shifting focus toward whole marine systems. Gaylord et al. [34] provide theoretical frameworks highlighting three key points: (1) increased CO may positively affect primary producers by providing more carbon; (2) acidification creates energy costs for many consumers; (3) understanding biological interconnections is crucial. Research should focus on: (1) producer responses to high-CO conditions; and (2) complex changes in population- and community-level interactions under acidification, including effects on consumer productivity utilization, intra- and inter-population processes, community structure, and biodiversity.

5. Challenges to the Ocean Acidification Concept and Exploration of Other Causes

Caldiera and Wickett' s [1] concept attributes ocean acidification solely to anthropogenic CO emissions, supported by observations at Mauna Loa and Aloha stations showing parallel atmospheric and seawater CO trends [35]. However, this view is incomplete for coastal areas. Hofmann et al. [36] compared pH dynamics across ecosystems, finding high variability in coastal waters due to complex physical and biological processes. Duarte et al. [37] summarized these processes, showing anthropogenic CO absorption is just one factor. Recent studies demonstrate other causes: eutrophication-driven acidification in the Gulf of Mexico [38]; watershed processes and seasonal variations causing pH fluctuations in Chesapeake Bay and Tampa Bay [39]. In coastal zones, ocean acidification may not be entirely caused by CO emissions. Challenging the concept doesn' t deny ocean acidification but seeks to identify primary drivers in different coastal regions for more effective, targeted management beyond simple CO reduction.

3. Outlook

This study used bibliometric analysis to summarize current ocean acidification research. The field requires multidisciplinary support—for example, studying eutrophication-driven acidification needs marine science, biology, and ecology. Future research should promote multidisciplinary collaboration.

A limitation is that our Web of Science Core Collection sample with "ocean acidification" as the sole keyword cannot elaborate on specific trends for particular issues. Future studies could add thematic keywords for more detailed analysis.

References

[1] Caldeira K, Wickett M E. Oceanography: anthropogenic carbon and ocean pH. *Nature*, 2003, 425(6956): 365–365.
[2] Gattuso J P, Hansson L. *Ocean Acidification*. Oxford: Oxford University Press, 2011.
[3] Tang Q S, et al. Ocean acidification and its relationship with marine organisms and ecosystems. *Science*, 2013, 58(14): 1307–1314.
[4] Cheng L, et al. Research progress on ocean acidification impacts on coral reef ecosystems. *Acta Ecologica Sinica*, 2012, 32(5): 1606–1615.
[5] Pan Y T. Significance, steps and common problems in writing literature reviews. *Academic Degrees & Graduate Education*, 2010, (11): 49–52.
[6] Lemasson A J, Fletcher S, Hall-Spencer J M, Knights A M. Linking the biological impacts of ocean acidification on oysters to changes in ecosystem services: a review. *Journal of Experimental Marine Biology and Ecology*, 2017, 492: 49–62.
[7] Segman R F, Dubinsky Z, Iluz D. Impacts of ocean acidification on calcifying macroalgae: *Padina* sp. as a test case—a review. *Israel Journal of Plant Sciences*, 2016, doi:10.1080/07929978.2016.1237491.
[8] Chen Y. The context of knowledge mapping research. *Library and Information Service*, 2015, 41(5): 16–34.
[9] Li J, et al. Survey on knowledge mapping construction techniques. *Journal of Computer Research and Development*, 2016, 53(3): 582–600.
[10] Zhong H X. Co-word analysis: process and methods. *Information Science*, 2008, 27(5): 70–72.
[11] Kamada T, Kawai S. An algorithm for drawing general undirected graphs. *Information Processing Letters*, 1989, 31(1): 7–15.
[12] Chen C M, Morris S. Visualizing evolving networks: minimum spanning trees versus pathfinder networks. *Proceedings of 2003 IEEE Symposium on Information Visualization*. Seattle, WA, USA: IEEE, 2003: 67–74.
[13] Zhong H X. Principles and characteristics of co-word cluster analysis. *Information Science*, 2008, 27(7): 118–120.
[14] Chen C M, Ibekwe-SanJuan F, Hou J H. The structure and dynamics of cocitation clusters: a multiple-perspective cocitation analysis. *Journal of the American Society for Information Science and Technology*, 2010, 61(7): 1386–1409.
[15] Hou J H. Visualization of international metadata research frontiers and hotspots using CiteSpace. [D]. Dalian University of Technology, 2014.
[16] Zhao D Z. Visualization analysis of occupational safety and health research in construction industry. [D]. Dalian University of Technology, 2009.
[17] Wang X F. Visualization analysis of business administration discipline evolution and frontiers. [D]. Dalian University of Technology, 2013.
[18] Kleinberg J. Bursty and hierarchical structure in streams. *Data Mining and Knowledge Discovery*, 2003, 7(4): 373–397.
[19] Wang Z Y. Research on scientific and technological frontiers under knowledge flow theory. [D]. Dalian University of Technology, 2011.

[20] Chen C M. CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. *Journal of the American Society for Information Science and Technology*, 2006, 57(3): 359-377.
[21] Zhao D Z, Wang Z Y. Bibliometric content analysis. National Library of China Publishing House, 2008: 1-5.
[22] Beniash E, Ivanina A, Lieb N S, Kurochkion I, Sokolova I M. Elevated level of carbon dioxide affects metabolism and shell formation in oysters *Crassostrea virginica*. *Marine Ecology Progress Series*, 2010, 419: 95-108.
[23] Byrne M, Przeslawski R. Multistressor impacts of warming and acidification of the ocean on marine invertebrates' life histories. *Integrative and Comparative Biology*, 2013, 53(4): 582-596.
[24] McCulloch M, Falter J, Trotter J, Montagna P. Coral resilience to ocean acidification and global warming through pH up-regulation. *Nature Climate Change*, 2012, 2(8): 623-627.
[25] Harvey B P, Gwynn-Jones D, Moore P J. Meta-analysis reveals complex marine biological responses to the interactive effects of ocean acidification and warming. *Ecology and Evolution*, 2013, 3(4): 1016-1030.
[26] Thomsen J, Casties I, Pansch C, Körtzinger A, Melzner F. Food availability outweighs ocean acidification effects in juvenile *Mytilus edulis*: laboratory and field experiments. *Global Change Biology*, 2013, 19(4): 1017-1027.
[27] Koch M, Bowes G, Ross C, Zhang X H. Climate change and ocean acidification effects on seagrasses and marine macroalgae. *Global Change Biology*, 2013, 19(1): 103-132.
[28] Thor P, Dupont S. Transgenerational effects alleviate severe fecundity loss during ocean acidification in a ubiquitous planktonic copepod. *Global Change Biology*, 2015, 21(6): 2261-2271.
[29] Parker L M, Ross P M, O' Connor W A, Pörtner H O, Scanes E, Wright J M. Predicting the response of molluscs to the impact of ocean acidification. *Biology*, 2013, 2(2): 651-692.
[30] Pespeni M H, Sanford E, Gaylord B, Hill T M, Hosfelt J D, Jaris H K, LaVigne M, Lenz E A, Russell A D, Young M K, Palumbi S R. Evolutionary change during experimental ocean acidification. *Proceedings of the National Academy of Sciences of the United States of America*, 2013, 110(17): 6937-6942.
[31] Sunday J M, Calosi P, Dupont S, Munday P L, Stillman J H, Reusch T B H. Evolution in an acidifying ocean. *Trends in Ecology & Evolution*, 2014, 29(2): 117-125.
[32] Chan N C S, Connolly S R. Sensitivity of coral calcification to ocean acidification: a meta-analysis. *Global Change Biology*, 2013, 19(1): 282-290.
[33] Wittmann A C, Pörtner H O. Sensitivities of extant animal taxa to ocean acidification. *Nature Climate Change*, 2013, 3(11): 995-1001.
[34] Gaylord B, Kroeker K J, Sunday J M, Anderson K M, Barry J P, Brown N E, Connell S D, Dupont S, Fabricius K E, Hall-Spencer J M, Klinger T, Milazzo M, Munday P L, Russell B D, Sanford E, Schreiber S J, Thiyagarajan V, Vaughan M L H, Widdicombe S, Harley C D G. Ocean acidification through the lens of ecological theory. *Ecology*, 2015, 96(1): 3-15.
[35] Feely R A, Doney S C, Cooley S R. Ocean acidification: present conditions

and future changes in a High-CO world. *Oceanography*, 2009, 22(4): 36–47.
[36] Hofmann G E, Smith J E, Johnson K S, Send U, Levin L A, Micheli F, Paytan F, Price N N, Peterson B, Takeshita Y, Matson P G, Cook E D, Kroeker K J, Gambi M C, Rivest E B, Frieder C A, Yu P C, Martz T D. High-frequency dynamics of ocean pH: a multi-ecosystem comparison. *PLoS One*, 2011, 6(12): e28983.
[37] Duarte C M, Hendriks I E, Moore T S, Olsen Y S, Steckbauer A, Ramajo L, Carstensen J, Trotter J A, McCulloch M. Is ocean acidification an open-ocean syndrome? Understanding anthropogenic impacts on seawater pH. *Estuaries and Coasts*, 2013, 36(2): 221-236.
[38] Cai W J, Hu X P, Huang W J, Murrell M C, Lehrtter J C, Lohrenz S E, Chou W C, Zhai W D, Hollibaugh J T, Wang Y C, Zhao P S, Guo X H, Gunderson K, Dai M H, Gong G C. Acidification of subsurface coastal waters enhanced by eutrophication. *Nature Geoscience*, 2011, 4(11): 766–770.
[39] Wallace R B, Baumann H, Grear J S, Aller R C, Gobler C J. Coastal ocean acidification: the other eutrophication problem. *Estuarine, Coastal and Shelf Science*, 2014, 148: 1-13.

Note: Figure translations are in progress. See original paper for figures.