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RESEARCH ARTICLE

What factors cause ocean CO_2? A panel data analysis

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Abstract

Over the past three decades, industrial innovations and technological advancements have changed business dynamics, adversely devastating the overall environment. As a result, our oceans have been severely affected due to climate change and global warming. To address this issue, this study investigates the factors that cause ocean CO_2 using a sample of 44 countries over 2012–2021 and explores a dynamic and causal relationship between economic growth, ocean carbon dioxide emissions, energy consumption, and control variables relating to the ocean industry. This study finds that increasing economic activity tends to increase ocean carbon emissions. The results support the evidence of the environmental Kuznets curve (EKC) hypothesis suggesting an inverted U-shaped association between ocean emissions and real income for the sample countries. Moreover, this study reports that ocean health index, maritime container transport, trade of fishery and ocean species, aquaculture production and marine species, and employment rate in the fishery processing sector are the significant factors of ocean CO_2. Region-wise analyses suggest that real income positively influences ocean emissions and confirm the evidence of the EKC hypothesis in European sample countries but these relationships have an insignificant effect in Asia and the Pacific and the American regions. Furthermore, a short-run unidirectional panel causality flows from the production of aquaculture and other species to RD&D, from OHI and GDP to trade of fishery and other species, and from OHI to employment rate in the fishery sector. Likewise, bidirectional causality runs from energy consumption and maritime transport to ocean CO_2 in the long term. Regarding the long-run causal association, the results determine that all of the estimated coefficients of the lagged error correction terms are statistically significant which explains that they are crucial in the adjustment process as they deviate from the long-run equilibrium.

Keywords CO_2 emissions · Environmental Kuznets curve · Economic growth

JEL classifications O44 · O56 · Q53

Introduction

Greenhouse gas (GHG) emissions are the key factors influencing climate change and increasing global warming, enhancing the ocean temperature through the mix of CO_2. Ocean acidification results from a surge in CO_2 emissions — an important component of climate change. Tarakanov (2022) argued that increased CO_2 emissions in 200 years are the consequences of human actions. The ocean absorbs 26% of all human-induced CO_2, causing acute risk to marine life, ecosystem health, and people whose livelihoods are associated with the ocean (Tarakanov 2022).

The oceanic interest in anthropogenic CO_2 tends to reduce seawater pH, thereby decreasing the seawater state for carbon minerals. In another study, Zeebe et al. (2008) argued that "the oceans have taken up ~40% of the anthropogenic CO_2 emissions over the past 200 years." Bhargava (2020) studied the dynamic interrelatedness between CO_2 emissions and environmental effects, ambient temperatures, and ocean acidification and deoxygenation. Using the sample of 163 countries from 1985 to 2018, he found that economic activities and population were interlinked with increased CO_2 emissions.

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Over the last three decades, an increase in GHG emissions from energy consumption has adversely affected the overall environment. The decline in environmental quality has touched the terrifying conditions owing to global warming and climate change. As a result, our oceans are severely affected due to higher CO_2 emissions. Tarakanov (2022) forecast that roughly three billion people who rely on marine and coastal biodiversity for their livelihoods could be affected by acidification. According to the Sustainable Development Goals Report (2022), "continuing ocean acidification and rising temperatures threaten marine species and negatively impact ecosystem services." This implies that ocean emissions negatively affect marine species and threaten the lives of humans associated with the oceans. SDG 14 (life below water) envisages "conserving and sustainably using the oceans, seas, and marine resources" because healthy oceans and seas are critical for life on earth and human survival.

The ocean plays a critical role in regulating the amount of CO_2 in the atmosphere. As the CO_2 level increases, the ocean absorbs more carbon dioxide. According to the Intergovernmental Panel on Climate Change (2013), oceans have absorbed roughly 28% of the CO_2 produced by human activities over the past 250 years. Though the ocean absorbs CO_2 to safeguard atmospheric levels from rising even higher, mounting levels of CO_2 dispersed in the oceans can harm some marine life. When CO_2 interacts with seawater, it generates carbonic acid, which inflates the acidity level and imbalances the minerals in the water. To determine how much carbon dioxide is absorbed by the ocean sink, scientists have formulated various methods (e.g., atmosphere-ocean flux and geochemical or statistical procedures) to present the ocean's role in the anthropogenically influenced carbon cycle (World Ocean Review 2021). To overcome ocean-based CO_2, Ocean Visions[1] proposed a few solutions covering (a) restoring living blue carbon, (b) deep sea storage, (c) electrochemical ocean CO_2 removal, (d) microalgae cultivation, and (e) ocean alkalinity enhancement. The ocean economy encompasses ocean-based industries covering shipping, fishery, offshore wind, marine biotechnology, and tourism. These industries are contributing toward a blue economy; however, countries can explore untapped avenues by developing ocean policies and facilitating firms.

Among others, oceans absorb a significant chunk of carbon dioxide. Besides, methane (CH_4), nitrous oxide (NO_x), and shipping also contribute to add-on ocean emissions. Figure 1 explains the country-wise position of the absorption of ocean CO_2 across regions in 2012 and 2021. The results show that the ocean of every country has witnessed the soak up carbon dioxide; however, the magnitude of ocean emissions varies across countries. It can be determined that the USA is the leading contributor to ocean carbon emissions among all regions. Similarly, Belgium, Netherlands, Russia, and Spain absorbed higher ocean carbon emissions in Europe. Singapore and UAE mesmerized the highest ocean carbon emissions in Asia and Pacific and the Middle East and Arab States, respectively.

Researchers have widely explored the nexus between economic growth and GHG emissions. However, the evidence relating to economic growth and ocean emissions is limited. Badircea et al. (2021) studied the link between the blue economy and economic growth to climate change using the 28 European Union countries dataset from 2009 to 2018. They used the blue economy as the proxy of the gross added value contributing toward the ocean market and determined that the gross added value of the blue economy negatively influences GHG emissions. Moreover, they reported long-term cointegration among GHG emissions, the blue economy, and economic growth. They found a unidirectional causality flowing from GHG emissions to economic growth while bidirectional causality moving from economic growth to GHG emissions. Using a sample of fifteen countries, Kasman and Duman (2015) investigated the relationship between gross domestic product (GDP), CO_2 emissions, and energy consumption between 1992 and 2010. Results found a short-run unidirectional causality flowing from energy consumption to CO_2 emissions. They identified the estimated coefficients of lagged error correction terms (ECTs) in CO_2 emissions, energy consumption, and economic growth are statistically significant in the long-run causal association. Their data support the environmental Kuznets curve (EKC) hypothesis, which asserts an inverted U-shaped link between environment and income.

This study addresses an important research question: what factors cause ocean CO_2? The primary purpose of this paper is to investigate the relationship between ocean carbon dioxide emissions, economic growth, energy consumption, and control variables relating to the ocean industry for a panel of 44 countries across different regions over the period lasting from 2012 to 2021. This study identifies new evidence of the nexus between the ocean environment and economic growth. The contribution of this paper is fourfold: first, to examine the effect of economic growth on ocean CO_2 which has not been tested earlier; second, to test the EKC hypothesis for sample countries. Most studies investigated the hypothesis between economic growth and the environment but did not consider ocean carbon emissions. Third, this study incorporates control variables relating to the ocean industry to identify the determinants that cause ocean CO_2. Fourth, this study conducts region-wise analysis to determine the factors influencing ocean CO_2 in different regions.

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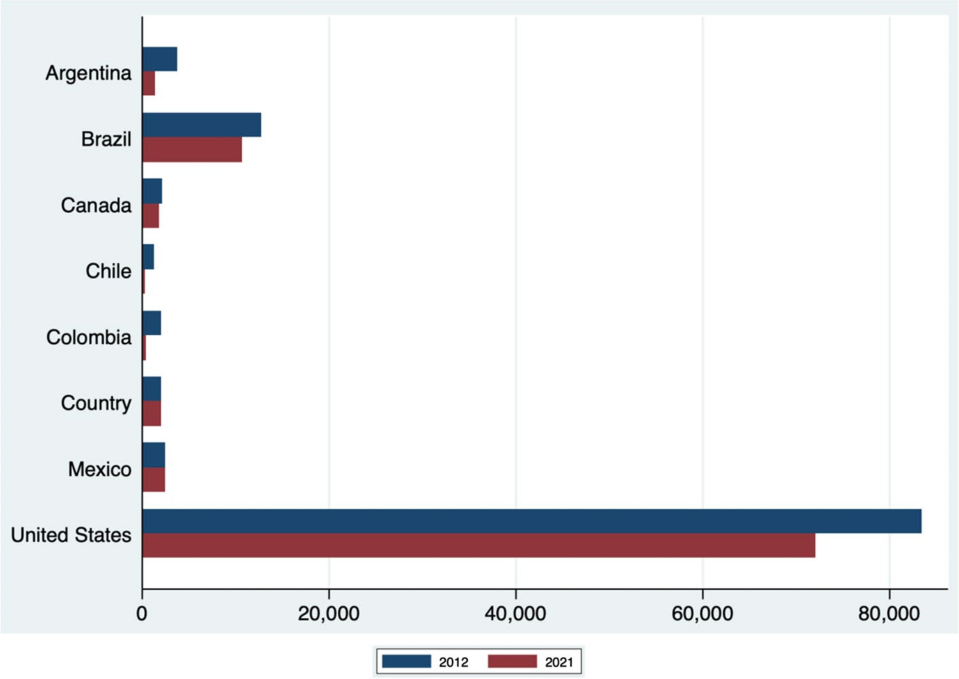
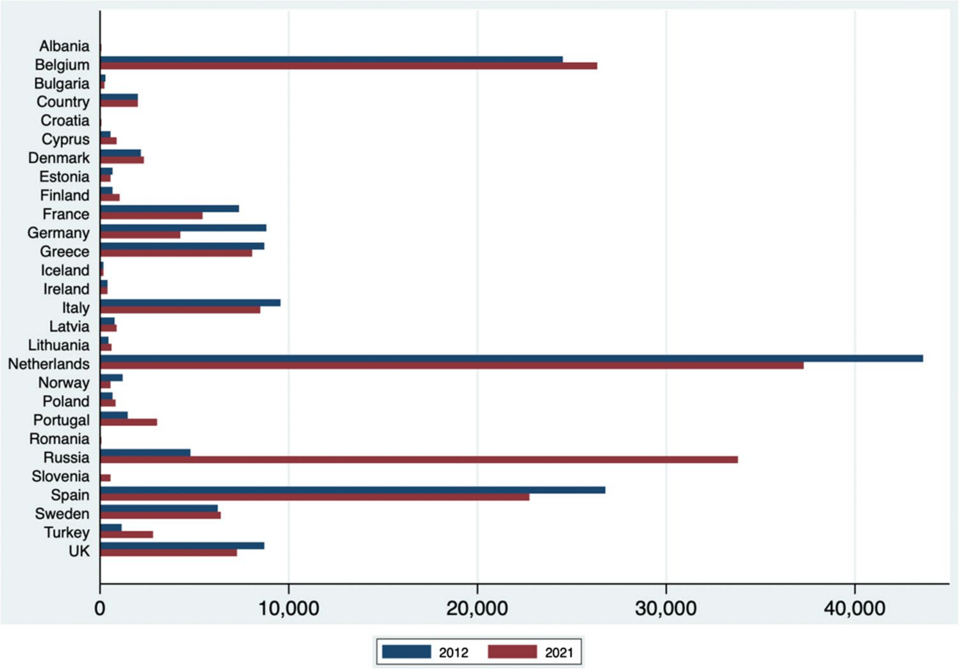
[1] https://oceanvisions.org/ocean-based-carbon-dioxide-removal/

Fig. 1 Country-wise position of ocean CO_2 across regions



Americas



Europe

This study utilizes various panel unit root tests and finds mixed results. Applying different panel cointegration tests, this study reports that variables in the analysis are cointegrated. To test the relationship between ocean CO_2 and economic growth, the system generalized method of momentum (GMM) technique is used and finds that an increase in real GDP per capita tends to produce more emissions, eventually inflating ocean carbon emissions. Moreover, this study finds an inverse relationship between squared real GDP per capita and ocean CO_2 illustrating an inverted U-shaped curve — this evidence supports the typical EKC hypothesis. The quadratic relationship suggests that ocean CO_2 increases at a certain point in the real GDP but then declines. In addition, this study finds that ocean health index (OHI), maritime container transport, trade of fishery and ocean species, aquaculture production and marine species, and employment rate in the fishery processing sector are the robust predictors of ocean CO_2. Based on the region-wise analysis, this study finds mixed results. Results report that an increase in real GDP per capita positively influences ocean carbon emissions in the European region but has an insignificant effect in Asia and the Pacific and the American regions. Using the panel Granger causality test, the results report the bidirectional causality flowing from energy consumption to ocean CO_2 in the long run but find no evidence of short- and long-term causality flowing from ocean carbon emissions to GDP and energy consumption to GDP.

The structure of this paper is as follows. "The model and econometric methodology" section explains the model and econometric methodology, "Data and empirical results" section describes the data and empirical results, and "Conclusion" section concludes the study.

The model and econometric methodology

The model

This study follows the methodology of Alaganthiran and Anaba (2022), Kasman and Duman (2015), Arouri et al. (2012), and Apergis and Payne (2009, 2010) to investigate the association between ocean CO_2, real income, and energy consumption, which is a mix of the EKC and growth in energy consumption. Hence, the following model is proposed to test the relationship:

$$Ocean\ CO_{2it} = \alpha + \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 EC_{it} + \varepsilon_{it} \quad (1)$$

where $Ocean\ CO_2$ is measured in thousand tons, and GDP is the per capita real GDP. EC indicates the per capita energy consumption. The coefficients β_1, β_2, and β_3 represent the long-run elasticities of ocean carbon dioxide emissions relating to GDP, GDP^2, and per capita energy consumption. The subscripts i and t show country and time, respectively. All variables are taken in the form of a natural logarithm. For testing the EKC hypothesis, it is assumed that $\beta_1 > 0$ and $\beta_2 < 0$. This refers to an inverted U-shaped pattern indicating that a surge in income level reduces ocean emissions. Moreover, $\beta_3 > 0$ predicts that rising energy consumption leads to increased ocean emissions.

As the nomenclature of ocean CO_2 emissions differs from CO_2 emissions, this study employs ocean-related variables to estimate their impact on ocean CO_2. Earlier studies used various proxies [e.g., trade openness (Farhani et al. 2014; Lau et al. 2014), urbanization (Kasman and Duman 2015), gross savings (Onofrei et al. 2022), and tourism (Alaganthiran and Anaba 2022; Dogan and Aslan 2017)] to examine their effect on CO_2 emissions. For the extension of model 1, this study specifies the quadratic EKC model as follows:

$$\begin{aligned} Ocean\ CO_{2it} = \alpha &+ \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 EC_{it} \\ &+ \beta_4 OHI_{it} + \beta_5 MT_{it} + \beta_6 RD\&D_{it} \\ &+ \beta_7 MA_{it} + \beta_8 FT_{it} + \beta_9 AP_{it} + \beta_{10} ER_{it} \\ &+ + \varepsilon_{it} \end{aligned} \quad (2)$$

where OHI refers to the score of the OHI. The expected sign of coefficient β_4 is negative, which directs that a higher level of OHI means a country is putting its best effort into overcoming ocean emissions. MT is total maritime container transport in a million tons. It is expected that coefficient (β_5) be positive, which shows that higher maritime transport activities will emit higher pollution, thereby increasing ocean emissions. $RD\&D$ is total energy research, development, and deployment in millions of US\$. β_6 is expected to be negative. In the wake of higher $RD\&D$ activities, the magnitude of ocean emissions would be lower. MA is a total marine protected area measured in square kilometers. FT is the total trade of fisheries and other species in US\$ million. AP refers to total aquaculture production and marine species in millions of US\$. ER shows people employed in the fishery processing sector by occupation rate (thousands). The coefficients β_5, β_6, β_7, β_8, and β_9 are measured in the form of a natural logarithm.

Econometric methodology

This study investigates the causal association between ocean CO_2, national income, energy consumption, OHI, maritime container transport, total energy research, development, and deployment (RD&D), total marine protected area, fisheries trade, aquaculture production, and people employed in fishery processing. The testing methods comprise the following phases. First, this study analyzes the stationarity of the data by using different panel unit root tests. In the absence of stationarity, the second phase investigates whether a cointegrating association exists between the series through suitable panel cointegration approaches. The long-term elasticities are estimated using the system GMM technique if the parameters are cointegrated. Lastly, this study applies panel error correction models to determine the relationship between the short- and long-run dynamics of the series.

Panel unit root tests

Various tests are utilized to test the stationarity of data. Levin, Lin, and Chu—LLC (2002) propose a panel unit root test as follows:

$$\Delta y_{it} = \varnothing_{it} \psi_i + \rho y_{it-1} + \sum_{j=1}^{ni} \varphi_{ij} \Delta y_{i,t-j} + \xi_{it} \quad (3)$$

where $\varnothing_{it}$ comprises unique deterministic factors, ρ shows the autoregressive coefficient, and n is the lag order. Nonetheless, the LLC method presumes ρ consistency across panels which may bear the loss of power (Breitung 2001). Im, Pesaran, and Shin — IPS (2003) suggest that ρ fluctuates across panels to extend the LLC method.

$$\Delta y_{it} = \varnothing_{it}\psi_i + \rho_i y_{it-1} + \sum_{j=1}^{ni} \varphi_{ij}\Delta y_{i,t-j} + \xi_{it} \tag{4}$$

To determine the stationarity of panel data, Breitung (2001) specifies the following model:

$$y_{it} = \alpha_{it} + \sum_{k=1}^{p+1} \beta_{it}x_{it-k} + \varepsilon_{it} \tag{5}$$

The null hypothesis of Eq. (5) states the procedure is difference stationary, $H_0 : \sum_{k=1}^{p+1} \beta_{ik} - 1 = 0$, and $H_0 : \sum_{k=1}^{p+1} \beta_{ik} - 1 < 0 \ \forall i$. Breitung (2001) employs the transformed trajectories to develop test statistic as follows:

$$\lambda_B = \frac{\sum_{i=1}^{N} \sigma_1^{-2} Y_i^{*\prime} X_i^{*\prime}}{\sqrt{\sum_{i=1}^{N} \sigma_1^{-2} X_i^{*\prime} A' A X_i^{*\prime}}} \tag{6}$$

where λ_B refers to the Breitung (2001) *t*-statistics indicating a standard normal distribution.

Im et al. (2003) suggested the *t*-bar test which argued that all cross-sectional units move to the equilibrium value at unlike paces relating to the alternative hypothesis.

$$t - bar = \sqrt{N}\frac{t_\alpha - \mathcal{K}_t}{\sqrt{\nu_t}} \tag{7}$$

where N refers to the panel size, and t_α is the average ADF *t*-statistics. $\mathcal{K}_t$ and ν_t compute the mean and variance of every $t_{\alpha i}$ statistic.

Choi (2001) proposes the Fisher tests (ADF and Phillips-Perron) for time series and panel data. The tests integrate every series to get a *p*-value from unit root testing rather than averaging a single test statistic as Im et al. (2003) suggested, which is the most unique characteristic. Hadri (2000) suggests a method to examine the stationarity of the series. Its structure is similar to KPSS for time series which is expressed as follows:

$$y_{it} = r_{it} + \beta_{it} + \varepsilon_{it} \tag{8}$$

where r_{it} represents random work indicating as $r_{it} = r_{it-1} + \nu_{it}$, where ν_{it} is white noise. Model (8) predicts testing the stationarity where $H_0 : \sigma_v^2 = 0$, and $H_1 : \sigma_v^2 > 0$.

Panel cointegration tests

Earlier studies used various testing methods [e.g., Kao 1999; Pedroni (1999, 2004); Westerlund 2007; and Maddala and Wu (1999)] to analyze long-run equilibrium among the variables. This study uses Pedroni (1999, 2004), Kao (1999), and Westerlund (2007) tests to assess the cointegrating association between ocean CO_2, GDP, and energy consumption (model 1). In model 2, the control variables are added along with the parameters in model 1. Pedroni (1999, 2004) suggests various measures that rely on the residuals of Engel and Granger's (Engel and Granger 1987) cointegration equation. The estimated residuals obtained from the long-run equation are specified as follows:

$$Y_{it} = \alpha_i + \lambda_i t + \sum_{j=1}^{m} \beta_{ji} X_{jit} + \varepsilon_{it} \tag{9}$$

where Y and X are supposed to be I(1) in levels. Residuals are described as $\varepsilon_{it} = \rho_i \varepsilon_{it-1} + \mathcal{U}_{it}$. $H_0 : \rho_i = 1; \forall i$, and $H_1 : \rho_i < 1; \forall i$. These tests are normally distributed. To determine the cointegration, statistics are compared with appropriate critical values. When critical values are higher than statistics, this confirms the evidence of cointegration and the long-run association between the variables. Kao's (1999) test is formulated on a similar foundation to Pedroni's (1999, 2004) test; however, it identifies cross-sectional intercepts and homogenous coefficients on the first stage regression (Equation 9). Additionally, this study employs Westerlund's (2007) panel cointegration test, which asserts that all cross sections are cointegrated in the panel. In this test, it is assumed that all variables are non-stationary and specifies G_τ, G_α, P_τ, and P_α test statistics. Westerlund (2007) test is expressed as follows:

$$\Delta y_{it} = \delta' d_t + \alpha_i \left(y_{it-1} - \beta_i x_{it-1} \right) + \sum_{j=1}^{p_i} \alpha_{ij} \Delta y_{it-j} + \sum_{j=-q_i}^{p_i} \gamma_{ij} \Delta x_{it-j} + \varepsilon_{it} \tag{10}$$

where N and T represent the cross sections and observations. Moreover, d_t comprises the deterministic factors.

System GMM estimator

This study employs the system GMM estimator proposed by Arellano and Bover (1995) and Blundell and Bond (1998) to reduce the possibility of endogeneity issues. Regular panel OLS and within-group estimations, which do not account for these two issues, lead to biased and inconsistent estimates, which is why system GMM is used in this study (Arellano and Bover 1995; Blundell and Bond 1998; Blundell et al. 2001; Bond et al. 2001; Hoeffler 2002). Moreover, OLS levels and within-groups estimates are unreliable as both methods ignore undetected country and time invariant effects (Hsiao 2014; Nickell 1981). On the other hand, the system GMM provides reliable and effective parameter estimates in an equation wherein independent variables are not stringently exogenous (Roodman 2009).

Panel Granger causality test

This study assesses the short-run error correction model after integrating the residuals on the model's right side. The cointegrating association shows a causal relationship among the variables, at least in one direction. It does not, however, reveal the direction of causation. The panel ECM with dynamic corrective error used in this study looks at both the short- and long-term causal relationships between variables. Following Engel and Granger's (Engel and Granger 1987) two-step method, the long-run factors are estimated using Eq. (1) and Eq. (2) through the system GMM technique.

The Granger causality test covering ECT is presented as under the following:

Model 1:

$$\begin{aligned}\Delta Ocean\ CO_{2it} = \alpha_{1i} &+ \sum_p \alpha_{11ip} \Delta Ocean\ CO_{2it-p} \\ &+ \sum_p \alpha_{12ip} \Delta GDP_{it-p} + \sum_p \alpha_{13ip} \Delta GDP^2_{it-p} \\ &+ \sum_p \alpha_{14ip} \Delta EC_{it-p} + \theta_{1i} ECT_{it-1} + \varepsilon_{1it}\end{aligned} \tag{11}$$

$$\begin{aligned}\Delta GDP_{it} = \alpha_{2i} &+ \sum_p \alpha_{21ip} \Delta Ocean\ CO_{2it-p} \\ &+ \sum_p \alpha_{22ip} \Delta GDP_{it-p} + \sum_p \alpha_{23ip} \Delta GDP^2_{it-p} \\ &+ \sum_p \alpha_{24ip} \Delta EC_{it-p} + \theta_{2i} ECT_{it-1} + \varepsilon_{2it}\end{aligned} \tag{12}$$

$$\begin{aligned}\Delta GDP^2_{it} = \alpha_{3i} &+ \sum_p \alpha_{31ip} \Delta Ocean\ CO_{2it-p} \\ &+ \sum_p \alpha_{32ip} \Delta GDP_{it-p} + \sum_p \alpha_{33ip} \Delta GDP^2_{it-p} \\ &+ \sum_p \alpha_{34ip} \Delta EC_{it-p} + \theta_{3i} ECT_{it-1} + \varepsilon_{3it}\end{aligned} \tag{13}$$

$$\begin{aligned}\Delta EC_{it} = \alpha_{4i} &+ \sum_p \alpha_{41ip} \Delta Ocean\ CO_{2it-p} + \sum_p \alpha_{42ip} \Delta GDP_{it-p} \\ &+ \sum_p \alpha_{43ip} \Delta GDP^2_{it-p} + \sum_p \alpha_{44ip} \Delta EC_{it-p} + \theta_{4i} ECT_{it-1} + \varepsilon_{4it}\end{aligned} \tag{14}$$

Model 2:

$$\begin{aligned}\Delta Ocean\ CO_{2it} = \alpha_{1i} &+ \sum_p \alpha_{11ip} \Delta Ocean\ CO_{2it-p} \\ &+ \sum_p \alpha_{12ip} \Delta GDP_{it-p} + \sum_p \alpha_{13ip} \Delta GDP^2_{it-p} \\ &+ \sum_p \alpha_{14ip} \Delta EC_{it-p} + \sum_p \alpha_{15ip} \Delta OHI_{it-p} \\ &+ \sum_p \alpha_{16ip} \Delta MT_{it-p} + \sum_p \alpha_{17ip} \Delta RD\&D_{it-p} \\ &+ \sum_p \alpha_{18ip} \Delta MA_{it-p} + \sum_p \alpha_{19ip} \Delta FT_{it-p} \\ &+ \sum_p \alpha_{20ip} \Delta AP_{it-p} + \sum_p \alpha_{21ip} \Delta ER_{it-p} \\ &+ \theta_{1i} ECT_{it-1} + \varepsilon_{1it}\end{aligned} \tag{15}$$

$$\vdots$$

$$\begin{aligned}\Delta ER_{it} = \alpha_{12i} &+ \sum_p \alpha_{121ip} \Delta Ocean\ CO_{2it-p} \\ &+ \sum_p \alpha_{122ip} \Delta GDP_{it-p} + \sum_p \alpha_{123ip} \Delta GDP^2_{it-p} \\ &+ \sum_p \alpha_{124ip} \Delta EC_{it-p} + \sum_p \alpha_{125ip} \Delta OHI_{it-p} \\ &+ \sum_p \alpha_{126ip} \Delta MT_{it-p} + \sum_p \alpha_{127ip} \Delta RD\&D_{it-p} \\ &+ \sum_p \alpha_{128ip} \Delta MA_{it-p} + \sum_p \alpha_{129ip} \Delta FT_{it-p} \\ &+ \sum_p \alpha_{130ip} \Delta AP_{it-p} + \sum_p \alpha_{131ip} \Delta ER_{it-p} \\ &+ \theta_{10i} ECT_{it-1} + \varepsilon_{10it}\end{aligned} \tag{16}$$

where Δ, ETC, and p represent the first difference of the variable, the ECT, and the lag length, respectively. Using Akaike's information criterion, optimal lag length is identified. The causality runs from ΔGDP and ΔGDP^2 to $\Delta Ocean\ CO_2$ (ΔEC) if the joint null hypothesis $\alpha_{31ip} = 0\ \forall_{jp}$ and $\alpha_{41ip} = 0\ \forall_{jp}$ ($\alpha_{23ip} = \alpha_{24ip} 0\ \forall_{jp}$) is rejected. The existence of two variables estimating GDP in the system which entails cross-equation restrictions to identify causality from ocean CO_2, energy consumption, OHI, maritime container transport, total energy RD&D, total marine protected area, total trade of fisheries, aquaculture production and marine species, and people employed in the fishery processing sector to GDP using a likelihood ratio.

Table 1 Panel unit root tests

	LLC	Breitung	IPS	Fisher	PP chi-sq	Hadri
	t^* stat	*t*-stat	*W*-stat	ADF chi-sq		*z*-stat
$lnOcean\ CO_2$	−0.710	0.361	−1.716*	116.559**	120.852**	7.590***
lnGDP	1.788	−1.198	1.969	51.974	132.487***	15.383***
$lnGDP^2$	1.761	−1.041	1.849	53.852	135.026***	15.645***
lnEC	−10.069***	0.866	−0.429	109.309*	235.102***	15.509***
OHI	−12.045***	5.881	−0.034	109.865*	112.562**	14.181***
lnMT	−4.168***	−0.013	−1.112	98.772**	106.689***	12.019***
lnRD&D	−56.295***	2.221	−3.117***	63.425*	111.558***	12.603***
lnMA	−3.212***	−0.959	−7.425***	66.732	91.644***	10.980***
lnFT	−6.268***	−6.044***	−0.005	81.096	250.855***	10.873***
lnAP	−3.039***	0.650	0.684	57.389	162.519***	11.321***
ER	−3.165***	0.811	0.600	60.922	171.632***	3.915***

This table reports the results of the panel unit root testing. *GDP*, per capita GDP; *EC*, energy consumption; *OHI*, ocean health index; *MT*, maritime container transport; *RD&D*, total energy research, development, and deployment; *MA*, marine protected area; *FT*, total trade of fisheries and marine species; *AP*, aquaculture production and marine species; *ER*, employment rate in the fishery processing sector. ***, **, and * show significance at 1, 5, and 10% levels, respectively

Table 2 Results — Pedroni's (2004) residual cointegration test

Statistics	Within-dimension		Statistics	Between-dimension	
	Value	*p*-value		Value	*p*-value
Model 1: lnGDP, $lnGDP^2$, lnEC					
Panel v-stat	−1.962	0.693			
Panel rho-stat	2.990	0.727	Group rho-stat	5.967	0.837
Panel PP-stat	−7.045***	0.000	Group PP-stat	−8.866***	0.000
Panel ADF-stat	−8.305***	0.000	Group ADF-stat	−10.058***	0.000
Model 2: lnGDP, $lnGDP^2$, lnEC, OHI, lnRD&D, …..					
Panel v-stat	−3.583	0.736			
Panel rho-stat	4.561	0.975	Group rho-stat	5.579	0.993
Panel PP-stat	−8.662***	0.000	Group PP-stat	−7.826***	0.000
Panel ADF-stat	−9.461***	0.000	Group ADF-stat	−9.894**	0.038

Results of the cointegration test are reported assuming that H_0 = variables are not cointegrated, and H_1 = variables are cointegrated. *** and ** show significance at 1 and 5% levels, respectively

Data and empirical results

Data

The sample used in this study covers ocean CO_2, per capita GDP, per capita energy consumption, OHI, total maritime container transport (MT), total energy RD&D, a total marine protected area (MA), total trade of fisheries (FT), total aquaculture production and marine species (AP), and people employed in the fishery processing sector (ER) from 44 countries over the period 2012–2021. Table 9 explains the definition of all variables used in this study and data sources. Sample countries include Argentina, Australia, Belgium, Brazil, Bulgaria, Canada, Chile, China, Colombia, Croatia, Denmark, Estonia, Finland, France, Germany, Greece, Iceland, India, Indonesia, Ireland, Israel, Italy, Japan, Latvia, Lithuania, Malaysia, Mexico, Netherlands, New Zealand, Norway, the Philippines, Poland, Portugal, Romania, Russia, Slovenia, Spain, South Korea, Sweden, Thailand, Turkey, UK, USA, and Vietnam.

Table 10 presents the summary statistics of all the variables of each country for the period from 2012 to 2021. The data is divided into three regions: the Americas, Asia and Pacific, and Europe. The mean ocean CO_2 is 7786 thousand tons with a standard deviation of 13,439. The minimum and maximum values of ocean CO_2 are 12,450 and 83,506 thousand tons, respectively, showing the large dispersion among sample countries. In the Americas region, the USA emitted the highest ocean emissions of 65,793 thousand tons, followed by Brazil with about 11,551 thousand tons. In contrast, Chile produced the lowest ocean CO_2 of 674 thousand

Table 3 Results — Kao's (1999) residual cointegration test

	t-stat	*p*-value
ADF model 1	−3.271***	0.000
ADF model 2	−4.395***	0.000

This table presents the Kao (1999) cointegration test results assuming that H_0 = variables are not cointegrated and H_1 = variables are cointegrated. *** shows significance at a 1% level

Table 4 Results — Westerlund (2007) cointegration test: model 1

	Value	*p*-value	Robust *p*-value
G_τ	−1.301	0.060	0.212
G_α	−6.433	0.546	0.000
P_τ	−7.113	0.218	0.000
P_α	−3.210	0.019	0.000

This table presents the results of Westerlund's (2007) cointegration test

tons. When analyzing the Asia and Pacific region, it is found that China (29,745 thousand tons) and South Korea (29,388 thousand tons) are the leading contributors to ocean emissions. However, Vietnam produced the lowest ocean emissions (645 thousand tons). Among European countries, the Netherlands and Russia emitted the highest ocean CO_2 of 39,994 and 26,660 thousand tons respectively while Croatia is the lowest contributor to ocean CO_2 (33 thousand tons). The mean value of per capita GDP is US$28,822 and ranges from US$1434 to US$102,913 indicating considerable variations in the sample. The data shows the highest per capita GDP obtained by the Netherlands (US$65,124) and the USA (US$57,760). In contrast, India has the lowest per capita GDP of US$1689. The mean per capita energy consumption is 3978 kg of oil equivalent. The mean score of the OHI is 68.589, with a standard deviation of 4.997. The sample shows that the Netherlands has the highest OHI score of 81.963 whereas Israel has the lowest OHI score of 59.891. On average, maritime container transport is US$56.133 million. Total energy RD&D is a crucial variable illustrating that a higher value of RD&D reduces the likelihood of ocean CO_2 emissions. The mean values of RD&D and total marine protected area are US$517.877 million and 181,571 km^2, respectively. On average, fisheries trade is US$5.383 billion, with a standard deviation of US$6.383 billion. The mean value of aquaculture production and marine species is US$2.240 billion. On average, people employed in fishery processing (thousands) are 366. The dispersion between minimum and maximum values shows a higher variation of people associated with fishery processing among sample countries.

Table 5 Effect of ocean CO_2 on economic growth

	Model 1		Model 2	
	Coefficient	Std. error	Coefficient	Std. error
lnOcean $CO_{2it\text{-}1}$	0.723***	0.042	0.777***	0.069
lnGDP	4.439**	1.722	4.121**	1.714
lnGDP^2	−0.220**	0.088	−0.101**	0.048
lnEC	0.145**	0.061	0.111*	0.064
OHI			−0.066***	0.031
lnMT			0.206***	0.051
lnRD&D			−0.016	0.034
lnMA			−0.024	0.016
lnFT			0.163***	0.048
lnAP			−0.064**	0.029
ER			0.002**	0.001
Constant	0.188**	0.079	0.232	0.822
Observations	396		396	
Sargen test (*p*-value)	0.364		0.995	
AR(2) (*p*-value)	0.631		0.651	
F-test	231.29***		347.54***	

This table presents the factors that influence ocean CO_2. *GDP*, per capita GDP; *EC*, energy consumption; *OHI*, ocean health index; *MT*, maritime container transport; *RD&D*, total energy research, development, and deployment; *MA*, marine protected area; *FT*, total trade of fisheries and marine species; *AP*, aquaculture production and marine species; *ER*, employment rate in the fishery processing sector. ***, **, and * show significance at 1, 5, and 10% levels, respectively

Empirical results

Panel unit root tests

This study employs various tests to identify the stationarity of the variables (Table 1). The different panel unit root tests report mixed results. The LLC and Breitung tests do not reject the null hypothesis of the non-stationarity of ocean CO_2; however, IPS, Fisher, and Hadri tests reject the null hypothesis. Results of GDP and GDP^2 variables show non-stationarity of data in all tests except Fisher and Hadri *z*-statistics. Similarly, in a few instances, results report the non-stationarity of other variables. The results of all variables are stationary at the first difference.

Panel cointegration tests

This study examines the cointegration by applying the Pedroni (1999, 2004) cointegration tests of both models (Table 2). Most of the statistics are highly significant, thus confirming the evidence of no cointegration. In both models, the results suggest that variables are cointegrated. Table 3 exhibits the results of Kao's (1999) cointegration test. Results show that variables are statistically cointegrated at a 1% level in both models.

Table 6 Effect of ocean CO_2 on growth: a region-wise analysis

	Asia & Pacific		Europe		Americas	
	(1)	(2)	(3)	(4)	(5)	(6)
lnOcean CO_{2it-1}	0.741*** (0.053)	0.741*** (0.053)	0.898*** (0.037)	0.583*** (0.071)	0.919*** (0.059)	0.667*** (0.086)
lnGDP	1.536 (1.925)	1.991 (3.147)	4.554*** (1.925)	13.221*** (4.773)	3.970 (3.877)	5.821 (4.888)
$\ln GDP^2$	−0.103 (0.098)	−0.118 (0.166)	−0.103*** (0.030)	−0.644*** (0.282)	−0.174 (0.180)	−0.186 (0.235)
lnEC	0.705*** (0.241)	0.771** (0.322)	0.206* (0.122)	0.193 (0.151)	0.386 (0.408)	0.134** (0.054)
OHI		−0.044*** (0.014)		−0.042** (0.021)		−0.014 (0.035)
lnMT		0.183* (0.105)		0.488*** (0.095)		0.250 (0.167)
lnRD&D		−0.138* (0.072)		−0.060 (0.050)		−0.073 (0.066)
lnMA		0.052* (0.028)		0.040 (0.026)		0.110** (0.045)
lnFT		0.409*** (0.102)		0.151*** (0.049)		−0.341* (0.175)
lnAP		0.064 (0.075)		−0.115 (0.111)		0.826** (0.346)
ER		0.002 (0.015)		−0.006 (0.011)		−0.003 (0.001)
Constant	−0.845 (0.815)	−0.100 (0.134)	0.245 (0.258)	0.668*** (0.240)	−0.183 (0.182)	−0.280 (0.227)
Sargen test (*p*-value)	0.915	0.980	0.865	0.110	0.556	0.225
AR(2) (*p*-value)	0.103	0.145	0.175	0.145	0.107	0.137
Countries	12	12	25	25	7	7
F-test	169.21***	178.57***	311.52***	350.77***	143.96***	143.20***

This table presents the factors influencing ocean CO_2 across regions. *GDP*, per capita GDP; *EC*, energy consumption; *OHI*, ocean health index; *MT*, maritime container transport; *RD&D*, total energy research, development, and deployment; *MA*, marine protected area; *FT*, total trade of fisheries, total aquaculture production, marine and partly marine species; *AP*, aquaculture production, marine, and partly marine species; *ER*, employment rate in the fishery processing sector. ***, **, and * show significance at 1, 5, and 10% levels, respectively

Finally, this study employs Westerlund's (2007) panel cointegration test (Table 4). This test only applies in model 1. This study rejects the null hypothesis that variables are not cointegrated, indicating the long-run relationship between the variables in all the cases except G_τ. Results verify the cointegration in the scenario of bootstrapped *p*-values and the null hypothesis of no cointegration is rejected (G_α, P_τ, and P_α).

Effect of ocean CO_2 on economic growth

This section estimates the impact of ocean CO_2 on the per capita real GDP using the system GMM estimator. Two models were estimated to test the hypothesis (Table 5). In model 1, the coefficient of lagged ocean CO_2 is positive and statistically significant, illustrating that ocean carbon emissions follow previous trends. This study employs GDP^2 to measure a probable non-linear linkage between ocean CO_2 and GDP to test the EKC hypothesis. The result shows a direct association explaining that higher economic activities lead to higher ocean carbon emissions. This implies that in the wake of higher GDP, firms produce more and generate higher GHG emissions which ultimately surge in ocean emissions. The coefficient of GDP^2 is negative and statistically

Table 7 Results of panel Granger causality tests — model 1

Dependent variables	*Independent variables*			
	Δ lnOcean CO_2	Δ lnEC	Δ lnGDP ($ln\Delta GDP^2$)	ECM
Δ lnOcean CO_2	–	0.700* (0.406)	0.216 (0.539)	−0.553*** [−12.73]
Δ lnEC	0.015*** (0.005)	–	0.081 (0.064)	−0.261*** [−8.02]
Δ lnGDP ($ln\Delta GDP^2$)	0.002 (0.004)	0.040 (0.039)	–	−0.127*** [−5.12]

The *p*-values and *t*-statistics are shown in parentheses and brackets, respectively. *** and * show significance at 1 and 10% levels, respectively

Table 8 Results of panel Granger causality tests — model 2

Dependent variables	*Independent variables*										
	Δ lnOcean CO_2	Δ lnEC	Δ lnGDP ($ln\Delta GDP^2$)	Δ OHI	Δ lnMT	Δ lnRD&D	Δ lnMA	Δ lnFT	Δ lnAP	Δ ER	ECT
Δ lnOcean CO_2	–	0.742* (0.405)	0.316 (0.563)	0.000 (0.015)	0.246*** (0.093)	−0.029 (0.029)	−0.021 (0.033)	−0.033 (0.176)	−0.033 (0.326)	0.000 (0.000)	−0.543*** [−11.93]
Δ lnEC	0.016*** (0.005)	–	0.109 (0.067)	−0.004*** (0.001)	−0.004 (0.011)	−0.000 (0.003)	0.045 (0.004)	−0.008 (0.021)	−0.003 (0.027)	0.000 (0.000)	−0.271*** [−8.22]
Δ lnGDP ($ln\Delta GDP^2$)	0.001 (0.004)	0.049 (0.037)	–	0.007*** (0.001)	−0.000 (0.008)	−0.000 (0.003)	0.002 (0.003)	0.039*** (0.016)	−0.009 (0.021)	0.000 (0.000)	−0.144*** [−5.08]
Δ OHI	−0.029 (0.134)	−1.948 (1.199)	7.664*** (1.609)	–	0.353 (0.278)	0.016 (0.087)	−0.099 (0.098)	0.819 (0.519)	0.318 (0.669)	−0.000 (0.000)	−0.443*** [−10.61]
Δ lnMT	0.066*** (0.022)	−0.116 (0.199)	0.076 (0.276)	0.003 (0.007)	–	0.046*** (0.014)	0.196*** (0.013)	0.143* (0.085)	0.081 (0.112)	−0.000 (0.000)	−0.366*** [−11.28]
Δ lnRD&D	−0.159** (0.062)	0.464 (0.558)	−0.770 (0.771)	−0.007 (0.021)	0.304** (0.128)	–	0.282*** (0.044)	0.526** (0.240)	0.636** (0.309)	−0.000 (0.000)	−0.602*** [−16.49]
Δ lnMA	−0.017 (0.054)	0.349 (0.486)	0.207 (0.671)	−0.007 (0.018)	1.341*** (0.093)	0.138*** (0.034)	–	0.335 (0.210)	0.050 (0.271)	0.000 (0.000)	−0.573*** [−17.07]
Δ lnFT	−0.010 (0.012)	0.006 (0.107)	0.371** (0.147)	0.010** (0.004)	0.054** (0.024)	0.018** (0.007)	0.007 (0.008)	–	−0.045 (0.060)	−0.000 (0.000)	−0.434*** [−10.86]
Δ lnAP	−0.006 (0.010)	−0.017 (0.087)	−0.053 (0.120)	0.003 (0.003)	−0.002 (0.020)	0.007 (0.006)	0.008 (0.007)	0.053 (0.037)	–	0.001*** (0.000)	−0.322*** [−9.02]
Δ ER	25.053 (43.730)	122.995 (391.813)	−214.939 (541.421)	25.956* (15.374)	−59.832 (90.670)	−0.110 (28.364)	4.031 (31.997)	25.014 (16.532)	67.942*** (21.938)	–	−0.370*** [−7.72]

The *p*-values and *t*-statistics are shown in parentheses and brackets, respectively. *GDP*, per capita GDP; *EC*, energy consumption; *OHI*, ocean health index; *MT*, maritime container transport; *RD&D*, total energy research, development, and deployment; *MA*, marine protected area; *FT*, total trade of fisheries, total aquaculture production, marine and partly marine species; *AP*, aquaculture production, marine, and partly marine species; *ER*, employment rate in the fishery processing sector. ***, **, and * show significance at 1, 5, and 10% levels, respectively significant, reporting a non-linear association between the real GDP and ocean CO_2. This finding illustrates an inverted U-shaped relationship between two variables that is in line with the typical EKC hypothesis. This quadratic association shows that ocean CO_2 rises at a certain level of the real GDP and begins to decline. These findings are consistent with Maalej and Cabagnols (2020), Kasman and Duman (2015), and Ahmed and Qazi (2014). On the other hand, Zoundi (2017) finds no evidence of EKC prediction between CO_2 emissions and real income.

Model 2 looks at how different factors affect ocean CO_2. In model 2, every variable utilized in model 1 is statistically significant, demonstrating the significance of each variable in estimating ocean carbon emissions. The OHI negatively influences ocean CO_2, suggesting that a higher value of OHI means a country is taking necessary measures to make its ocean blue and emit fewer ocean emissions. The MT coefficient is positive and significant at a 1% level, indicating that increased maritime transport activities increase ocean carbon emissions. The result shows that a higher trade of fisheries and marine species may increase the probability of ocean emissions. This implies the presence of ocean species (e.g., fisheries and mangroves) make the ocean environment clean but a higher level of their exportation may inflate the ocean emissions. Aquaculture production is another significant predictor that negatively affects ocean emissions. This finding illustrates that the production of aquaculture and other species probably reduces the magnitude of ocean emissions as they purify ocean health. The coefficient of employment rate in fishery processing and marine species is positive and statistically significant. This evidence suggests that a higher employment rate associated with fishery pollutes higher ocean CO_2; therefore, training fishermen to use the latest technology to help reduce ocean emissions is crucial. However, RD&D and marine protected areas are insignificant factors in the analysis.

Effect of ocean CO_2 on economic growth: a region-wise analysis

Using the system GMM estimator, this section examines the impact of ocean CO_2 on GDP in the Asia and Pacific, European, and Americas regions (Table 6). Ocean emissions in the Asia-Pacific region are considerably impacted by lagged ocean CO_2 and energy consumption in model 1. This suggests that the likelihood of ocean emissions increases with greater energy usage. According to the outcomes of other covariates in model 2, a higher OHI indicates that a country is taking the necessary steps to reduce ocean carbon emissions. The coefficient of marine container transport is positive and significant at a 10% level implying that higher activities of maritime transport emit higher pollution and contribute to an increase in ocean CO_2. The likelihood of producing ocean emissions is reduced when a country considers energy RD&D. A marine protected area is another covariate with a positive relationship with ocean CO_2. This finding suggests that a larger marine area will increase the likelihood of ocean emissions. The coefficient of trade of fisheries and other species is positive and significantly influences ocean emissions. The surge in the outflow of marine species will enhance ocean carbon emissions suggesting that marine species protect ocean health. Aquaculture production and marine species and employment rate in fishery processing are insignificant factors in the analysis.

Models (3) and (4) report the results of the factors that cause ocean emissions in the European region. The results of model (3) show the significance of all variables. The result reports a positive relationship between real per capita GDP and ocean CO_2, explaining that higher production activities of goods and services in a country increase the probability of ocean emissions. The squared per capita GDP is negative, which means that ocean emissions increase with an increase in GDP at a certain point but afterward, ocean emissions increase at a decreasing rate. In model (4), OHI is negative, meaning that a country's lower emissions lead to improved ocean health. It is important to note that higher maritime transport activities tend to increase the magnitude of ocean emissions. Additionally, this study reports that the overall trade in fisheries and other species positively impacts ocean carbon emissions. This evidence shows that a surge in the outflow of marine species may increase the possibility of ocean emissions. However, the rest of the variables are insignificant.

Lastly, models (5) and (6) report the determinants of ocean CO_2 in the Americas region. The sole reliable predictor in model (5) is lagged ocean carbon emissions, per capita GDP, and energy consumption are statistically insignificant. Model (6) indicates that marine protected areas, fishery and marine species trade, and aquaculture production and other species are statistically significant determinants. In a nutshell, it can be concluded that the factors that cause ocean emissions vary across the region owing to the size of marine and blue economy.

Panel Granger causality tests

This section applies Granger causality tests to investigate the short-run and long-run relationship. The results of causality tests are reported in Tables 7 and 8. The results of both models are the same; therefore, this study interprets the results of model 2. The results suggest bidirectional causality running from energy consumption and maritime transport to ocean CO_2 in the long run. Moreover, this study finds bidirectional causality running from the OHI and the trade of fishery and ocean species to GDP in the long run. The result reports no evidence of short- and long-term causality from energy consumption to GDP, implying that strategic actions increasing energy efficiency are executed without threatening economic growth. Likewise, no evidence of causality is found running from ocean CO_2 to GDP, suggesting that concerned organizations must formulate necessary measures for overcoming ocean emissions without affecting economic growth. The results of the Granger causality test indicate bidirectional causality running from total energy RD&D, marine protected area, and trade of fishery and ocean species to marine transport containers. Another bidirectional causality flows from marine protected areas and the trade of fishery and ocean species to RD&D. However, this study reports a short-run unidirectional panel causality running from the production of aquaculture and other species to RD&D, from OHI and GDP to trade of fishery and other species, from OHI to employment rate in the fishery sector. This study estimates every regression's ECT to examine the long-run association. The statistical significance of the ECT coefficient describes the error-correction process emphasizing the variables' long-term association. The ECT coefficient is statistically significant in all equations. As the system deviates from the long-run equilibrium, all parameters may be crucial to the adjustment process. In short, the findings show evidence of bidirectional Granger causation between these variables.

Conclusion

This study examined the association between ocean CO_2, real income, energy consumption, and control variables of the ocean industry using the dataset of 44 countries across regions from 2012 to 2021. This study also tested the EKC hypothesis using panel unit and cointegration tests. This study reports a long-run cointegrated relationship between variables in the analysis. This study uses the system GMM estimator to test the hypothesis and finds a positive relationship between economic growth and ocean carbon dioxide emissions. This finding illustrates that higher economic activities produce higher emissions, ultimately affecting ocean CO_2. The results also suggest the presence of an inverted U-shaped curve between real income and ocean carbon dioxide emissions, which supports the evidence of the EKC hypothesis. This finding illustrates that ocean CO_2 increases with an increase in real income at a certain level and then decreases. Moreover, this study finds that OHI, maritime container transport, fishery and ocean species trade, aquaculture production and marine species, and employment rate in the fishery processing sector are robust predictors of ocean CO_2. Regarding the region-wise analysis, real GDP per capita positively affects ocean CO_2 in the European region but has no significant effect in the other regions.

This study employs a panel error correction model to identify short- and long-term causal relationships. The results indicate a short-run unidirectional panel causality running from the production of aquaculture and other species to RD&D, from OHI and GDP to trade of fishery and other species, and from OHI to employment rate in the fishery sector. Regarding the long-run causal association between the variables, the findings show that the lagged ECT in all the variables is significant at a 1% level explaining that all these predictors are critical in the adjustment process as the system departs from the long-run equilibrium. The study reports a bidirectional causality running from energy consumption and maritime transport to ocean CO_2 in the long run. Moreover, this study finds bidirectional causality running from the OHI and the trade of fishery and ocean spices to GDP in the long run. However, no evidence of short- and long-term causality from energy consumption to GDP is found. The bidirectional causal relationship between energy consumption and ocean CO_2 implies that ocean emissions will not decline in sample countries if energy consumption continues to increase soon. Hence, policymakers and concerned agencies must formulate policies for the ocean sector to reduce CO_2, ensuring the survival of people associated with the ocean industry. Furthermore, the sample countries must follow the energy efficiency plan to emit lower emissions which helps achieve ocean sustainability.

Appendix

Table 9 Variables definition

Variable	Symbol	Measure	Source
Ocean carbon dioxide emissions	Ocean CO_2	Ocean carbon dioxide emissions in thousand tons.	UNCTAD
Gross domestic product	GDP	Per capita GDP in constant 2015 US$.	WDI
Energy consumption	EC	Per capita energy consumption in a kilogram of oil equivalent (kgoe).	WDI, IEA
Ocean health index	OHI	An index that measures ocean health.	OHI
Maritime container	MT	Total maritime container transport in million tons.	OECD
Research, development, and deployment	RD&D	Total energy research, development, and deployment in US$ million.	OECD
Marine protected area	MA	A total marine protected area in square kilometers.	OECD
Trade of fisheries	FT	Total trade of fisheries in US$ million.	OECD
Total aquaculture production and marine species	AP	Total aquaculture production & marine species in US$ million.	OECD
People employed in fishery processing sector	ER	People employed in the fishery processing sector, total by occupation rate in thousands.	OECD

This table describes the variables' definition, their measurement, and data sources

Table 10 Summary statistics

	Ocean CO_2	GDP	EC	OHI	MT	RD&D	MA	FT	AP	ER
Americas										
Argentina	3568.942	13,184	1900.545	62.883	-	-	1,168,793.160	1097.402	33.778	15.491
Brazil	11,551.163	8699	1316.535	72.139	-	1250.640	327,553.551	1561.743	422.992	768.499
Canada	1390.766	43,648	7915.179	70.164	34.63	944.208	82,507.995	7567.386	893.894	29.894
Chile	674.292	13,514	1942.237	70.899	37.147	-	594,728.010	5791.403	8057.955	49.184
Colombia	1359.114	6148	686.047	62.895	-	-	75,238.124	589.717	17.101	20.298
Mexico	2634.860	9681	1624.058	74.278	103.631	238.457	362,725.398	1945.332	559.048	220.863
USA	65,792.662	57,760	7173.437	72.756	250.060	7675.253	1,621,955.080	25,851.001	533.659	172.712
	12,424.543	21,805	3222.577	69.431	60.781	1444.080	604,785.903	6343.426	1502.644	182.420
Asia & Pacific										
Australia	1864.873	57,389	5687.438	71.646	72.691	240.875	1,396,683	2542.890	280.501	11.2
China	29,744.933	8809	1860.838	62.021	-	-	3740.278	29,404.022	50,324.577	8932.957
India	4551.567	1689	539.426	59.367	116.457	-	12,934.360	5234.230	2709.138	-
Indonesia	725.784	3492	826.398	63.448	-	-	147,713	4371.330	5719.972	63.886
Israel	838.234	37,446	2928.434	59.891	26.204	-	7.56	523.198	44.069	0.996
Japan	13,796.796	35,026	3711.187	64.005	283.990	3324.912	372,3690	17,740.559	5150.515	168.5
Malaysia	890.589	10,000	2662.833	66.974	-	-	-	1823.249	648.822	23.898
New Zealand	1009.092	38,992	4236.255	81.963	20.670	20.372	1,222,470	1394.047	577.218	2.05
Philippines	412.598	3109	438.106	67.284	-	-	-	1171.706	2113.494	1868.440
South Korea	29,387.588	29,746	4970.195	62.160	401.926	913.610	4458.348	6426.255	1791.983	2938.588
Thailand	3611.449	5917	1693.544	69.421	-	-	-	9837.276	2162.478	394.544
Vietnam	641.511	2839	606.733	64.479	-	-	-	8541.373	4126.206	244.578
	7289.585	19,538	2513.454	66.055	76.828	374.981	263,363.850	7417.552	6304.081	1220.807
Europe										
Belgium	22,357.030	41,351	5132.945	65.982	105.847	293.269	1224.720	3361.631	1.028	0.532
Bulgaria	254.526	7488	2530.995	62.807	2.265	-	2369.692	-	-	-
Croatia	32.803	12,786	2156.383	63.835	1.910	-	2748.100	-	-	-
Denmark	2074.496	54,738	3282.859	65.581	5.395	156.204	16,171.119	8187.100	136.949	3.614
Estonia	923.616	18,592	4179.716	75.796	1.824	-	5396.922	359.088	2.873	2.343
Finland	749.352	44,436	6492.070	72.021	12.401	272.220	8697.870	593.295	64.874	2.233
France	6544.295	37,092	3921.161	73.418	49.702	2209.008	117,048.620	8227.568	841.785	15.634
Germany	7364.681	41,707	3926.818	73.236	127.351	1479.142	22,997.664	8471.273	92.48	7.071
Greece	7095.188	18,230	2459.962	70.498	40.708	-	17,298.360	1442.137	584.123	14.973
Iceland	169.541	53,924	16,712.894	70.113	7.023	-	2091.636	2288.100	80.961	4.482
Ireland	439.774	65,124	2820.210	66.762	6.953	40.418	7864.631	1033.415	179.418	3.698
Italy	7676.438	30,816	2822.687	68.695	90.205	823.656	23,528.871	6917.271	478.197	5.977
Latvia	737.866	14,531	2119.716	72.866	4.206	-	4308.048	408.827	0.586	0.577
Lithuania	418.348	15,370	2590.396	67.497	4.765	6.828	1154.871	1017.726	1.261	4.998
Netherlands	39,993.671	46,183	4687.116	67.201	114.479	295.247	14,390.973	7841.582	116.103	2.699
Norway	761.634	74,882	6125.253	72.661	5.980	356.811	6356.396	11,680.394	6598.855	11.257
Poland	628.092	13,425	2648.519	64.261	16.117	206.873	5529.680	3982.111	50.880	19.214
Romania	98.384	9802	1767.704	65.998	5.257	-	4855.635	-	-	-
Russia	26,660.464	9635	4835.054	71.315	47.226	-	182,815.398	6409.366	332.066	50.235
Portugal	2191.198	19,877	2208.373	75.128	24.656	85.676	46,217.743	3237.731	80.273	14.874
Slovenia	307.333	22,081	3492.759	68.908	6.974	-	118.800	137.498	4.567	0.262
Spain	24,298.751	26,003	2782.216	41.410	166.445	201.423	72,159.336	11,438.430	557.930	7.778
Sweden	5922.709	51,656	5245.218	75.575	13.516	224.323	13.516	8277.252	55.113	2.094
Turkey	2218.138	11,293	1476.466	65.684	96.708	121.923	-	1078.636	961.674	34.237
UK	8210.551	44,947	3132.317	71.992	62.308	887.350	132,149.475	7075.075	1163.295	3.246
	6725.155	31,439	4533.820	69.570	40.809	306.415	28,588.268	4138.620	495.412	8.481

Table 10 (continued)

	Ocean CO_2	GDP	EC	OHI	MT	RD&D	MA	FT	AP	ER
Consolidated										
Mean	7785.811	28,822	3978.112	68.589	56.133	517.877	181,571.494	5383.639	2239.836	366.494
Maximum	83,505.860	102,913	18,178.139	83.070	562.850	9198.800	3,012,616.710	38,597.320	57,221.020	9294.990
Minimum	12.450	1434	410.843	57.050	0.000	0.000	0.000	0.000	0.000	0.000
Standard deviation	13,439.141	21,590	3369.381	4.997	86.272	1301.340	449,563.076	6382.828	7676.108	1407.300

This table shows the summary statistics of all variables of each country from 2012 to 2021. *GDP*, per capita GDP; *EC*, energy consumption; *OHI*, ocean health index; *MT*, maritime container transport; *RD&D*, total energy research, development, and deployment; *MA*, marine protected area; *FT*, total trade of fisheries and marine species; *AP*, aquaculture production and marine species; *ER*, employment rate in the fishery processing sector

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