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Context-dependent changes in maritime traffic activity during the first year of the COVID-19 pandemic

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ABSTRACT

Rapid implementation of human mobility restrictions during the COVID-19 pandemic dramatically reduced maritime activity in early 2020. But where and when activity rebounded, or remained low, during the full extent of 2020 restrictions remains unclear. Using global high-resolution datasets, we reveal a surprising degree of complexity in maritime activity patterns during 2020, yielding a more nuanced picture of how restrictions affected activity. Overall, shipping activity in Exclusive Economic Zones decreased (1.35 %), as expected, however high-seas activity increased (0.28 %). While these annual changes appear modest, there were striking spatially and temporally asynchronous variations in different vessel types' activity in the second half of 2020, ranging from an > 80 % sustained reduction in passenger vessel activity to a 150 % increase in fishing activity. Results suggest systems-level responses were highly context-dependent, pinpointing areas that experienced significant reductions and spikes in activity, and providing hitherto missing details of COVID-19 impacts on economic and environmental sustainability.

1. Introduction

On 11th March 2020, the World Health Organisation (WHO) declared a state of pandemic due to the fast spread and severe consequences of a novel coronavirus (SARS-CoV-2, who.int; Wang et al., 2020). This led to the rapid implementation of containment measures in many countries, including restrictions on national and international mobility. Overall, these non-pharmaceutical interventions resulted in an anthropause, a drastic global reduction in human mobility, with an estimated 4.4 billion people – more than half of the world's population – under partial or full lockdown by April 2020 (Rutz, 2022, Rutz et al., 2020, Bates et al., 2021). At the height of restriction measures around the globe, as many as 100 countries closed their borders, disrupting resource supply chains and altering demand of many goods and services (UNCTAD, 2020). The associated reduction in trade and human mobility sent a shockwave through the global economy in 2020: global gross domestic product (GDP) declined by 3.3 % (World Bank, 2022), and maritime trade contracted by 3.8 % in the first half of the year (UNCTAD, 2021). Alongside this, reductions in pollutant emissions and atmospheric aerosols resulted in improvements in air quality in some regions (Le Quéré et al., 2020; Szopa et al., 2021), and reduced levels of human mobility altered the movements and distributions of terrestrial and marine wildlife (Bates et al., 2021).

Maritime trade networks encompass 80 % of the global trade

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volume, accounting for more than 70 % of its total value (UNCTAD, 2017). Commercial, industrial and leisure activity varied not only with government-imposed restrictions, but also with the knock-on effects resulting from shortages in supply and reductions in trade. The services industry was most heavily affected, as cruise ships were reported as being substantial sources of disease transmission in the early stages of the pandemic, resulting in large decreases in international sea travel across the world (UNWTO, 2022, Rocklöv et al., 2020, Ito et al., 2020). In addition, essential crew and port-operations personnel were affected by the asynchronous spread of COVID-19, and the associated restrictions imposed on mobility, as the anthropause unfolded at different times around the globe (UNCTAD, 2021).

To aid in the design of public health interventions, unparalleled volumes of data were made available to governments and researchers during the pandemic, such as the release of anonymised aggregated human mobility data (Buckee et al., 2020, Santamaria et al., 2020) or the creation of the COVID-19 Government Response Stringency Index (Ritchie et al., 2020). However, such datasets largely apply to the terrestrial domain. So far, in the marine domain, analyses have focused on the early reductions in maritime activity (March et al., 2021), examining a limited range of vessel classes on a broad global scale or in specific locations (Millefiori et al., 2021, March et al., 2021, Russo et al., 2021, Pita et al., 2021). In such studies, it is crucial to disentangle lockdown effects from background changes. For example, changes to human mobility due to COVID-19 have directly impacted the marine environment, including reductions in underwater noise and coastal turbidity (Gabriele et al., 2021, Diffenbaugh, 2022). However, reports that reductions in fishing activity may have had beneficial effects on the sustainable management of fish stocks may have been offset with potential increases in Illegal, Unreported and Unregulated (IUU) fishing due to a reduction in monitoring capacity (OECD, 2021). As such, researchers using the COVID-19 pandemic as a quasi-experimental perturbation to better understand system-level processes need robust quantitative data documenting changes across the different components of human mobility, ideally across multiple spatio-temporal scales. Given this, quantifying where and how human mobility changed on the oceans during 2020 will provide an invaluable foundation for targeted investigations of how marine environments were impacted by lockdowns.

Maritime vessel movements can be monitored at increasingly high spatiotemporal resolutions using the Automatic Identification System (AIS) and satellites (S-AIS; Dunn et al., 2018, March et al., 2021). These provide international coverage due to legislation requiring most shipping vessels to use AIS. For vessels emitting light and smaller vessels not monitored with AIS (see Supplementary Methods for more information on AIS requirements), a complementary source of information are Visible Infrared Imaging Radiometer Suite (VIIRS) Boat Detection (VBD) data, which are satellite-sensed observations of anthropogenic light emissions present on the Earth's surface (Elvidge et al., 2015, Zhao et al., 2019). With trade rebounding in the second half of 2020 (UNCTAD, 2021), the heterogeneous reopening of domestic and international travel (World Bank, 2022) and a succession of lockdowns, activity patterns across the world's oceans in the second half of 2020 remain unknown. To gain a comprehensive view of maritime activity across the first year of the pandemic, researchers, policymakers and managers need access to as many data sources as possible, covering a wide variety of vessel classes.

Here we assess patterns in global maritime activity across the first year of the COVID-19 pandemic across multiple sectors (e.g., shipping, tourism, fishing, conservation) and at multiple spatial scales (global, and within Food and Agriculture Organization of the United Nations [FAO] Major Fishing Areas, Exclusive Economic Zones [EEZs], and Marine Protected Areas [MPAs]) to determine the spatio-temporal dynamics of reductions and increases in activity. To do this we use three complementary data products (Global Fishing Watch [GFW] shipping and fishing datasets, and VIIRS Boat Detection). Through selected regional and local case studies we demonstrate the complexity of this global event on human mobility patterns at sea. Our analyses identify environments and sectors most affected and assess the economic and environmental impacts of the COVID-19 anthropause in a marine context.

2. Results

2.1. Changes in overall global maritime vessel activity

We produced global shipping and fishing vessel activity maps reflecting the extent and intensity of vessel activity and VIIRS Boat Detections in 2020 (Fig. 1a–c). Activity footprints were highly variable between datasets. Shipping vessel activity, encompassing classes such as cargo, passenger and tanker vessels, largely reflected well-established thoroughfares such as the major transoceanic shipping routes around the Cape of Good Hope and through the Suez and Panama Canals (Fig. 1a). This differed significantly from fishing vessel activity, which exhibited a footprint that was far more diffuse and widespread across the globe (Fig. 1b). Fishing vessels were tracked in both EEZs and in the Areas Beyond National Jurisdiction (ABNJ), although certain EEZs, such as the Maldives in the Indian Ocean, and St. Helena, Ascension and Tristan da Cunha islands in the South Atlantic Ocean, were clearly delineated by the absence of AIS-tracked fishing vessel activity (Supplementary Figure 1). VBDs were more highly concentrated in coastal regions and within EEZs than either of the two AIS datasets, and especially prevalent in the Gulf of Thailand, the South China Sea, and the Yellow Sea (Fig. 1c). While matching VBD data to individual vessels is impossible, certain classes of vessels that emit more light than others, such as passenger vessels or squid jigging fishing fleets (Ruiz et al., 2019), are likely to have been detected reliably by this dataset, for example, off the coast of Argentina in the South Atlantic Ocean and to the south and west of the Galápagos Islands in the central Pacific Ocean.

While there was a clear lockdown signal overall (Fig. 1d–f), the spatial extent and magnitude of changes varied between datasets. Most changes in shipping vessel activity between the two periods occurred within transoceanic shipping routes (Fig. 1d). Areas with both the largest increases (positive change, in red) and decreases (negative change, in blue) in activity included the Strait of Hormuz and coastal waters in proximity to the port of Shanghai, with changes of $\pm$ 200 vessel detections compared to the baseline period. Change in fishing vessel activity was spatially heterogeneous, with widespread areas of positive and negative fluctuations in both EEZs and in ABNJ (Fig. 1e). Changes in VIIRS Boat Detections were also spatially variable (Fig. 1f). Certain coastal areas, such as the Mediterranean Sea and the Sea of Japan, presented large-scale reductions compared to the baseline. The most widespread changes (both positive and negative) occurred in the Sea of Japan and in the South China Sea.

The footprint and intensity of activity varied between different vessel classes in 2020 (Fig. 2a–b, Supplementary Figure 2–3, 6). Cargo vessel activity was widespread, highlighting the major shipping routes across the globe (Fig. 2a). Activity in the major shipping thoroughfares remained largely comparable to baseline levels, as indicated by the white coloration of these routes, with the majority of both positive and negative changes occurring elsewhere (Fig. 2c). Passenger vessel activity in 2020 was also largely contained to specific routes, and was concentrated in the Mediterranean Sea, in the northwest Atlantic and in the Caribbean Sea (Fig. 2b). Global passenger vessels experienced a negligible decrease in activity, with an average of 0.6 ($\pm$3.3 S.D.) fewer detections in 2020 compared to the baseline (Fig. 2d). However, some areas experienced large decreases, for example in the East China Sea, with up to 44 fewer detections on passenger vessel routes and the Sea of Japan with up to 37 more detections on passenger vessel routes.

Importantly, AIS-tracked shipping vessel activity in 2020 deviated from forecasted trends based on data for the previous three (baseline) years, revealing a clear lockdown signal for six out of nine shipping vessel classes examined (Fig. 2e–h, Supplementary Figure 4, Supplementary Tables 1,2. The 2017–2019 baseline activity was highly

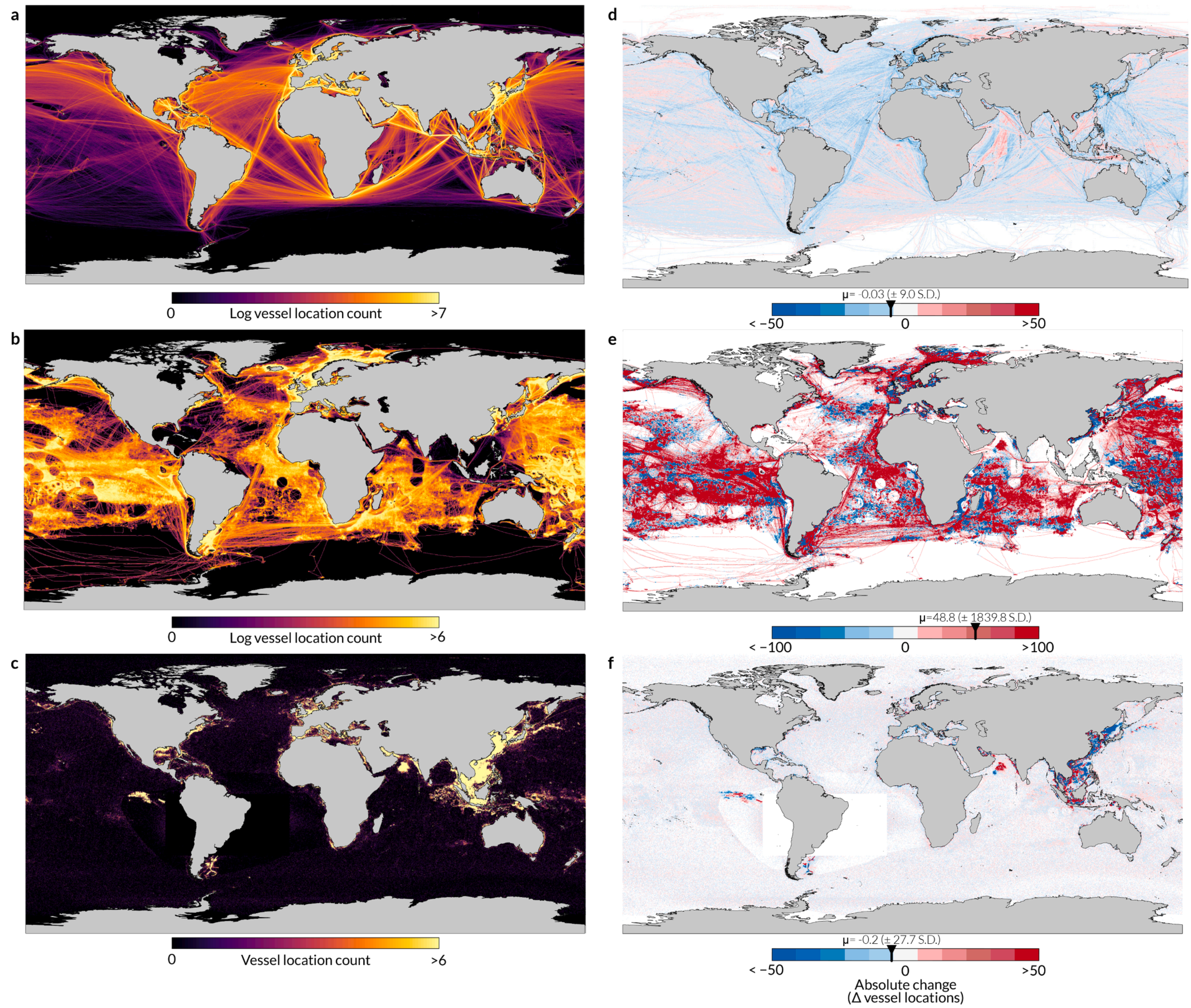

Fig. 1. Global maritime traffic in 2020 and changes in vessel activity. a–c, Spatial footprints of maritime traffic in 2020. Lighter colours reflect higher vessel activity. a, AIS-tracked shipping vessel activity (logged total count of AIS-tracked shipping vessel locations within 0.1° × 0.1° resolution cells). The mean vessel location count per grid cell was 105 (±1052 S.D.). b, AIS-tracked fishing vessel activity (logged total count of AIS-tracked fishing vessel locations within 0.25° × 0.25° resolution cells). The mean vessel location count per grid cell was 272 (±4625 S.D.). c, VIIRS Boat Detection density (total count of VBDs within 0.25° × 0.25° resolution cells). The mean vessel location count per grid cell was 6 (±75 S.D.). d–f, Absolute differences in total count of vessels in 2020 as compared to the mean yearly 2017–2019 baseline, derived using cell-by-cell subtraction. Red indicates increased activity; white, similar activity; and blue, reduced activity. The black bar on each colour scale indicates the global mean change observed across the globe in 2020 for each dataset. d, Absolute change in AIS-tracked shipping vessel activity (within 0.1° × 0.1° resolution cells). e, Absolute change in AIS-tracked fishing vessel activity (within 0.25° × 0.25° resolution cells). f, Absolute change in VBD density (within 0.25° × 0.25° resolution cells). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

seasonal for all vessel classes examined. Across the baseline (i.e., pre-pandemic), cargo vessel activity remained stable (Fig. 2e), whereas global tanker and passenger vessel activity increased (Fig. 2f–g) and container reefer vessel activity decreased (Fig. 2h). Tanker (Friedman test (FT), $\chi^2_1 = 12$, $p < 0.001$) and passenger (FT, $\chi^2_1 = 12$, $p < 0.001$) vessel activity was lower than expected for 2020, remaining below the 80 % confidence limits of the forecasts. For passenger activity levels, the Mean Absolute Percentage Error (MAPE), the average difference between the forecasted and observed value, was 53.09 %, indicating that there was a significant difference between the forecast and the observed data. In particular, passenger vessel activity showed a sharp, atypical decrease compared to the forecast in April 2020, and the peak activity in July and August 2020 was ~ 30 % lower than in 2019. For container reefers, which was the only shipping vessel class examined that was already declining in activity over the baseline period, vessels were more active over the first year of the COVID-19 pandemic than forecast (FT, $\chi^2_1 = 12$, $p < 0.001$), with a MAPE of 15.44 %. Finally, there was less cargo vessel activity in the first third of 2020, remaining below 80 % confidence limits of the forecast, although activity recovered to levels similar to those forecast for the latter third of the year; overall, the forecast distribution was not significantly different to the observed distribution (FT, $\chi^2_1 = 5.33$, $p < 0.05$), with a MAPE of 3.70 %.

2.2. *Changes in maritime vessel activity in EEZs*

Whilst maritime shipping vessel activity in ABNJ increased by 0.28 % in 2020 compared to 2017–2019 baseline levels, activity in EEZs decreased by 1.35 % (Supplementary Figure 5). ‘Shipping vessels’

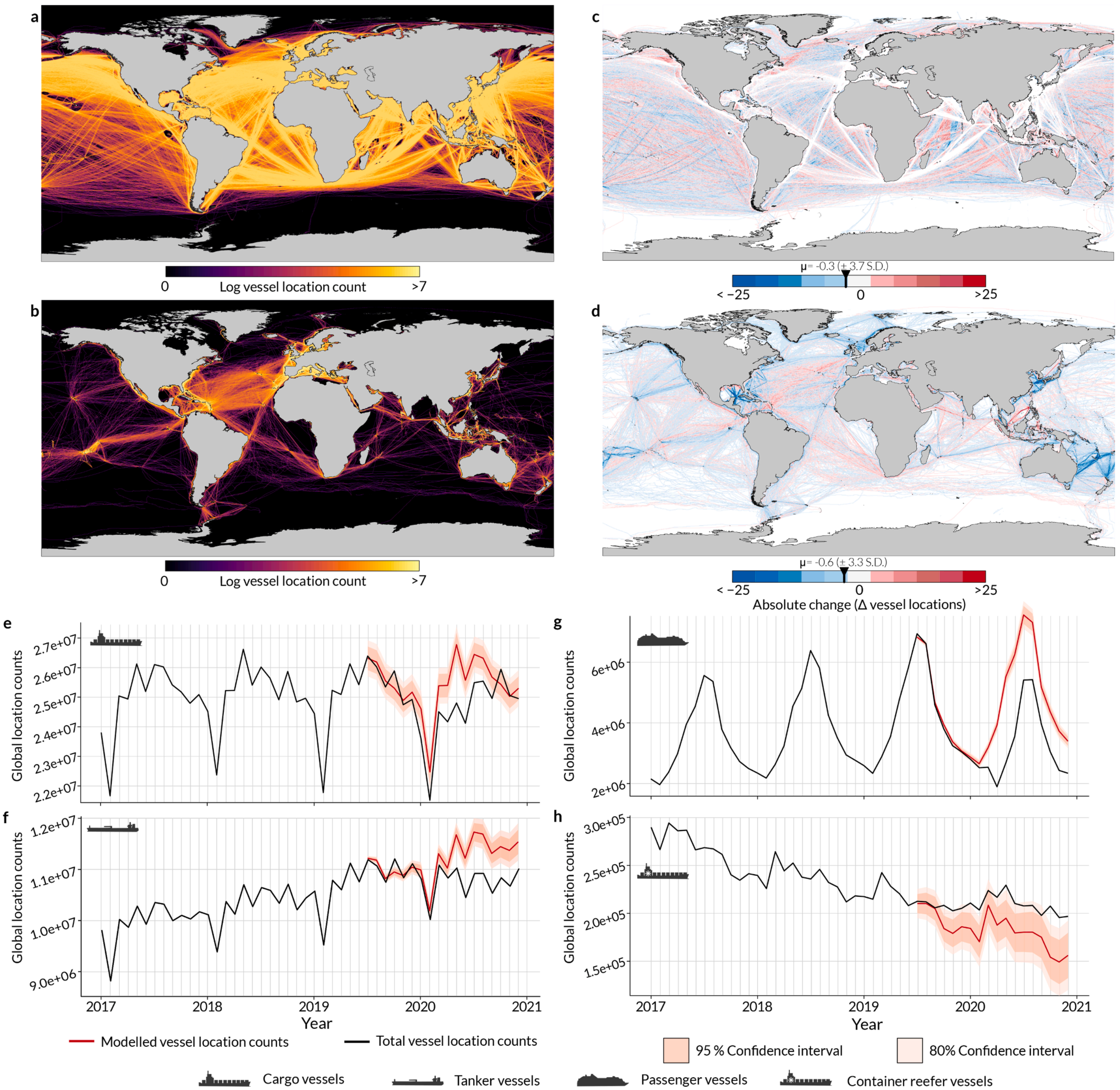

Fig. 2. Global shipping traffic by vessel class in 2020 and vessel activity forecasts for 2020. Global a, cargo and b, passenger vessel activity in 2020 (logged total count of AIS-tracked shipping vessel locations within 0.2° × 0.2° resolution cells). Lighter colours reflect higher vessel activity. The mean vessel location count per grid cell was 17 (±19 S.D.) for cargo vessels, and 3 (±7 S.D.) for passenger vessels. Global changes in c, cargo and d, passenger vessel activity in 2020 compared to the 2017–2019 baseline (absolute difference between the total count of AIS-tracked cargo and passenger vessel locations during 2020 and the mean yearly total count of AIS-tracked cargo and passenger vessel locations across 2017–2019 within 0.2° × 0.2° resolution cells). Red indicates increased activity in 2020; white, similar activity; and blue, reduced activity. The black bar on each colour scale indicates the global mean change observed across the globe in 2020 for each dataset. e-h, Global vessel activity forecasts during 2020 for AIS satellite-tracked e, cargo, f, tanker, g, passenger, and h, container reefer vessels using Holt-Winters models. The black line indicates the total monthly number of AIS-tracked vessel locations for the years 2017 to 2020. The red line indicates the forecasted data predicted by the model, surrounded by the 95 and 80 % confidence intervals (in shades of red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

encompass all nine classes of shipping-related vessels, and this global decrease obscures highly variable activity patterns through time, across different regions and EEZs, and between different vessel classes.

Comparing maritime activity patterns in 2020 to the baseline revealed significant variation between months and EEZs (Fig. 3). Passenger vessel activity experienced the most consistent global decrease in vessel activity compared to baseline levels: between April and June 2020, passenger vessels were less active in 97 % of Mediterranean Sea coastal states compared to 2017–2019. That said, passenger vessel activity was spatially heterogeneous across the remainder of the year, with increases observed in some EEZs, such as Turkey and Bulgaria, and levels remaining well below the baseline in others. In the Italian EEZ, passenger vessel activity remained below, or near, the baseline until November 2020. Whilst April 2020 saw the most widespread decrease in

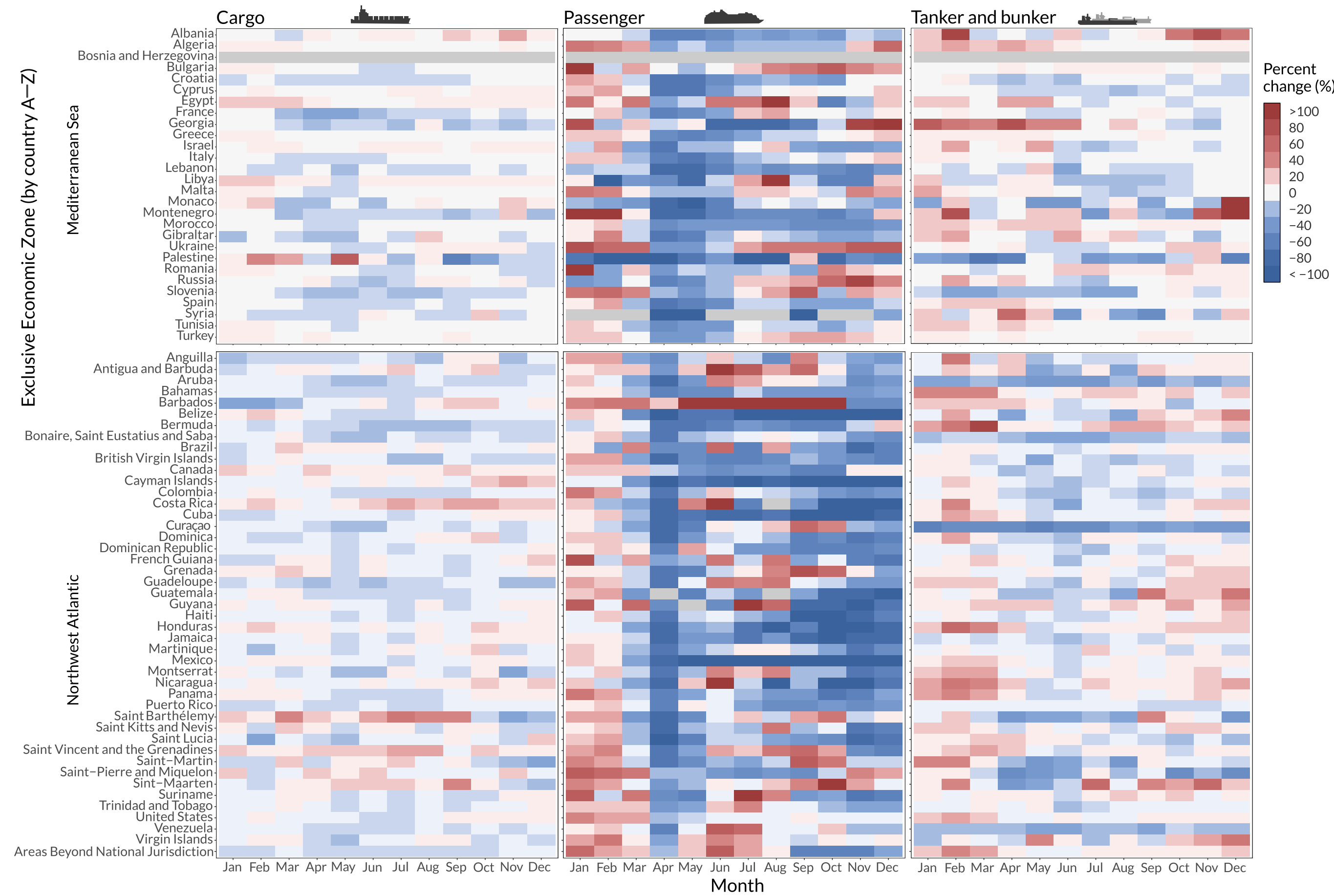

Fig. 3. Monthly changes in shipping vessel activity during 2020. Monthly variation in cargo, passenger, bunker and tanker vessel activity (percentage change of total monthly count of AIS-tracked vessel detections) during 2020 in individual EEZs, as compared to the 2017–2019 baseline, across Mediterranean and northwest Atlantic coastal states' EEZs and the ABNJ in the northwest Atlantic. Grey cells indicate a lack of data. There are no ABNJ in the Mediterranean Sea.

passenger vessel activity in the northwest Atlantic, many EEZs experienced a second large decrease in vessel activity in November and December, with reductions of between 80 % and 100 % compared to the baseline. Only a few EEZs experienced a consistent increase in passenger vessel activity across the first stage of the pandemic, such as Barbados, where activity levels remained 80 % above baseline levels until November 2020.

Trends in activity for cargo, and the combined tanker and bunker vessel classes, were far less pronounced than for passenger vessels. In May 2020, there was a broad decrease in cargo vessel activity across the Mediterranean and the northwest Atlantic EEZs, as compared to the baseline, whereas the northwest Atlantic ABNJ remained up to 20 % below the baseline throughout 2020 (Fig. 3). In the Mediterranean Sea, bunker and tanker vessel activity in EEZs was spatially and temporally heterogeneous, with both increases and decreases in vessel activity compared to the baseline. Conversely, there were decreases in activity in the majority of EEZs in the northwest Atlantic in April 2020, albeit less pronounced than those observed for passenger vessels (Fig. 3).

We extended our analysis to examine seasonal variation within selected Mediterranean Sea EEZs. In these areas there were always fewer VBDs than AIS-tracked vessel detections. The selected countries illustrate the high levels of variation between different EEZs, and how overall patterns in vessel activity reflect the dominant activities in the respective EEZs (Fig. 4). For example, in the Italian and Greek EEZs, overall vessel activity trends were driven by passenger vessels, evident from the strong, single-peak seasonality present in both the overall shipping and passenger vessel time series (Fig. 4a–b). In contrast, in countries with EEZs that encompassed major shipping routes, such as Egypt, overall activity patterns were largely driven by cargo vessel activity, which did not decline during 2020 and there was a reduction in passenger vessel activity (Fig. 4c). Furthermore, in the Syrian EEZ, there were <20 monthly passenger vessel detections across the examined time period, with vessel activity patterns largely driven by cargo vessel activity (Fig. 4a).

2.3. Changes in maritime vessel activity in FAO Major Fishing Areas

Fishing vessel activity (presence of all fishing vessels, both fishing and in transit) in FAO Major Fishing Areas in the Western Central and North-Western Atlantic Ocean was heterogeneous and depended on both the area and vessel class examined (Fig. 5a–b). For example, in Area 31 which encompasses the Western Central Atlantic, the activity of most fishing vessel classes increased substantially during 2020, as compared to the baseline; any decreases below the baseline typically lasted less than a month. In Area 21, the Northwest Atlantic, there were synchronous decreases in fishing vessel activity from the end of March through to April 2020 for all sub-areas (21.2–21.6) except 21.2. Similarly, activity patterns in FAO Major Fishing Areas in the Northeast and Eastern Central Pacific Ocean varied across areas and fishing vessel classes (Fig. 5c–d). For example, in Area 67, the Northeast Pacific, trawling vessels were more active in 2020 compared to baseline levels, while in Area 77, which encompasses part of the Eastern Central Pacific, there was a uniform decrease in trawler activity (Supplementary Figure 7).

The activity for many fishing vessel classes intensified in 2020 compared to baseline levels. There was a 2.5 times increase in squid

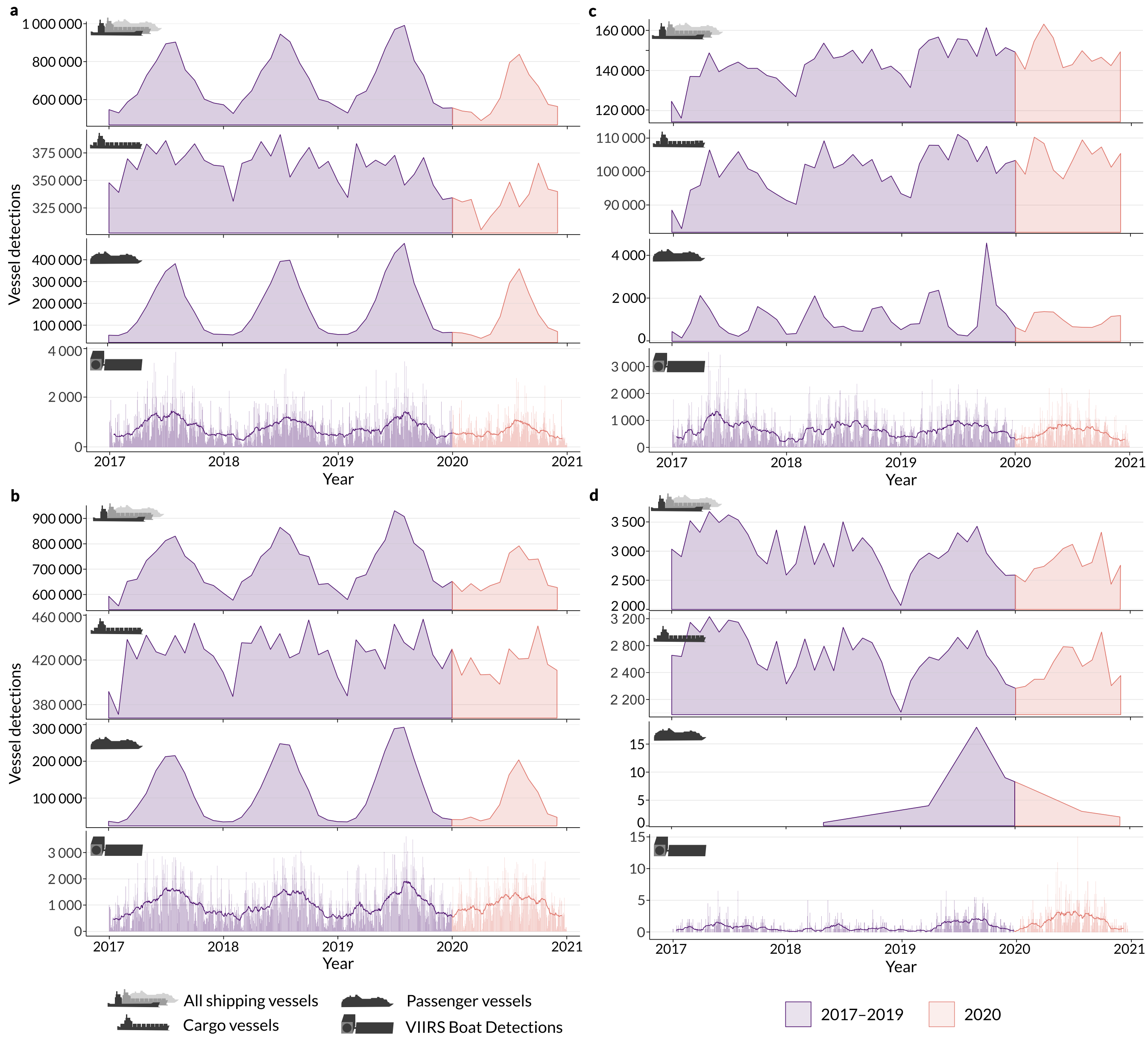

Fig. 4. Changes in vessel activity within selected EEZs during 2020. Vessel activity is represented as the total monthly count of AIS-tracked shipping, cargo and passenger vessel detections, and total daily count of VIIRS Boat Detections (VBD with rolling 28 day means to remove the influence of the moon on detection totals) in a, Italian b, Greek c, Egyptian and d, Syrian exclusive economic zones. The first category for each country, 'All shipping vessels', is the total sum of all nine categories of shipping-related vessels, and includes cargo and passenger vessel counts.

jigging fleet detections in FAO Major Fishing Area 77 in 2020 compared to the baseline (Fig. 6a–c). The majority of the increase was associated with increased transiting activity from squid fishing grounds in the eastern Pacific (located outside area 77) to fishing grounds in the North Pacific (partly inside area 67), and, mostly, to ports in the Northwest Pacific (Fig. 6a; red lines). There was large seasonal variation in fleet activity in 2020, more than in the three baseline years (Fig. 6b). Specifically, squid jigging vessels were more active from mid-March to December 2020 than in the corresponding period in the baseline, except for two weeks in late June and the start of July, coinciding with the main squid-fishing seasons in the North (summer) and Eastern Pacific (spring to autumn), indicating increased movements between fishing grounds and ports. Similarly, in Area 67, the Northeast Pacific, activity was seasonal, and was more intense, lasting longer in 2020 than at any point in the baseline period. Increased activity was centred on the North Pacific squid fishing grounds (Fig. 6a), indicating that changes in 2020 may reflect fishers' responses to squid abundance or distribution changes due to environmental variations in addition to potential COVID-19 effects on fishing activity. In FAO Major Fishing Area 77, tuna purse-seine vessel activity intensified over most of 2020 (Fig. 6d–f; Supplementary Figure 7). For example, in April 2020, tuna purse-seine activity was 125 % higher than baseline levels, and activity remained high throughout most of the year, with the exception being the last week of August and the month of September (Fig. 6e–f).

2.4. Change in maritime vessel activity in marine Protected areas (MPAs)

Vessel activity levels were temporally and spatially heterogeneous across selected MPAs (Fig. 7). For example, in the National Oceanic and Atmospheric Administration (NOAA) Florida Keys National Marine Sanctuary, a key thoroughfare for maritime traffic was visible crossing the MPA in 2020 (Fig. 7a). Monthly cargo vessel activity remained

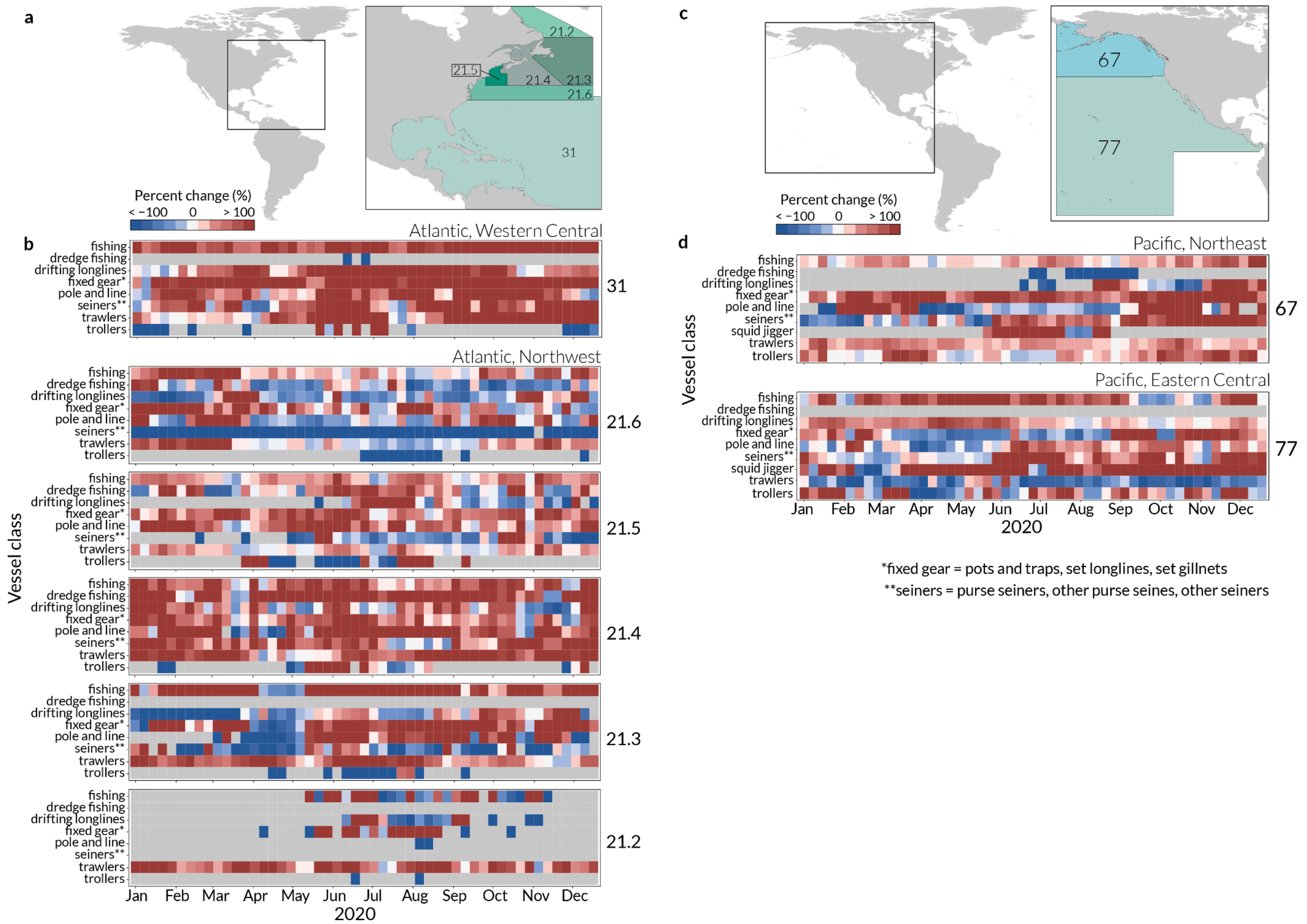

Fig. 5. Changes in fishing vessel activity (presence of all fishing vessels, both fishing and in transit) in FAO Major Fishing Areas during 2020. Relative changes in weekly vessel activity (presence of all fishing vessels, both fishing and in transit) is represented as the weekly average of total daily vessel detections in each area during 2020, compared to the 2017–2019 baseline. a, FAO Major Fishing Areas 21 (Subareas: 21.6, 21.5, 21.4, 21.3, 21.2) and 31 in the northwest Atlantic Ocean. b, Relative change in vessel activity in FAO Major Fishing Areas 31 and 21 by vessel class. c, FAO Major Fishing Areas 67 and 77 d, Relative change in vessel activity in FAO Major Fishing Areas 67 and 77 by vessel class. Grey cells indicate a lack of data. Vessel classes that had no detections in an area were excluded.

below the 2017–2020 baseline throughout 2020, whereas passenger vessel activity peaked in June 2020, with 75 % higher activity than in the baseline period, only dipping below the baseline in April and May 2020 (Fig. 7c). A spike in passenger vessel activity in June 2020 did not occur in any other year in the dataset (Fig. 7b). VBDs also exhibited large increases from March to May, and in June 2020. In the Agoa Marine Mammal Sanctuary, which encompasses the EEZs of multiple Small Island Developing States (SIDS; Guadeloupe and Martinique), cargo vessels were less active in 2020 than during the baseline period, with the lowest levels recorded in November and December 2020, at 25 % below the baseline (Fig. 7f). There were also two main periods of reduced passenger vessel activity in 2020 – a reduction of over 75 % in April 2020, and of over 50 % in November 2020, compared to the baseline (Fig. 7e). VBDs were much more variable than data for any of the AIS-tracked vessel classes, fluctuating during 2020 in comparison to the baseline period in 2020. In contrast, across both selected MPAs, fishing vessel activity levels were consistently more active in 2020 than during the baseline period.

3. Discussion

In this study, we used a combination of satellite AIS tracking data and VIIRS Boat Detections to quantify changes in global maritime vessel activity during the first year of the COVID-19 pandemic. Our analyses uncovered high levels of complexity in activity patterns, adding important granularity to the widely-held view that lockdowns caused an overall slowdown in maritime activity. Generally, the most widespread reduction in activity for most vessel classes was observed during the early stages of the pandemic, from March to June 2020, followed by spatial and temporal variations in activity during the remainder of the year. We observed a small decrease in shipping vessel activity within EEZs, contrasting with a slight increase in ABNJ. Furthermore, whilst passenger vessel activity experienced a decline coinciding with the imposition of widespread restrictions to human mobility in some regions of study, many fishery vessel classes were increasingly active during this same time period.

3.1. The Blue Economy: Temporarily on hold?

The ocean is under unprecedented pressure from human exploitation, from the acquisition of renewable and non-renewable resources, to the presence of large thoroughfares for global transport and trade (FAO, 2020; Jouffray et al., 2020). Countries are increasingly connected by complex trade networks, and companies seek to maximise profit by streamlining logistics and supply chains. Measures put in place to mitigate the spread of COVID-19 disrupted these processes, contributing to a global anthropause (Rutz et al., 2020, Bates et al., 2020) and a slowdown in world GDP growth in 2020 (UNCTAD, 2021, World Bank, 2022). We observed an initial decline in overall maritime vessel activity in the first stages of the pandemic, and our in-depth analyses revealed

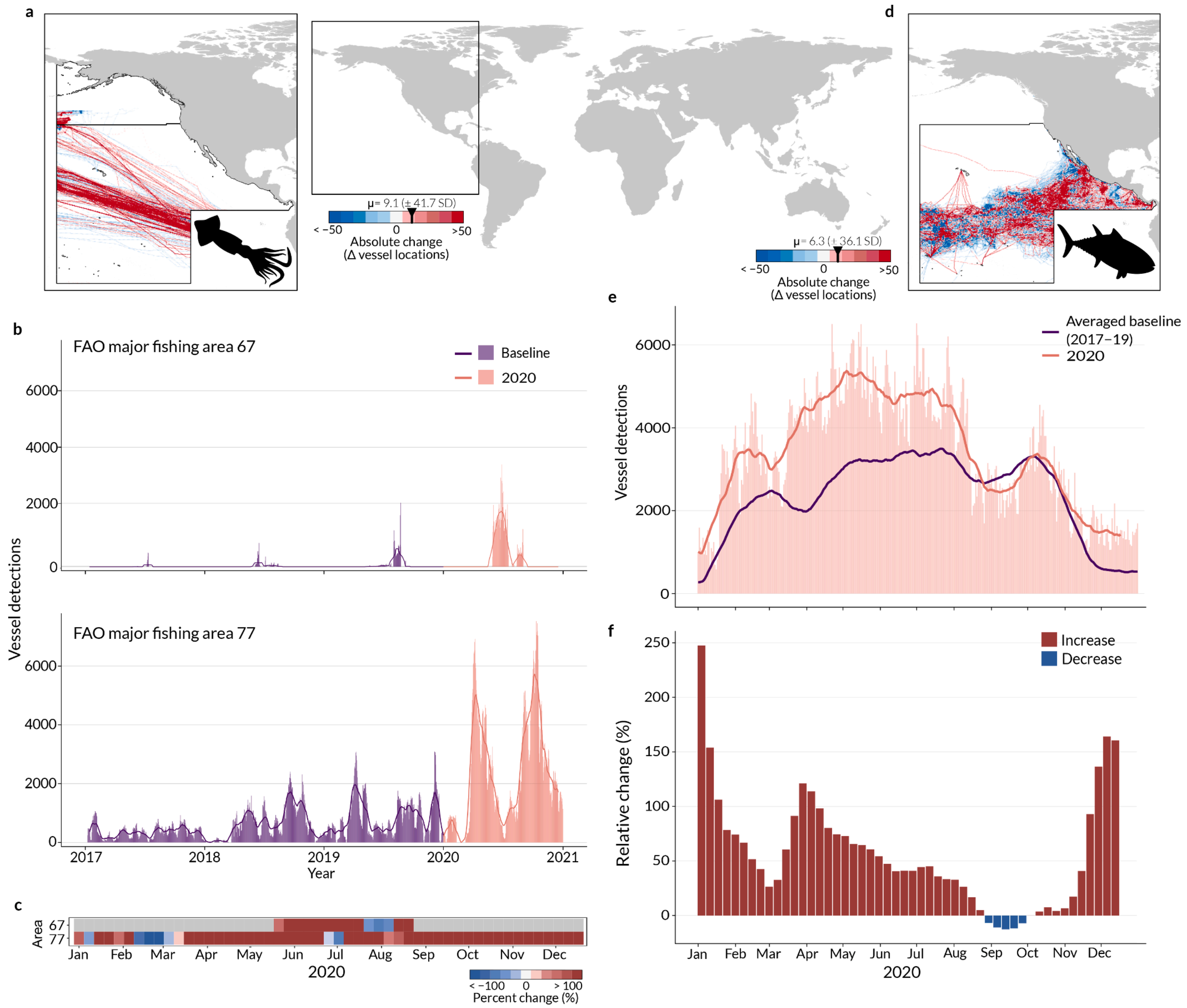

Fig. 6. Squid and tuna purse-seine fisheries in the Pacific Ocean during 2020. a–c, Squid jigging vessel activity. a, Absolute changes in squid jigging vessel activity in FAO Major Fishing Areas 67 (Pacific Northeast) and 77 (Pacific Eastern Central) in 2020 compared to the 2017–2019 baseline, based on a grid of 0.1°x0.1° resolution. Red indicates increased activity; white, similar activity; and blue, reduced activity. The black bar on the colour scale indicates the mean change observed across the globe in 2020. b, Squid jigging vessel activity in FAO Major Fishing Areas 67 and 77 from January 2017 to December 2020, represented as a rolling 7-day mean derived from the total daily vessel detections in each area (pink and purple line), and as the total daily vessel detections in each area (columns). c, Relative change in monthly squid jigging vessel activity in the Northeast and Eastern Central Pacific Major Fishing Areas. d–f, Tuna purse-seine vessel activity. d, Absolute changes in tuna purse-seine vessel activity in FAO Major Fishing Area 77 in 2020 compared to the 2017–2019 baseline, based on a grid of 0.1° × 0.1° resolution. Red indicates increased activity; white, similar activity; and blue, reduced activity. The black bar on the colour scale indicates the mean change observed across the globe in 2020 for each dataset. e, Tuna purse-seine vessel activity in FAO Major Fishing Area 77 during 2020 and averaged across the baseline, represented as a 7-day mean derived from the total daily vessel detections in each area (pink and purple lines), and as the total daily vessel detections in each area during 2020 (columns). f, Relative change in the weekly average of total daily tuna purse-seine vessel detections in FAO Major Fishing Area 77. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

heterogeneous activity patterns in the following months. This may reflect an initial reduction in human mobility, followed by the effects of rapid swings in supply and demand felt by different sectors, through supply-chain shortages, increased freight prices, port congestion and other processes (Buckley, 2020, Russo et al., 2021). For example, container and dry bulk freight rates increased to all-time highs, and tanker freight rates fell to record lows, as global fuel demand decreased alongside the slowdown in economic activity (UNCTAD, 2021).

In early 2020, the initial focus of many governments was to contain the pandemic through non-pharmaceutical interventions, such as lockdowns, social distancing, and school and workplace closures, culminating in more than half of the world's human population being under some form of lockdown in April 2020 (Bates et al., 2020). Changes in maritime activity reflect these measures, especially in sectors that rely heavily on the movement of people, such as the tourism industry. According to the United Nations World Tourism Organisation, there were 73 % fewer international tourist arrivals across the globe in 2020 when compared to 2019, with a reduction of 77 % and 97 % in September and April, respectively (UNWTO, 2022). Our results echo these findings: in tourist hotspots such as the Mediterranean and Caribbean Seas, maritime passenger vessels were less active and VBDs were reduced when compared to the baseline period. That said, our data indicate that

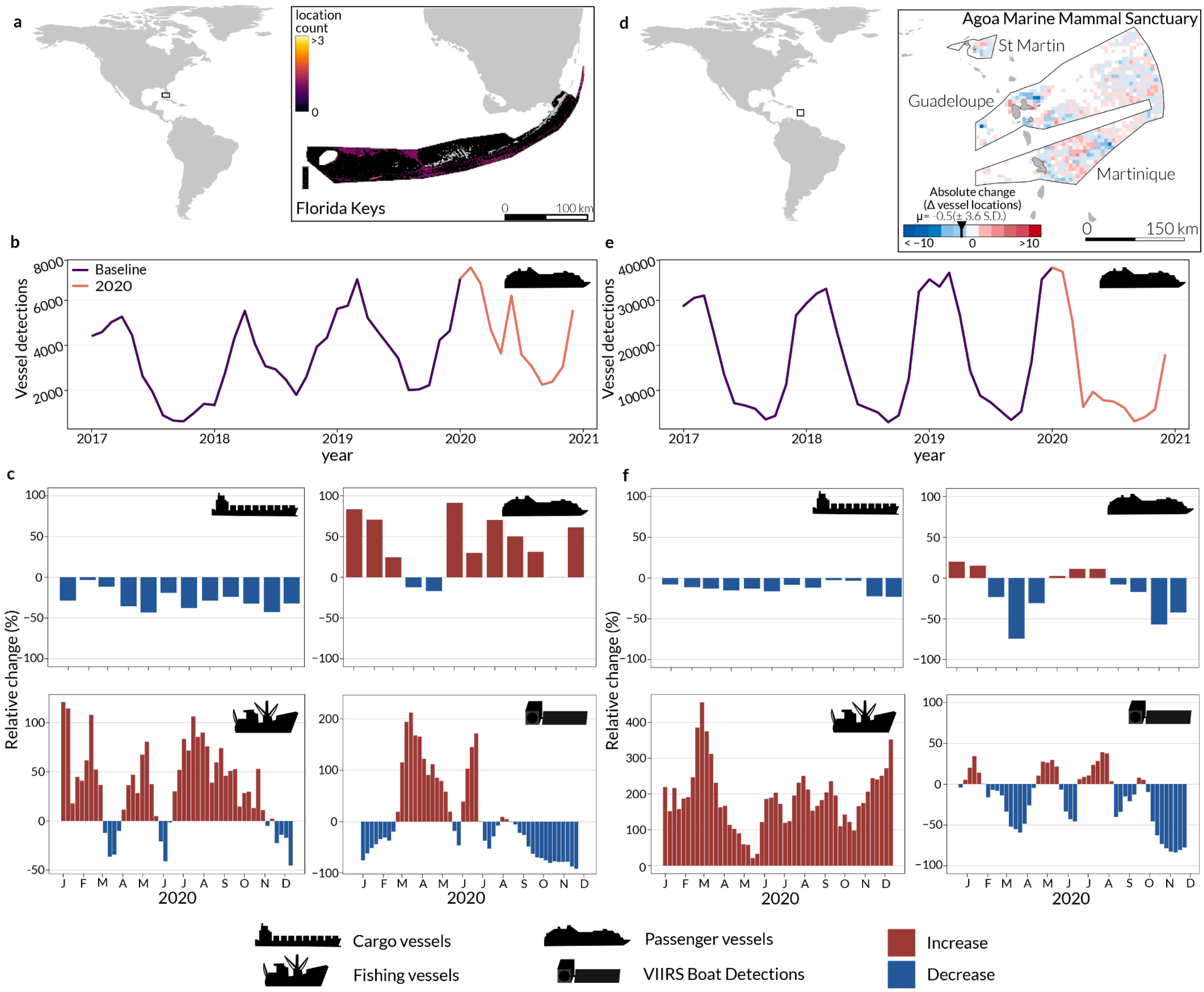

Fig. 7. Changes in vessel activity in the Florida Keys National Marine Sanctuary and the Agoa Marine Mammal Sanctuary during 2020. a–c, Florida Keys National Marine Sanctuary. a, Total fishing vessel activity in 2020, based on a grid of 0.01° × 0.01° resolution. b, Monthly total passenger vessel data from 2017 to 2020. c, Relative change in vessel density by vessel class – monthly for cargo and passenger, and weekly for VBD and GFW fishing vessel data. d–f, Agoa Marine Mammal Sanctuary. d, Absolute changes in cargo vessel density between 2020 and the baseline, based on a cell-by-cell subtraction on a grid of 0.1° × 0.1° resolution. e, Monthly total passenger vessel data from 2017 to 2020. f, Relative change in weekly average of total vessel activity by data class – monthly for cargo and passenger, and weekly for VBD.

recovery of passenger vessel activity to pre-pandemic levels in many countries' EEZs did not occur in 2020, potentially resulting in long-lasting detrimental effects on economies, livelihoods as well as heritage and biodiversity conservation efforts, where funding is often linked to ecotourism (Buckley, 2020, Hentati-Sundberg et al., 2021). For coastal states that are heavily reliant on tourism, this decrease in revenue is likely to have long-term negative impacts on conservation monitoring activity, especially in emerging economies (UNCTAD, 2021, UNWTO, 2022).

The asynchronous re-imposition of lockdowns during 2020, and the associated slowdown in trade and tourism, appear to have disproportionately impacted SIDS, which are highly dependent on imports arriving by sea, and often on the tourism industry for jobs (UNWTO, 2022). Our results show that in the Agoa Marine Mammal Sanctuary – a 143,256 km^2 marine protected area designated in 2010, covering the EEZs of two SIDS: Guadeloupe and Martinique, – cargo vessels were less active during 2020 than in baseline years. Our findings corroborate that SIDS have been particularly impacted by the pandemic: a reduction in the number of shipping companies providing services to these regions, and low connectivity to shipping networks has been exacerbated by reductions in vessel carrying capacity and increases in the number of blank sailings (Sirimanne, 2021). This likely resulted in reduced services and increased freight prices with knock-on effects on a nation's recovery from the COVID-19 pandemic and development aspirations, at least in the short to medium term.

3.2. Fisheries and COVID-19-imposed lockdowns

Seafood is one of the world's most traded commodities, and this sector is the largest employer of ocean-based industries (FAO, 2020). Some fleets, such as the Italian trawling and other fishing vessels in the Adriatic Sea, reported large declines in fishing during our study period (Russo et al., 2021, Coll et al., 2021, Clavelle, 2020). Nevertheless, previous studies have proposed that the industrial fishery sector was more resilient than expected to COVID-19 effects due to government subsidies and support within EEZs (March et al., 2021). With 31 % of global stocks currently below sustainable biological levels, these declines suggest a potential easing of fishing pressure on marine environments (OECD, 2021). Our results indicate that, where declines in fishing vessel presence occurred, they were usually localised and short-lived. Whether these changes translated into a reduction in fishing effort and lasted long enough to have positive benefits on stock levels, is likely to depend on the species, their biological characteristics and their preferred habitats; assessing these potential impacts is an important future focus of research in understanding the wider impacts of the pandemic on the environment. Reductions in fishing vessel presence in some areas may have also been linked with increased restrictions on the travel and tourism sector: following hotel and restaurant closures, many fleets will have experienced reduced demand in 2020, but following the asynchronous reopening of the industry, demand is likely to have recovered quickly (OECD, 2021).

Alongside potential reductions in local demand, reduced surveillance capacity was reported for many fisheries management organisations, such as fishery observer programmes (Carpenter, 2020). This resulted in concerns that occurrences of IUU fishing may have increased (NOAA Fisheries, 2022, OECD, 2021). Efforts to examine the spatial distribution and mobility of fishing vessels in more remote and unregulated areas such as ABNJ may offer some insight into whether, where and why changes in activity occurred. Our data indicate that most fishing vessel classes had increased activity levels in the northwest and central Atlantic, and activity of squid-jigging and tuna purse seine vessels increased in the northeast Pacific over the course of 2020. Interestingly, localised decreases in activity within EEZs were more common than in ABNJ. One reason that could explain this apparent disparity is that activity outside of EEZs was likely to be less well monitored during this period, increasing opportunities for reduced adherence to national and regional regulatory processes (OECD, 2021). IUU fishing undermines conservation efforts, and the sustainable management of fish stocks, and is threatening small-scale and artisanal fisheries (FAO, 2020). While it is not possible to directly monitor fishing vessel activity, indirect methods, such as VBD and AIS, provide a useful proxy to quantify this damaging trade and direct regulatory efforts to reduce it (Weimerskirch et al., 2020).

3.3. Conservation and COVID-19

Researchers have started using the COVID-19 pandemic as a quasi-experimental perturbation to better understand the impact of human activities on the environment, including in the marine realm (Rutz, 2022, Rutz et al., 2020, Magalhães et al., 2021, Bates et al., 2021). The results presented here will enable researchers to strategically target areas for further investigation where maritime vessel activity levels changed during the pandemic, where other proxies of human mobility may not be readily available. In fact, this is the chosen study approach of the marine sub-project of the COVID-19 Bio-Logging Initiative, which will analyse – using animal tracking data – how wildlife responded to temporarily reduced, or increased, levels of maritime vessel activity. Our findings can inform such analyses of maritime vessel impacts on marine wildlife from the local to the global scale, and may be especially important for studies of large pelagic animals that migrate across jurisdictional boundaries (Pirotta et al., 2019, Huveneers et al., 2021). For example, when evaluating how reductions in maritime vessel activity due to the pandemic may have affected of ship strike rates on marine megafauna (Schoeman et al., 2020; Womersley et al., 2022), or when examining behavioural responses to underwater soundscapes (Breeze et al., 2021, Gabriele et al., 2021, Pine et al., 2021), quantitative data on maritime vessel activity are essential.

Our study provides an effective measure of maritime activity and can support conservation efforts in local areas and in MPAs. At the local scale, MPAs may act as useful study sites to investigate the effects of COVID-19 induced impacts on the environment and on local wildlife, as human activities are likely to be more closely monitored in those areas (Phua et al., 2021). That said, as a result of the large variation in the legislative framework governing MPA use, justifications for protection, accessibility, and changes to maritime traffic, impacts in these areas are likely to be highly variable. For example in the Florida Keys National Marine Sanctuary, the observed reduction in passenger vessel activity levels may partly be explained by access to the reserve being restricted for non-residents during lockdowns, and a key thoroughfare for cruise ships being closed temporarily following a no-sail order from the US Centers for Disease Control and Prevention on 14 March 2020 (CDC, 2022). Our observations provide at least one type of quantitative measure of the effectiveness of such restrictions and could inform future management strategies in these areas.

The effects of restrictions on national and international human mobility are not just limited to the local ecosystem. Many communities rely on MPAs and the marine environment for revenue from ecotourism or external funding, which may have been inhibited by reductions in global passenger vessel activity, such as the countries managing the Agoa Marine Mammal Sanctuary. Without sufficient resources to manage them effectively, and/or with state-implemented restrictions on human mobility, these areas may have been left vulnerable to increased poaching pressure, as a result of reduced monitoring and enforcement (Magalhães et al., 2021, Quesada-Rodríguez et al., 2021, Bates et al., 2021). In conclusion, a nuanced, case-by-case approach to MPAs is necessary to tease out relevant context to any observed patterns.

3.4. Potential interacting drivers of vessel activity

Changes to maritime vessel activity in 2020 were not only driven by the COVID-19 pandemic. As maritime trade is integral to the proper functioning of many sectors and economies, it is affected by numerous socio-economic variables (UNCTAD, 2021, Cullinane and Haralambides, 2021). A non-exhaustive list of such variables includes geopolitical tension, conflict and other unexpected events such as blockage of trade routes, as well as decisions made by shipping companies and regulations that apply to the vessels themselves such as the IMO 2020 sulphur limit (Yuan et al., 2022, UNCTAD, 2021). For example, in countries such as Syria, where our data indicated that maritime vessel activity patterns were primarily driven by cargo vessels, active conflict and the impact of sanctions will affect maritime vessel activity levels and make it more difficult to identify a COVID-19 related signal in the data. Longer-term trends observed in the world fleet also influence global maritime vessel activity (UNCTAD, 2021), such as an ageing fleet and the ongoing decline in service of the container reefer vessel type, whose downward trend was clearly observable in our analyses, despite the decline not being as extreme as predicted by forecasts.

Changes in weather and climate conditions are also expected to affect global maritime vessel activity both indirectly through changes in the trade of agricultural commodities, as well as directly through changes to the distribution and abundance of commercially harvested stocks (Bertrand et al., 2020, Yu et al., 2021). Seasonal fishing grounds may change depending on the movement of the target species, with the direction and scale of shifts of commercial stocks having documented links with large-scale temperature changes associated with climate phenomena such as the El Niño/La Niña Southern Oscillation (ENSO; Lehodey et al., 1997) Migratory animals, such as squid, whose populations are highly sensitive to climate variability, form seasonal aggregations targeted by fisheries (Arkhipkin et al., 2015, Chen and Chiu, 2003). Our results showed that squid-jigging vessel activity was greatly increased in the North and Eastern Pacific during 2020 compared to 2017–2019 as a likely consequence of both increased fishing and transiting activity. It is possible that the large increase in vessel activity was driven by the onset of La Niña conditions that began in 2020 following several ENSO neutral years, and which in the North Pacific are known to shift squid distributions further northward, with fishing grounds distributed more sporadically over large areas, compared to El Niño years (Chen et al., 2007). Similarly in the Eastern Pacific, suitable habitats for commercially fished squid expand during La Niña years (Yu et al., 2021). However, the onset of La Niña conditions did not occur until September 2020 (World Meteorological Organization, 2022), indicating that the increased activity of squid jigging vessels in 2020, at least in the first two thirds of the year, were less likely to have resulted solely from ENSO events. Potentially, the increased number of vessel detections in the latter third of 2020 could have arisen from increased time spent at sea by the fleet transiting further to extended fishing grounds, and then back to more distant ports as a result of La Niña, because as a species distribution changes, a fishery's footprint and activity levels will also change. Equally however, a factor contributing to the 2020 pattern could also be that squid-jigging vessels spent longer at sea in 2020 as a whole compared to previous years as a result of uncertainties about when fishing by national fleets might be curtailed by new national lockdown rules. Further research will be required to disentangle the relative contributions of climatic change and COVID-19 lockdown in driving the observed patterns of fishing activity.

3.5. Value of using multiple vessel datasets

Finally, the method used to monitor activity will influence the resulting data. For instance, there were always fewer VBDs than AIS-tracked vessel detections. This is likely caused by reduced activity on the ocean at night combined with environmental factors affecting detectable levels of illumination, such as clouds, moonlight glint, and the fact that many vessels only carry dim lights. However, VBD data offer the opportunity to map the changing activity patterns of vessels that do not use AIS, such as smaller vessels or those fishing illegally (Elvidge et al., 2021), which are absent from much of the broad-scale, AIS-monitored vessel analyses (Kroodsma et al., 2018). Thus, we found that when used alongside other data sources such as Automatic Identification Systems (AIS) and Vessel Monitoring Systems (VMS) on ships, VBD data became a powerful tool in the continued monitoring of human activity on the ocean (Ruiz et al., 2019).

4. Conclusions

Collectively, our findings suggest that activity patterns of maritime traffic across the first year of the COVID-19 pandemic were far more complex than indicated by earlier studies. We demonstrate a surprisingly high degree of heterogeneity in responses during 2020, presumably as a result of the asynchronous implementation of restrictions across countries. Activity varied not only between vessel classes, but also became more complex at smaller spatial scales. Global shipping vessel activity patterns largely reflected the rapid changes in demand and supply capability, whereas fishing vessel activity mostly increased during 2020, despite some short-lived declines. Passenger vessels, which are responsible for the transport of larger numbers of humans, exhibited the most widespread reduction at the peak of the anthropause. Nevertheless, our results suggest that examining maritime vessel activity solely on a global scale risks overlooking important regional and vessel class-specific patterns. Continued monitoring of maritime traffic using a multitude of data sources therefore becomes essential, especially when evaluating the long-term impacts of the COVID-19 pandemic on both maritime industries and the marine environment, including its wildlife. Unprecedented access to human mobility data has proven to be a powerful tool for managing the COVID-19 pandemic. If data accessibility and use are promoted beyond the duration of the pandemic, it will significantly improve our understanding of human-environment interactions, helping us pinpoint where, and when, mitigations may be necessary to safeguard vulnerable populations, as well as to support more effective management of future crises.

5. Materials and methods

5.1. Satellite AIS data

Satellite AIS tracking data (see Supplementary Methods for further details on AIS) for shipping (monthly) and fishing (daily) vessels from January–December 2017–2020 were obtained from the Global Fishing Watch (GFW) at $0.1^\circ \times 0.1^\circ$ and $0.01^\circ \times 0.01^\circ$ resolution, respectively. The GFW passes data on vessel characteristics derived from vessel registries through a neural network classifier, allowing for the classification of AIS transmissions by vessel type. The shipping vessel dataset is sorted into 9 classes (bunker, bunker or tanker, cargo, cargo or reefer, cargo or tanker, container reefer, passenger, specialized reefer, tanker), and the fishing vessel dataset is sorted into 16 classes (fishing, squid jigger, drifting longlines, pole and line, trollers, fixed gear [including pots and traps, set longlines and set gillnets], trawlers, dredge fishing and seiners [encompassing purse seines, tuna purse seines, other purse seines, and other seines]).

For this study, fishing vessels were aggregated to 9 classes (fishing, squid jigger, drifting longlines, pole and line, trollers, fixed gear, trawlers, dredge fishing and seiners). Additional details on fishing vessel classification can be found in Supplementary Figure 8 (Global Fishing Watch Datasets and Code, 2023). For fishing vessels, "activity" refers to both the positions of fishing and non-fishing vessels and is therefore not representative of the fishing effort being carried out.

5.2. VIIRS Boat Detection (VBD)

VIIRS Boat Detection (VBD) data were obtained for 2017–2020 from the Earth Observation Group, Payne Institute for Public Policy. The Visible Infrared Imaging Radiometer Suite (VIIRS) is the primary imager on the Suomi National Polar Partnership, a polar-orbiting satellite flown by NASA and NOAA (Elvidge et al., 2021). The VIIRS day/night band (DNB) spectral bandpass spans 0.5 to 0.9 μm, straddling the visible and near infrared, detecting light sources present on the Earth's surface. At night, the DNB maintains a nearly constant pixel footprint of 742 m on a side, with latitude and longitude positions located at the pixel centres. The 'Boat Detection' algorithm developed by Elvidge et al. (2015) filters out any features on land and other unwanted signals, such as gas flares, and assigns each detection a quality flag, yielding information about the quality and type of detection (e.g. QF1 = highest quality detections, QF2 = weaker detections, QF3 = blurry detections, and QF11 = platforms). Environmental factors, such as clouds and moonlight glint interfere with detections, and the South Atlantic Anomaly prevent reliable detections above South America and the southwest Atlantic (Fig. 1c,f, Supplementary Figure 9). At night, VIIRS can only detect vessels that emit light, such as passenger vessels, and fishing vessels that use light to target animals (e.g., squid jiggers). This includes some Small-Scale Fishery Vessels that are not monitored by AIS (Elvidge et al., 2018).

In the present analyses, only VBD data associated with the strongest detections (QF1) were used. VBD time series data were smoothed using a running mean of 28 days, to minimise interference from moonlight.

5.3. Maritime activity and COVID-19

All analyses were run in R 4.1.2, and raster visualisations were carried out in QGIS (3.24.2-Tisler). For all datasets, vessel activity does not represent the number of unique vessels in an area, but instead the spatial extent and relative activity occurring within an area.

To enable clear visualisation of the data at the global scale, GFW fishing and VBD data were re-gridded to a lower resolution ($0.25^\circ \times 0.25^\circ$). Likewise, cargo and passenger data from the GFW shipping dataset were re-gridded to a lower resolution ($0.2^\circ \times 0.2^\circ$). At the global scale, we compared vessel activity during 2020 to the average vessel activity across a baseline period (average yearly vessel locations for each grid cell across 2017–2019). This approach is consistent with other studies examining impacts of COVID-19 (Le Quéré et al., 2020; Liu et al., 2020; March et al., 2021). From the resulting global-change maps, three regions were identified representing important areas of maximum change in maritime vessel activity: the Mediterranean Sea, the North East Pacific Ocean and the North West Atlantic. These areas are also of general importance in terms of human mobility (e.g., recreation, shipping), conservation efforts (e.g., biodiversity and associated ecosystems, recovery areas for damaged ecosystems and vulnerable species), and the intersection of these two activities (e.g., ecotourism, nature-based recreation, reported areas of high fishing pressure). Within these regions of change, absolute and relative vessel activity were examined across three jurisdictional frameworks of varied scale and focus: Exclusive Economic Zones (EEZs; version 10; Flanders Marine Institute, 2019), Food and Agriculture Organization of the United Nations (FAO) Major Fishing Areas (Flanders Marine, 2019), and Marine Protected Areas (MPAs, Supplementary Figure 1; (Website). We selected case studies to showcase (non-exhaustively) the variety of activity patterns observed in these regions across different vessel classes. Where vessel classes are grouped (e.g. fixed gear = pots and traps, set longlines, set gillnets), we followed the hierarchy set out by the GFW. Please see supplementary methods for further detail on these jurisdictional frameworks, and for the full set of results (by vessel class).

We calculated vessel activity as the daily (fishing vessel dataset) or monthly (shipping vessel dataset) total number of unique vessel identifiers present in each grid cell. As vessels can move between multiple grid cells in a day, extents larger than a single grid cell may capture the same vessel multiple times. For VBD, since no unique identifier is associated with detections, vessels cannot be filtered by class.

Temporal variation of global changes in maritime vessel activity was assessed by calculating the total number of vessel detections present in each chosen spatial extent (EEZ, FAO Major Fishing Area, MPA) and quantifying the absolute and relative differences of weekly or monthly activity in comparison with the same reference period in the 2017–2019 baseline, to account for seasonal variability in maritime activities.

5.4. Time series forecasting

We chose the Holt-Winters time series forecasting method chosen because of its capacity to capture seasonality in a dataset (Chatfield, 1978, Winters, 1960, Swapnarekha et al., 2021) to model expected monthly global maritime vessel activity in 2020 based on patterns observed in the three previous years of data (2017–2019). For each vessel class, activity values were separated into training (January 2017–May 2019), testing (June 2019–December 2019), and 2020 (January–December 2020) subsets. The training dataset was decomposed to extract the trend, seasonality and random components (Supplementary Figure 4). Both additive and multiplicative Holt-Winters models were fitted to each training dataset, and the best model for each dataset was selected. A multiplicative model was used to account for increasing long-term trends in the passenger and tanker data, whereas an additive model was used for cargo and container reefer activity data, as the seasonal variation was relatively constant throughout the time series. Models were examined for fit using smoothing functions, and autocorrelation plots informed on the correlation of fitted residuals between points of various temporal separations in the time series. Ljung-Box tests indicated that model residuals were independent and had a normal distribution (Lima et al., 2019). The predictive power of the model was examined by comparing the forecasted data from the training dataset to the test dataset, by visualising the confidence intervals and by calculating Mean Absolute Percentage Error (MAPE) for each vessel class forecast. MAPE is the mean of all absolute percentage errors between the predicted and actual values. A higher MAPE indicates a bigger distance between the forecasts and the model predictions.

The forecast was then compared to the 2020 data to examine how different the first year of the pandemic was to the forecasted activity. Friedman tests were used to compare the distributions of observed data to those of the modelled forecasts for monthly global maritime vessel activity in 2020 for each vessel class to identify whether observed data differed significantly from the forecast (Supplementary Table 2). Tests were two-sided and used an alpha level of 0.05.

6. Data availability

The raw VIIRS Boat Detection (VBD) data are freely available from the Earth Observation Group, Payne Institute for Public Policy at https://payneinstitute.mines.edu/eog/, and the raw fishing vessel data are freely available from the Global Fishing Watch at https://globalfishingwatch.org/. The raw shipping data are available upon reasonable request from the Global Fishing Watch at https://globalfishingwatch.org/. The derived data underlying Fig. 1d–f (Absolute change in vessel activity in 2020 vs the 2017–19 baseline) and from which all other results were calculated will be provided upon publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Author contributions

A.L., C.R. and D.W.S. conceived the project and designed the research. C.D.E., D.A.K. and T.D.W. curated the data. A.L. analysed data, and visualised results. C.R. obtained funding, with input from D.W.S., and C.R. and D.W.S. administered the project. A.K. and Y.R.-C. provided additional project administration. D.W.S. provided supervision. A.L. and D.W.S. wrote the original draft. All authors reviewed and edited subsequent drafts, providing feedback on analyses, interpretation, and presentation.

Appendix A. Supplementary data

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