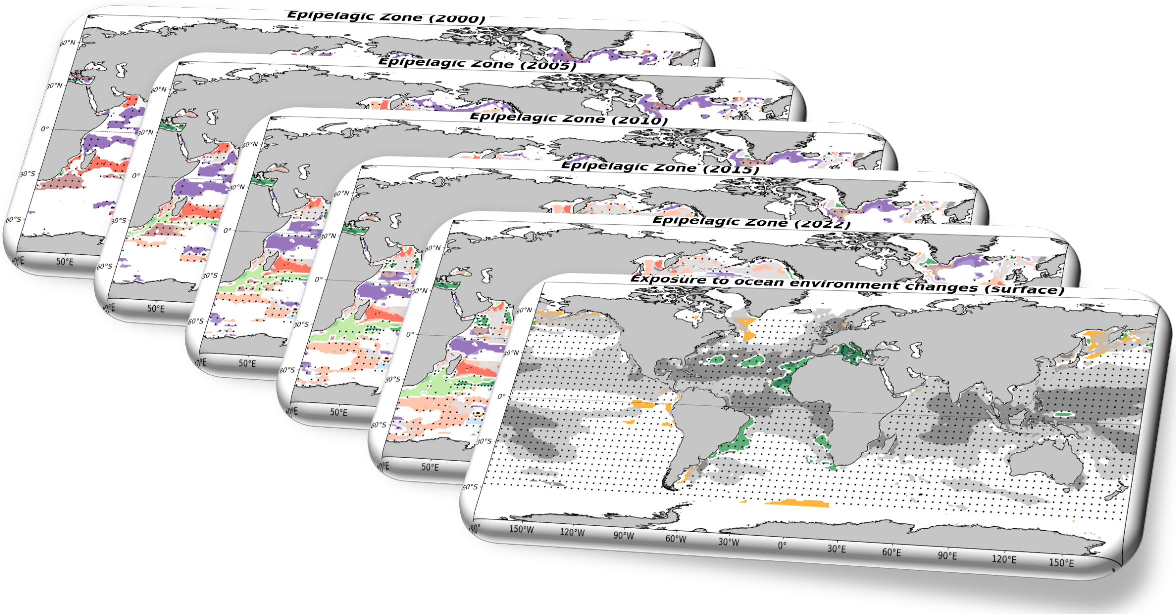
IAP Ocean Compound Climatic impact-drivers (compound CIDs) Monitoring Dataset (v0.1)



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Outline

1. Overview

The IAP Ocean Compound Climatic impact-drivers (CIDs) Monitoring Dataset integrates global, three-dimensional observations of physical and biogeochemical variables to capture long-term, compound ocean state changes with global coverage (1-degree) from the surface to mesopelagic zone. This dataset, combining time-of-emergence (ToE) analyses and exposure metrices from 1960 to 2023 for the concurrent change of **multiple Essential Climate Variables (ECVs) includes ocean temperature, salinity, dissolved oxygen, and surface pH,** provides a robust foundation for assessing the interplay between individual and compound CIDs. This dataset, together with the analysis framework shown in the corresponding paper, can servers as a science-policy interface tool and indicators to facilitate the integration of our understanding of oceanic environmental change with broader knowledge of the compound impacts on the ocean and human societies.

This dataset could offer a unique opportunity for the scientific community to explore the temporal dynamics and regional impacts of these compound changes, and offer the global community, general public and the policy makers a valuable choice to understand the evolution of ocean compound climate change and the compound state. This dataset could also serve as an invaluable monitoring tool for advancing climate studies by the global community, and further raising awareness of the general public, improving the accuracy of Earth system models, and informing policy-relevant assessments such as those conducted by the IPCC, IPBES and WMO.

KEY STRENGTHS:

- ✧ Time of emergence (ToE) for individual and compound CIDs estimation since 1960.
- ✧ Global, gridded dataset of compound climatic impact-drivers at three different layers: surface, epipelagic zone (0-200m) and mesopelagic zone (200-1000m) from 1980-onward.
- ✧ Observational-based analysis: uses several state-of-the-art physical and biogeochemical observational products with consistent estimation methods across different variables.

- ✧ Comprehensive error estimates provided (95% uncertainty range), accounting for instrumental uncertainty, mapping uncertainty, sampling uncertainty, and uncertainty due to the quantification of the ‘signal’ and ‘baseline choice’.

LIMITATIONS:

- ✧ Unable to resolve long-term changes in ocean small-scale processes.

2. Data Information

Format: netCDF

Time: 1980 – onward

Temporal resolution: Annual

Spatial resolution: 1° x 1°

Spatial coverage: Global ocean

Vertical resolution: surface, epipelagic zone (0-200m), mesopelagic zone (200-1000m).

Version: v0.1 (Beta version)

DOI: in preparation [DOI will be available soon]

3. Data description

3.1 File naming convention

We use a standardized file naming convention. For the netCDF files the form is:

- **ToE_compound_[year].nc**

The sections of the names are:

[year]: The calendar year of the data in the file. In this dataset, the year are ranging from 1960 to 2022, with one year interval.

3.2 netCDF Variables

The table below describes the variables that can be found in the netCDF files:

Table 1. The list of the variables and its brief introduction in the IAP Ocean Compound Climatic Impact-Drivers Monitoring Dataset.

netCDF variable	dimension	Description
lon	360x1	The (centre) longitudes of the grid points (degrees)
lat	180x1	The (centre) latitudes of the grid points (degrees)
ToE_compound_surface	360x180	Time of emergence (ToE) of compound climatic impact-drivers in the surface (units: calender year)
ToE_compound_direction_surface	360x180	The ToE direction of compound climatic impact-drivers in the surface layer. See Table 1 for definition.
ToE_compound_significant_flag_surface	360x180	Significant flags of compound emergences at 95% confidence level in the surface layer. See Table 1 for definition.
ToE_compound_epipelagic	360x180	ToE of compound climatic impact-drivers in the epipelagic zone (units: calender year)
ToE_compound_direction_epipelagic	360x180	ToE direction of compound climatic impact-drivers in the epipelagic zone. See Table 1 for definition.
ToE_compound_significant_flag_epipelagic	360x180	Significant flags of compound emergences at 95% confidence level in the epipelagic zone. See Table 1 for definition.
ToE_compound_mesopelagic	360x180	ToE of compound climatic impact-drivers in the mesopelagic zone (units: calender year)
ToE_compound_direction_mesopelagic	360x180	ToE direction of compound climatic impact-drivers in the mesopelagic zone. See Table 1 for definition.
ToE_compound_significant_flag_mesopelagic	360x180	Significant flags of compound emergences at 95% confidence level in the

		mesopelagic zone. See Table 1 for definition.
ToE_pH_surface	360x180	ToE of surface pH
ToE_pH_significant_flag_surface	360x180	Significant flags of surface pH emergence at 95% confidence level
Exposure_level_surface	360x180	Exposure level to the significant emergence of individual and compound CIDs in the surface layer. See Table 2 for definition.
Exposure_type_surface	360x180	Ocean environmental exposure type (which and number of CIDs) in the surface layer. See Table 2 for definition.
Exposure_level_epipelagic	360x180	Exposure level to the significant emergence of individual and compound CIDs in the epipelagic zone. See Table 2 for definition.
Exposure_type_epipelagic	360x180	Ocean environmental exposure type (which and number of CIDs) in the epipelagic zone. See Table 2 for definition.
Exposure_level_mesopelagic	360x180	Exposure level to the significant emergence of individual and compound CIDs in the mesopelagic zone. See Table 2 for definition.
Exposure_type_mesopelagic	360x180	Ocean environmental exposure type (which and number of CIDs) in the mesopelagic zone. See Table 2 for definition.
Exposure_pH_level_surface	360x180	Ocean environmental exposure level score of surface pH.

Here, there are **two sets** of variables:

- **Set #1:** **[ToE_compound_*]** – These variables are used to indicate **the spatial pattern of the time of emergence (ToE) of individual or compound CIDs in different depth layers** (surface, epipelagic zone, mesopelagic zone). Here, the emergence year, emergence directions, and uncertainty estimation (significant level) are provided. These are used to illustrate the Figure 2 in the Tan et al., 2025 (under review). This set is used to **quantitatively** evaluate the compound ocean state change (Table 2).

- **Set #2: [Exposure_*]** – These variables are used to indicate **the spatial pattern of the global exposure of the ocean to the significant emergence of individual and compound CIDs in different layers** (surface, epipelagic zone, mesopelagic zone). Here, the exposure level (low, medium, high) and exposure types (single, double, triple) are provided. These are used to illustrate the Figure 3 in the Tan et al., 2025 (under review). This set is used to **qualitatively** evaluate the compound ocean state change (Table 3).

Table 2. The flags definition in the Set #1 for variables [ToE_compound_direction_*] and [ToE_compound_significant_*]

Variables	Flag	Definition	Comments
ToE direction flag	0	No emergence	/
	1	Only warming emergence	Single emergence
	2	Only salinization emergence	
	3	Only freshening emergence	
	4	Only deoxygenation emergence	
	5	Warming & salinization emergences	Double emergences
	6	Warming & freshening emergences	
	7	Warming & deoxygenation emergences	
	8	Warming & salinization & deoxygenation emergence	Triple emergences
	9	Warming & freshening & deoxygenation emergence	
ToE significant flag	0	Insignificant emergence at 95% confidence level	/
	1	Significant emergence at 95% confidence level	

Table 3. The flags definition in the Set #2 for variables [Exposure_level _*] and [Exposure_type_ *].

	Flag	Definition	Comments
Exposure level	1	Low exposure	Environmental exposure score
	2	Medium exposure	
	3	High exposure	
Exposure type	1	Single CID (Temperature)	Single CID
	2	Single CID (Salinity)	
	3	Single CID (dissolved oxygen)	
	4	Double CIDs (Temperature & Salinity)	Double CIDs
	5	Double CIDs (Temperature & dissolved oxygen)	
	6	Triple CIDs (Temperature & Salinity & dissolved oxygen)	Triple CIDs

You can also check the long_name, units, standard name, values, notes, reference, and the comments for each variable in the netCDF file.

4. Data Access

The data can be found in the following websites:

(1) DOI: **In preparation [Notes for peer review: DOI will be provided before the final publication]**

(2) IAP website (http), including all data and most recent update: http://www.ocean.iap.ac.cn/ftp/cheng/Compound_CIDs/

(3) ToE **evolution video** from 1980 to 2023 could be accessed here: http://www.ocean.iap.ac.cn/ftp/cheng/Compound_CIDs/dynamic_video/

In addition, we also provide some **scripts to visualize the dataset** and reproduce the text figures (e.g., Figure 1 and Figure 2). The scripts can be accessed here via the Code Ocean https://doi.org/10.24433/CO.6650239.v1 and http://www.ocean.iap.ac.cn/ftp/cheng/Compound_CIDs/script_demo/

We also provide **a dashboard** to show the **dynamic evolution** (since 1980) of compound CIDs here: http://www.ocean.iap.ac.cn/

The above materials could be also accessed in the GitHub repository: https://github.com/zqtzt/Compound_ocean_climate_change

5. Dataset citation

Tan Z., K. von Schuckmann, S. Speich, L. Bopp, J. Zhu, L. Cheng*., 2025: Observed large-scale and deep-reaching compound ocean state changes over the past 60 years. *Nature Climate Change*.

6. Dataset guidance

6.1. A brief introduction on the methods

The IAP Compound CIDs dataset is a gridded ocean compound climatic impact-drivers (CIDs) product with complete global ocean coverage and full depth from surface to 1000m. This dataset can serve as a valuable resource for the deepening understanding of compound climate change by the global community, and further raising awareness of the general public, improving the accuracy of Earth system models, and informing policy-relevant assessments.

The 'Climatic impact-drivers (CIDs)' refers as the *physical climate system conditions (e.g., means, trends, extremes) that affect an element of society or ecosystems and their changes can be detrimental, beneficial, neutral or a mixture of each across interacting system elements and regions* (IPCC, 2022). In the ocean sector, CIDs include ocean temperature, ocean salinity, dissolved oxygen, pH, marine heatwaves, etc. In this dataset, the term 'compound CIDs' is defined as multiple CIDs occurring simultaneously, which may have complex relationships and interactions, such as through joint relationships, causal relationships, and composite relationships. They may exhibit complex interactions that can potentially affect the ocean by exacerbating or sometimes reducing the overall effects, thus posing challenges to the ocean. This could be illustrated by the simultaneous emergence regions (i.e., the double emergence and triple emergence), where the time of emergence (ToE) of more than one CID can be detected when their signals have all already emerged from their respective climatic backgrounds.

We mainly used the IAP gridded products (observational-based) to construct this dataset. The IAP temperature grid product (Cheng et al., 2024) is available at http://dx.doi.org/10.12157/IOCAS.20240117.002 (1-degree). The IAP salinity grid product (Cheng et al., 2020) is available at http://www.ocean.iap.ac.cn/ (1-degree). The IAP dissolved oxygen product is available at http://dx.doi.org/10.12157/IOCAS.20231214.006. For surface pH, we mainly used the Copernicus Marine Service - Global Ocean Surface Carbon product and OceanSODA-ETHZ product (Chau et al., 2020; Gregor and Gruber et al., 2021), which are available at https://doi.org/10.48670/moi-00047 and https://doi.org/10.5194/essd-13-777-2021. The Institute of Atmospheric Physics (IAP) provides this dataset through several innovative steps:

- Firstly: calculate the time of emergence (ToE), which refers to the time when the long-term signal emerges from the background noise and never falls back again into the noise threshold, for each variable and then identify when and where the signal of an individual CID has emerged from the noise level before 2023. Here, we define it as 'individual emergence'.

- Secondly, define regions and time where multiple CIDs emerge simultaneously and refer to them as 'double emergence' and 'triple emergence', respectively, following the approach that the ToE of more than one CID can be detected if the signal of these CIDs has already emerged (Fig. 1).
- Thirdly, estimate the intensity, duration, and magnitude of double emergence or triple emergence. This is to indicate how strong, how long, and how fast the individual or compound signal has changed since it emerged from the noise background.
- Finally, the ocean exposure to the long-term changes of compound CIDs emergence is estimated based on the classification of the intensity, duration, and magnitude of emergence (Fig. 2). The ocean exposure is shown in different categories (high, medium, low).

The above method was used to estimate the ocean state annually from 1960 to 2022.

The uncertainty of all these metrices is defined by using the 95% confidence level, taking into account the reconstruction uncertainty (sampling uncertainty and mapping uncertainty), instrumental uncertainty, and uncertainty due to baseline choice and decadal variability in quantifying the 'signal'.

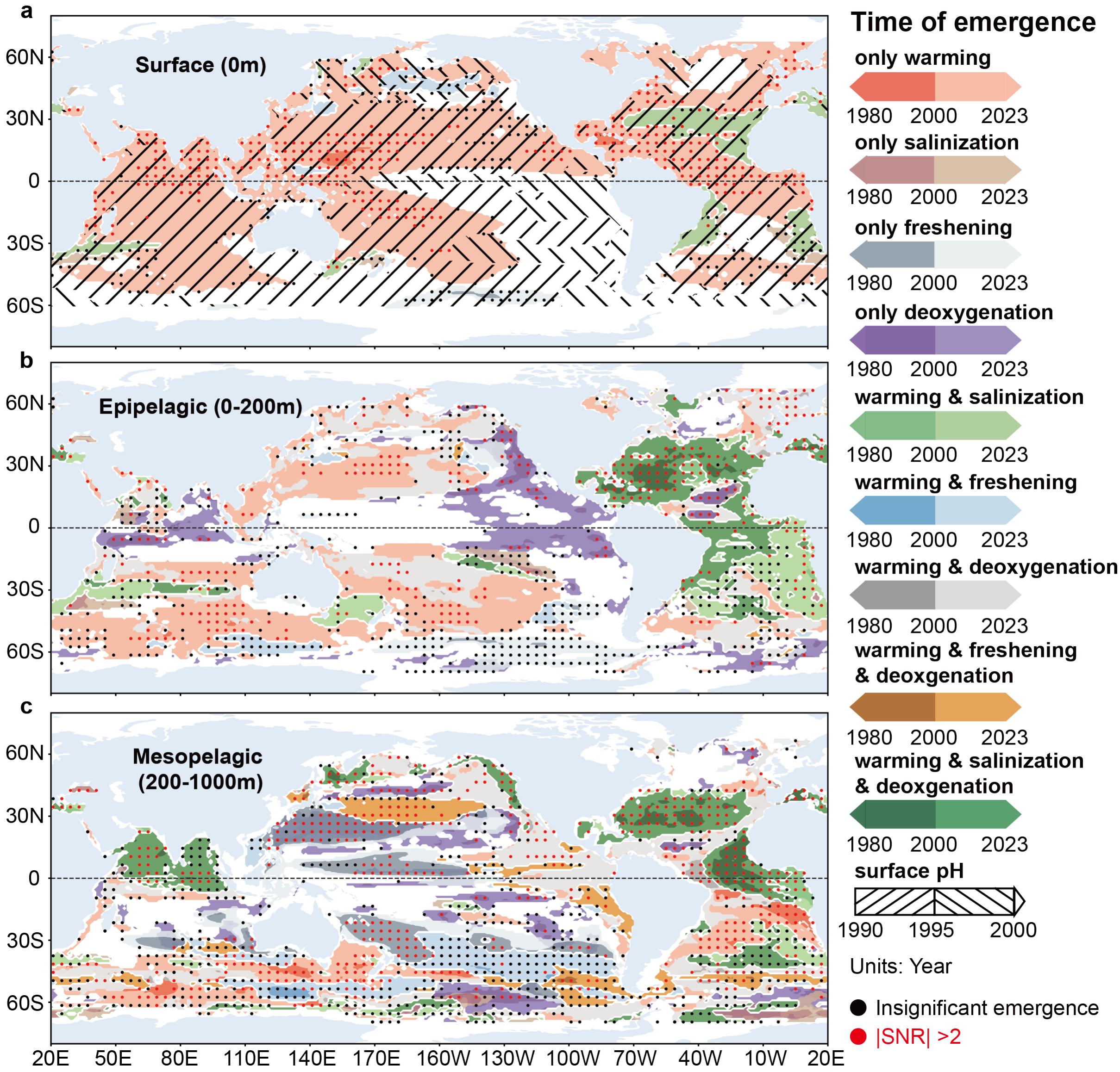

Figure 1. Global maps of the "transition time" and "direction" of compound state changes in the upper 1000 m, based on temperature, salinity, dissolved oxygen, and surface pH, with Time of Emergence (ToE) referenced to the 1960–1989 climatology: (a) surface, (b) epipelagic zone (0–200 m), and (c) mesopelagic zone (200–1000 m). Different color shadings denote different climatic impact-drivers concurrent change (e.g., warming & salinification & deoxygenation), and shading intensity (i.e., light or dark) indicates the onset year of the compound state change. Red dots mark regions (signal-to-noise ratio greater than 2) where the amplitude and complexity of the state change are much greater than other regions, which may potentially exceeding historical experience and existing classification schemes. Black dots indicate changes are not significant at the 95% confidence level. ToE for surface acidification (pH) is depicted separately with black hatching.

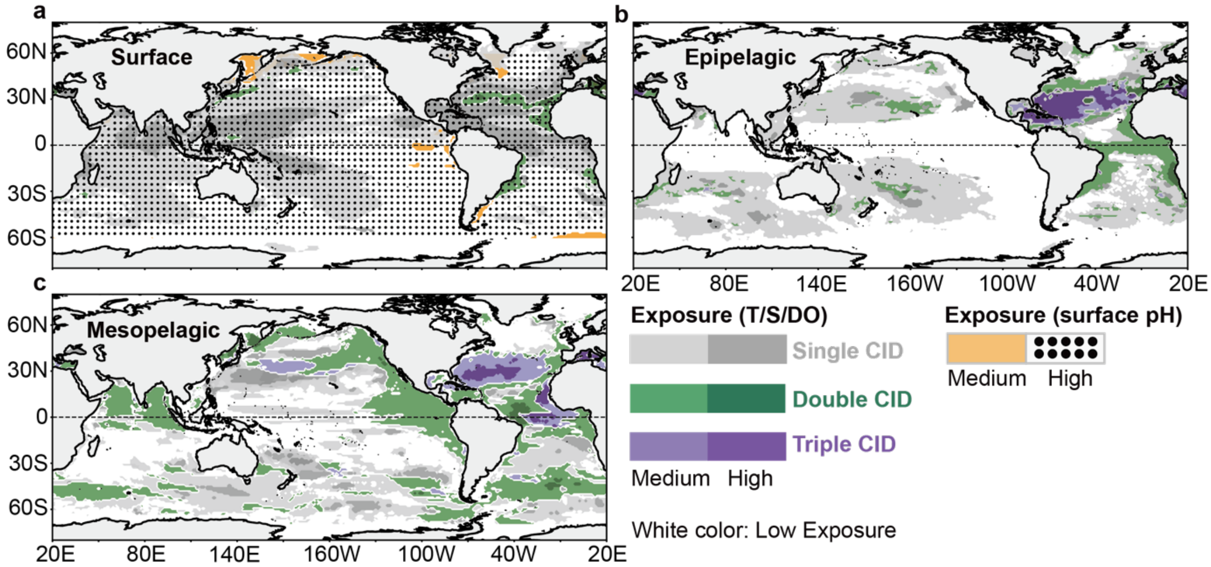

Figure 2. Global map of exposure of the ocean to compound state changes in four compound climatic impact-drivers (temperature, salinity, dissolved oxygen, and surface pH) since 1960: (a) surface (0 m), (b) epipelagic zone (0–200 m), and (c) mesopelagic zone (200–1000 m). White areas denote low exposure.

7. Scientific findings

We used this product to determine when oceanic long-term changes became detectable over large ranges of datasets and identified the regions most affected by this shift. Specifically, we found that the volume of the ocean, which has experienced concurrent changes in CIDs, has increased substantially over the last 60 years: over 30% of the global ocean is already experiencing compound emergence from at least two CIDs in various areas of the global ocean, especially in the subsurface layer. Critical regions that have experienced dramatic compound changes are also identified, such as the subtropical Atlantic Ocean, the tropical Atlantic Ocean, the Mediterranean Sea, and the Arabian Sea.

8. References

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