Strengthened Ocean-desert Process in the North Pacific over the Past Two Decades

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Introduction: Ocean Desert

North Pacific Ocean Desert (NPOD)

1. Their immense size (they occupy ~40% of low-latitude ocean area)

2. The carbon exported from the surface to the deep ocean.

3. Long-term variation

Figure 1: Global ocean surface mean Chl-a concentration from 1998 to 2018. The red dashed line represents the 0.07 mg/m³ contours of Chl-a, the boxes delimited by the blue dashed lines is the study area.
**Introduction: long-term variation ocean desert**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Journal</th>
<th>Time Range</th>
<th>Change in Mean Chl-a</th>
<th>Change In Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>McClain et al., 2004</td>
<td>Deep-Sea Research II</td>
<td>1996-2003</td>
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<td>Gregg et al., 2004</td>
<td>Geophysical Research Letters</td>
<td>1998-2003</td>
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<td>Behrenfeld et al., 2006</td>
<td>Nature</td>
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<td>Polovina et al., 2008</td>
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<td>Charles et al., 2009</td>
<td>Deep Sea Research Part II</td>
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<td>Boyce et al., 2010</td>
<td>Progress in Oceanography</td>
<td>1960-2008</td>
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<td>Babula et al., 2014</td>
<td>Deep-Sea Research I</td>
<td>1998-2010</td>
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</tbody>
</table>

*Based on a combined, longest dataset of Chl-a*

We investigate the deseasoned variations of NPOD during Year 1998 to 2018.
Introduction: potential factors

Figure 2 Map of areas with concomitant parallel or opposite changes of Chl and SST, as indicated between 1999 and 2004.

Gregg et al (2005)

1 - SST (sea surface temperature)
2 - WS (wind speed)
3 - SSH (sea surface height)
4 - PRE (precipitation)
5 - AOD (Aerosol Optical Depth)
6 - PAR (photosynthetically active radiation)

Elodie et al (2005)
Data

Chl-a:

Moderate-Resolution Imaging Spectroradiometer (MODIS)

Sea-viewing Wide Field-of-view Sensor (SeaWiFS)

spatial resolution: 1/12°

temporal resolution: 1 day

January 1, 1998 --- December 31, 2018 (a total of 21 years)
Figure 3 (a) NPOD geographical region (dashed black curve), and the color shadings show global ocean surface mean Chl-a concentration (b) Comparison of monthly surface Chl-a concentration retrieved by SeaWiFS and MODIS-Aqua during 2003–2007 in five ocean deserts (c) Time series of monthly Chl-a concentrations in global ocean deserts area (the black dashed line in a) retrieved by SeaWiFS (light blue curve for raw data; blue curve for merged data) and MODIS-Aqua (red curve).

$$\alpha_{lon} = \frac{\sum_{i=1}^{n} C_{chl-a} l_{lon}}{\sum_{i=1}^{n} C_{chl-a}}$$

$$\delta_{lat} = \frac{\sum_{i=1}^{n} C_{chl-a} l_{lat}}{\sum_{i=1}^{n} C_{chl-a}}$$
# Data and method

## Table S1. Details of all data description

<table>
<thead>
<tr>
<th>Variable</th>
<th>Source/Product</th>
<th>Unit</th>
<th>Temporal Resolution</th>
<th>Spatial Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorophyll-a (Chl-a) Concentration</td>
<td>SeaWIFS &amp; MODIS Level-3 Standard Mapped Images</td>
<td>mg m⁻³</td>
<td>Daily</td>
<td>~0.09°×0.09°</td>
</tr>
<tr>
<td>Sea Surface Temperature (SST)</td>
<td>NOAA optimum interpolation (OI) SST, V2</td>
<td>°C</td>
<td>Monthly</td>
<td>1°×1°</td>
</tr>
<tr>
<td>Precipitation (PRE)</td>
<td>European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 monthly, averaged data on single levels</td>
<td>mm day⁻¹</td>
<td>Monthly</td>
<td>0.25°×0.25°</td>
</tr>
<tr>
<td>Photosynthetically Active Radiation (PAR)</td>
<td>MODIS Level-3 Standard Mapped Images</td>
<td>einstein m⁻² day⁻¹</td>
<td>Monthly</td>
<td>~0.09°×0.09°</td>
</tr>
<tr>
<td>Sea Surface Height (SSH) Relative to Geoid, Wind Speed (U10)</td>
<td>National Centers for Environmental Prediction (NCEP)</td>
<td>m, m s⁻¹</td>
<td>Monthly</td>
<td>0.25°×0.25°</td>
</tr>
<tr>
<td>Horizontal Velocity Components (u,v), Temperature (T), Salinity (S) and Mixed Layer Depth (MLD)</td>
<td>Simple Ocean Data Assimilation version 2 (SODA)</td>
<td>m s⁻¹, °C, m</td>
<td>Monthly</td>
<td>0.2°×0.2°</td>
</tr>
<tr>
<td>Nutrients (N+P) Concentration</td>
<td>World Ocean Atlas 2013 (WOA 2005)</td>
<td>µmol L⁻¹</td>
<td>Monthly</td>
<td>1°×1°</td>
</tr>
<tr>
<td>Aerosol Optical Depth (AOD)</td>
<td>MODIS Level-3 Standard Mapped Images</td>
<td></td>
<td>Monthly</td>
<td>~0.09°×0.09°</td>
</tr>
</tbody>
</table>

**Nutrients (N + P) concentration**

**Mixed Layer Depth (MLD)**

**Horizontal velocity components, temperature, salinity data**

**A 1D K-Profile Parameterization (KPP) model**
Results and discussion: intensity and area of NPOD

The largest ocean desert globally is the North Pacific Ocean Desert (NPOD).

**Figure 4** Trends of intensity and area of the North Pacific Ocean Desert (NPOD).

- Oligotrophication: $-2.1 \times 10^{-4} \text{mg m}^{-3} \text{yr}^{-1}$ ($-0.43 \% \text{yr}^{-1}$)
- Expansion: $13.5 \times 10^4 \text{km}^2 \text{yr}^{-1}$ (around 0.9 \% \text{yr}^{-1})
Results and discussion: intensity and area of NPOD

Figure 5 Rates of 10-year sections in Chl-a concentration Changes of the NPOD

Figure 6 Climatological mean area (bar chart, left axis) and area change (line chart, right axis) with different thresholds.
Results and discussion: potential factors

Figure 7 (a) North Pacific Ocean Desert (NPOD) geographical region (dashed black curve), and the color represents the dominating factor of Chl-a variation. (b-e) Deseasoned time series of Chl-a concentration are correlated with the deseasoned sea surface temperature and sea surface height in NPOD.
Results and discussion: oscillation of NPOD position

Figure 8 (a) correlation coefficient between the PDO Index and deseasoned Chl-a time series. (b, c) Time series of PDO Index and NPOD central position

Pacific Decadal Oscillation (PDO)

‘horseshoe’ pattern of SST

Chl-a change at boundaries

northwest-southeast oscillation

Figure 8 (a) correlation coefficient between the PDO Index and deseasoned Chl-a time series. (b, c) Time series of PDO Index and NPOD central position
Results and discussion: Linkage of NPOD to ocean physics

vertical stratification

Temperature gradient
Density gradient
Mixture Coefficients (KM) in KPP model
Mixed layer depth (MLD)

Figure 9 Temperature gradient and density gradient in NPOD.

Figure 10 Impact of sea surface temperature (SST) variation on the NPOD oligotrophication
Conclusion

Oligotrophication

Expansion

NW-SE oscillation

SST SSH

PDO precesses

Figure 11 Schematic of the interactive mechanism between the North Pacific Ocean Desert (NPOD) and multiple climate factors.
Figure 12 Oligotrophication processes in different month.

Figure 13 Spatial (a) and temporal (b-e) changes of the SIOD, SPOD, NAOD and SAOD intensity.
Thanks for your attention