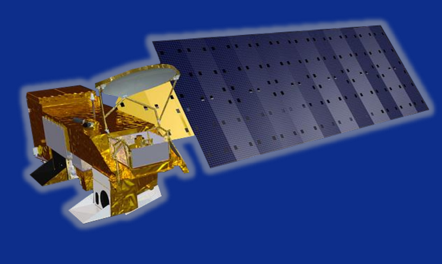

NASA Satellite: **MODIS-Aqua**

20-yr Monthly Global Maps of MODIS-Aqua Products

Drivers of Temporal Variability in Ocean Iron Stress in HNLC Regions using Ocean Color and Climate Modes

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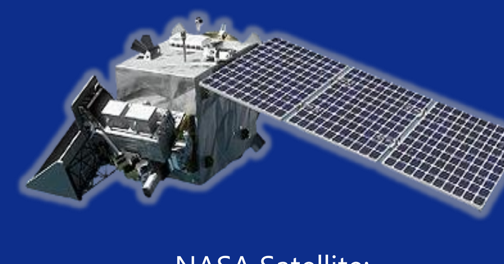

NASA Satellite: **PACE**

Motivation

- Phytoplankton are microscopic plants that carry out photosynthesis, produce 50-80% of Earth's oxygen, and is food for marine animals.
  - Photosynthesis requires micronutrient iron
  - Over 1/3 of the global ocean is iron limited (HLNC)
  - Ocean warming is predicted to limit iron supply
    - Impact oxygen supply & marine resources

13 CLIMATE ACTION — Monitor long-term climate change impacts on phytoplankton

14 LIFE BELOW WATER — Conserve marine resources for future ocean health

- Ship-based time-series measurements of dissolved Fe from high nutrient low chlorophyll (HNLC) regions (Equatorial Pacific, Subarctic N. Pacific, and Southern Ocean) are limited to nonexistent.
- **Objective: To determine the temporal variability (interannual & seasonal) of NPQ-corrected ϕ_{sat} (Eq 1), a satellite remote sensing-based estimate of phytoplankton iron (Fe) stress, across HNLC regions with related climate modes and other satellite remote-sensed products.**

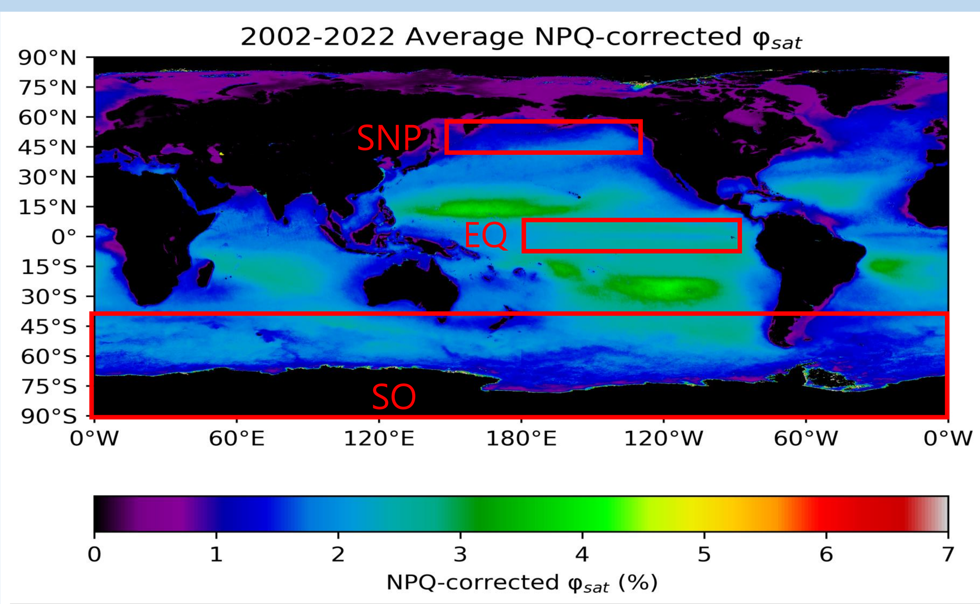

Figure 1. Global 20-yr average NPQ-corrected ϕ_{sat}. HNLC regions (red boxes) are nutrient replete, Fe limited, sunlit waters with relatively low rates of biological production/export. Subtropical gyres have chl<<0.1 or other nutrient stresses.

Background

- Phytoplankton pigments absorb light for photosynthesis, but excess light is fluoresced and emitted as red (675 nm).
  - Fluorescence is also an indicator of chlorophyll (chl) concentration, photosynthetic rates, and physiological status[1, 2, 7] (Eq 2).
- High fluorescence yields are associated with physiological and nutrient stress in phytoplankton[8].
- By correcting for (1) pigment concentration, (2) photoprotective response or nonphotochemical quenching (NPQ, heat dissipation), and (3) pigment packaging, **NPQ-corrected ϕ_f can be derived as a proxy for Fe stress** [1, 7].
- Under non-macronutrient-stressed conditions (N and P abundance), iron stress in Chl increases fluorescence quantum yields (ϕ_f)[1, 5].
- Satellite-derived ϕ_{sat} can indicate phytoplankton Fe stress [1].

Equations

Eq 1: $\textbf{NPQ}-\textbf{corrected}\ \phi_{sat} = 0.00043\,\frac{nFLH * IPAR}{Chl^{0.684}} * 100$

Eq 2: Fluorescence (F)=iPAR$*$Chl$*a^{*}_{phyto}*\phi_f$

- ***iPAR*:** Instantaneous photosynthetically available radiation
- a^{*}_{phyto}: chl−specific phytoplankton absorption coefficient
- ϕ_f (phi): Quantum yield of fluorescence
  - Ratio of light fluoresced by chlor-a pigments to total light absorbed by phytoplankton

Eq 3: $Particulate\ Carbon\ (PC) = PIC + POC$

Eq 4: $Coefficient\ of\ variation\ (CV) = \frac{std\ dev}{average} * 100$

Eq 5: $SST_{anomaly} = SST_{month} - SST_{monthly\ 20-yr\ average}$

Acknowledgements

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Results and Discussion

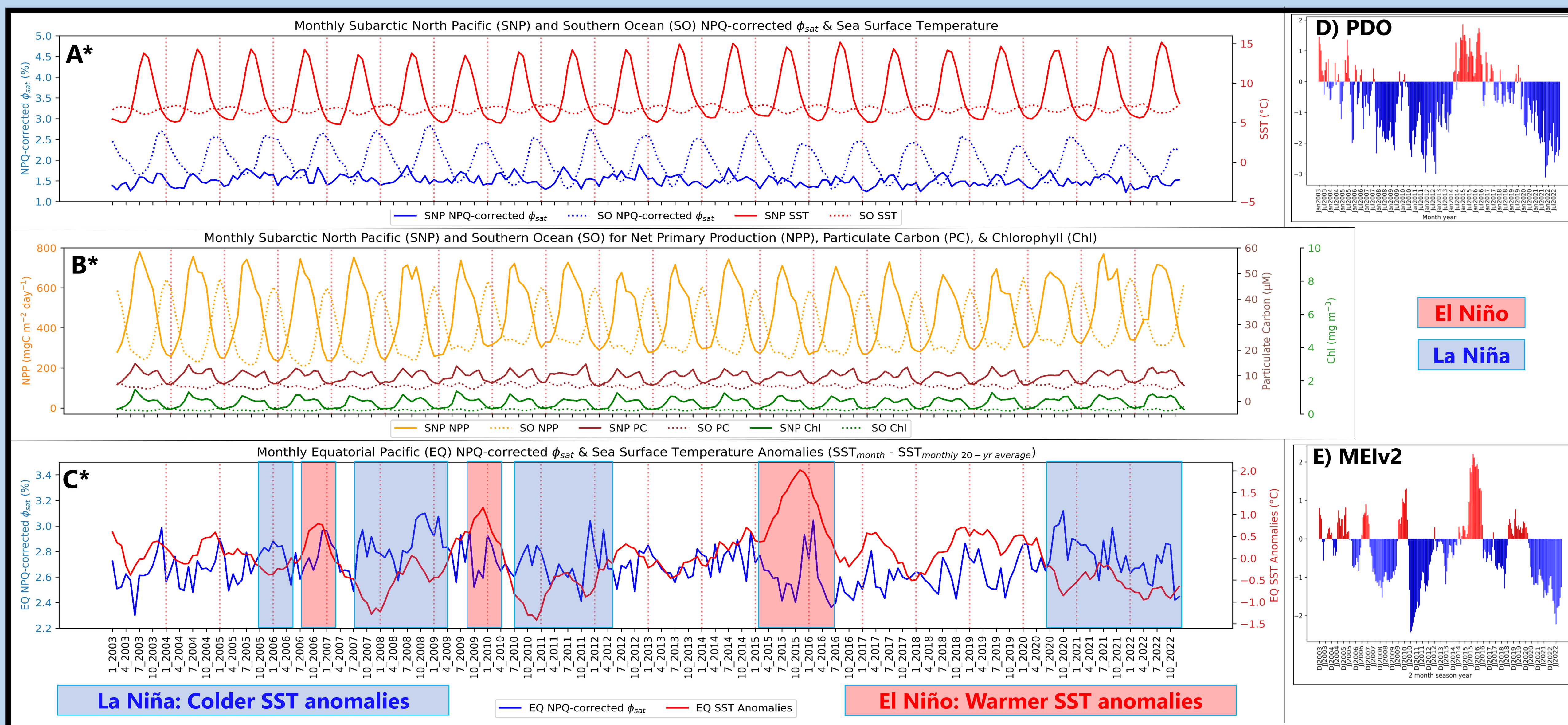

*Figure 2. Monthly (**A**) NPQ-corrected ϕ_{sat} and SST by SNP (solid line) and SO (dotted line); (**B**) NPP, PC, and chl by SNP and SO; (**C**) EQ NPQ-corrected ϕ_{sat} and SST anomaly; (**D**) PDO; (**E**) MEIv2 climate modes for 2002-2023. *Vertical dotted lines are one-year increments.*

- ***No secular trends in Fe stress** (Blue lines). **SNP and SO are subject to seasonal cycles**. SNP sea ice impact during November-March with a freshwater cap/stratification that prevents convective mixing in the winter[10].* East SNP gets more Fe inputs than west SNP[10]. *SO sea ice impact during April-October.*
- ***EQ Fe stress is tied to El Niño-Southern Oscillation (ENSO);** greater Fe stress with La* Niña events (colder SST anomalies); **El Niño 2015 (exception) had a lagging elevated Fe stress response with warmer SST anomalies.**

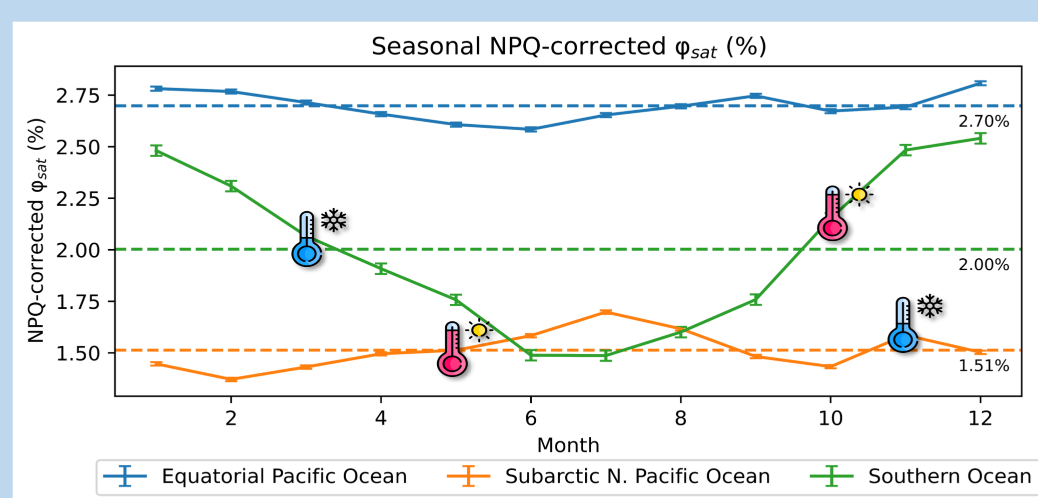

Figure 3. Seasonal NPQ-corrected ϕ_{sat} by HNLC. Winter starts. Summer starts.

Table 1. Seasonal statistics.	EQ	SNP	SO
Ave φ_{sat} (%)	2.70	1.51	2.00
Std Dev	0.16	0.13	0.39
Std Err	0.01	0.01	0.03
CV (%)	**5.76**	**8.51**	**19.56**

Fe stress: EQ>SO>SNP
- SNP peaks in July (summer)
- SO peaks in Dec (summer)

Fe stress variability: SO>SNP>EQ
- SO: highest variability (19.56%)
- EQ: highest stability (5.76%)

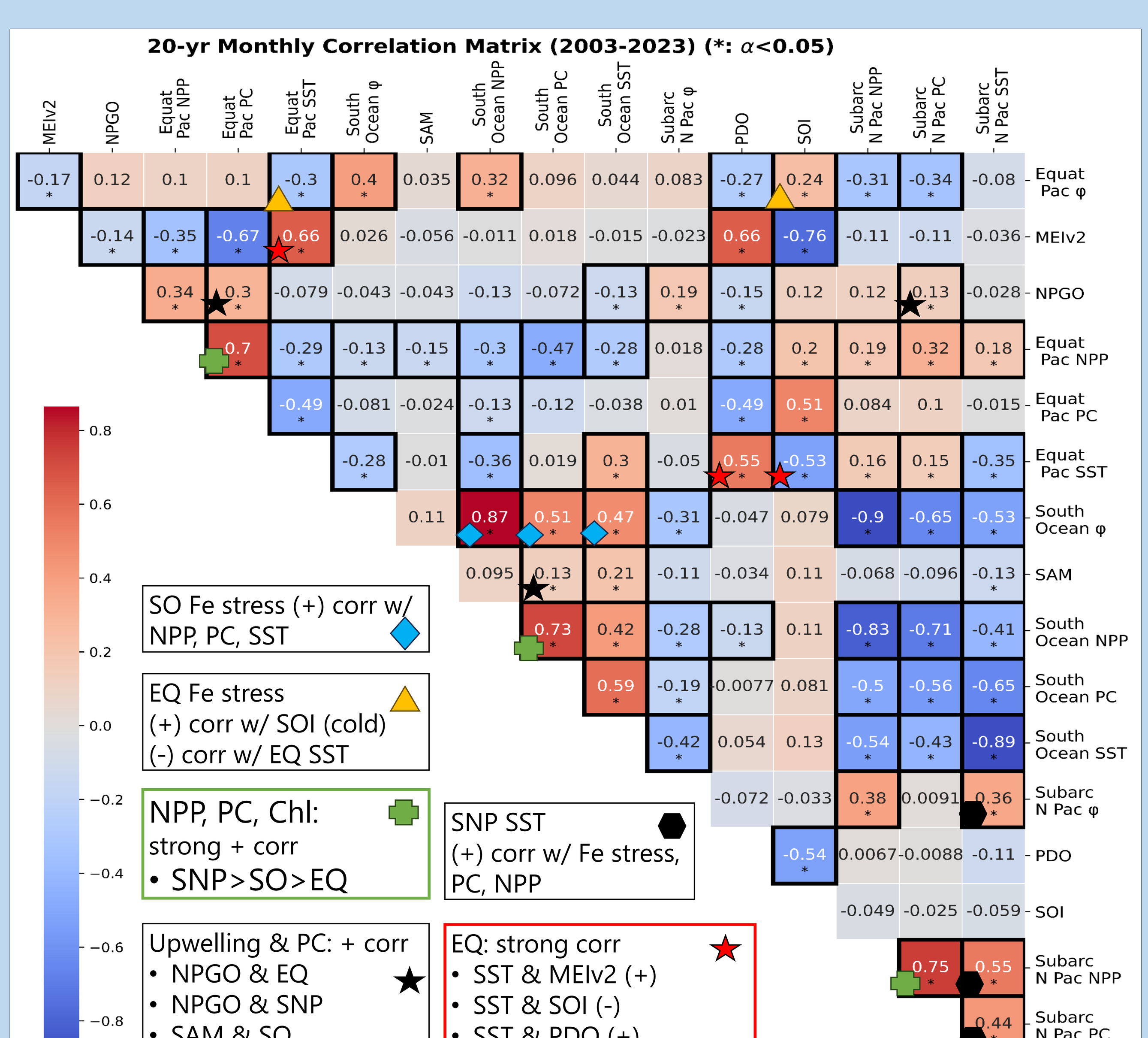

Figure 4. Matrix of Pearson's correlation (r) at α<0.05 significance level (*).

- In the EQ, Fe stress decreases as SST increases (positive phase MEIv2 & PDO; negative phase SOI)
  - **Fe stress driven by La Niña periods** (colder SST) (Fig. 2C).
  - No correlation among NPP and PC with Fe stress (Fig. 4).
- In the SNP and SO, as SST increase, NPP & PC increases, which increases Fe stress as nutrients are taken up (Fig. 2A).
  - Seasonal wintertime reduced Fe stress.
- As upwelling increases (+NPGO) in SNP, stimulated phytoplankton blooms contribute to higher dissolved Fe uptake and increased Fe stress following Fe depletion.
  - Previous research for the EQ found upwelling supplies Fe, thus, reducing Fe stress and increasing chlorophyll concentrations[3].
  - Our analysis expands this: **following nutrient input (upwelling) and/or seasonal warming, Fe stress may temporarily decrease, but it increases at carrying capacity.**
- Higher stability and minimal seasonal variability in the EQ may select phytoplankton with lower Fe requirements, while polar regions have greater seasonal shifts that cause restructuring of the phytoplankton community[3, 5].

Conclusions

1. Fe stress varies interannually based on supply, use, & SST.
2. Seasonal summer cycle (↑ SST, ↑ NPP) enhances Fe stress in high latitudes at carrying capacity with respect to Fe supply.
   - Upwelling phase correlated with Fe stress in SNP.
3. Lowest Fe stress in SNP, but highest PC & NPP, indicates more Fe input supply than EQ & SO.
4. Highest Fe stress variability in SO due to sea ice cover
5. Cooler SST/ La Niña cycle drives Fe stress in EQ
6. EQ has the highest Fe stress and high NPP, but lowest PC, indicating faster carbon cycling.
7. Not all variation can be explained by climate modes
   - i.e. phytoplankton taxonomic composition, accessory pigmentation, physical circulation, and Fe inputs[10].

Future Work

- Focus on localized limitation in narrower latitudinal bands.
- Conduct validation tests of NPQ-corrected ϕ_{sat} with cruise data.
- Tease out changes in phytoplankton community composition as adaptation and community shifts occur due to ocean warming and environmental responses with NASA's satellite **PACE** (Plankton, Aerosol, Cloud, ocean Ecosystem).

Methodology and Analysis

HNLC regions

- **SNP**: Subarctic North Pacific:
  - 60°N-40°N: 140°E-120°W
- **EQ**: Equatorial Pacific Ocean:
  - 10°N-10°S: 180°E-85°W
- **SO**: Southern Ocean:
  - 40°S-90°S

Monthly, Seasonal, Interannual Analysis

- Monthly averages by HNLC region (Fig. 2)
- Monthly 20-yr averages for HNLC regions (Fig. 3)
- Seasonal statistics (Table 1)
- Linear correlation coefficients with Pearson's correlation (r) at a α<0.05 significance level (Fig. 4)

Climate Modes

PDO: Pacific Decadal Oscillation: ~SNP
- SST EOF
- +: El Niño & – : La Niña

NPGO: North Pacific Gyre Oscillation: ~SNP
- SSH EOF
- +: Upwelling & –: Downwelling

SOI: Southern Oscillation Index: ~EQ
- SLP difference btw Tahiti and Darwin
- +: La Niña & – : El Niño

MEIv2: Multivariate ENSO Index: ~EQ
- SST, SLP, wind (U & V), outgoing thermal radiation EOF
- +: El Niño & – : La Niña

SAM: Southern Annular Mode: ~SO
- Zonal sea level pressure (SLP) means at 40°S and 65°S
- +: Upwelling & –: Downwelling

MODIS-Aqua Products

Two decades (2003-2022) of Moderate-resolution Imaging Spectroradiometer **(MODIS)-Aqua** mapped monthly Level-3 products at 9 km spatial resolution from NASA ocean color (*http://oceancolor.gsfc.nasa.gov*)

- **Chl_{sat}**: mg chl m^{-3} (Detection limit <<0.1)[4]
- **$iPAR_{sat}$**: μmol photons $m^{-2}\ s^{-1}$
- **$nFLH_{sat}$**: mW $cm^{-2}\ \mu m^{-1}\ sr^{-1}$
  - (Detection limit <0.003)[6]
  - normalized fluorescence line height
- **PIC_{sat}** : particulate inorganic carbon (μM)
- **POC_{sat}** : particulate organic carbon (μM)
- **SST_{sat}** : sea surface temperature (°C)
- **NPP_{sat}** : net primary productivity (mg C $m^{-2}\ day^{-1}$)
  - CAFÉ algorithm[9].