# Coastal upwelling off the California coast – a satellite perspective

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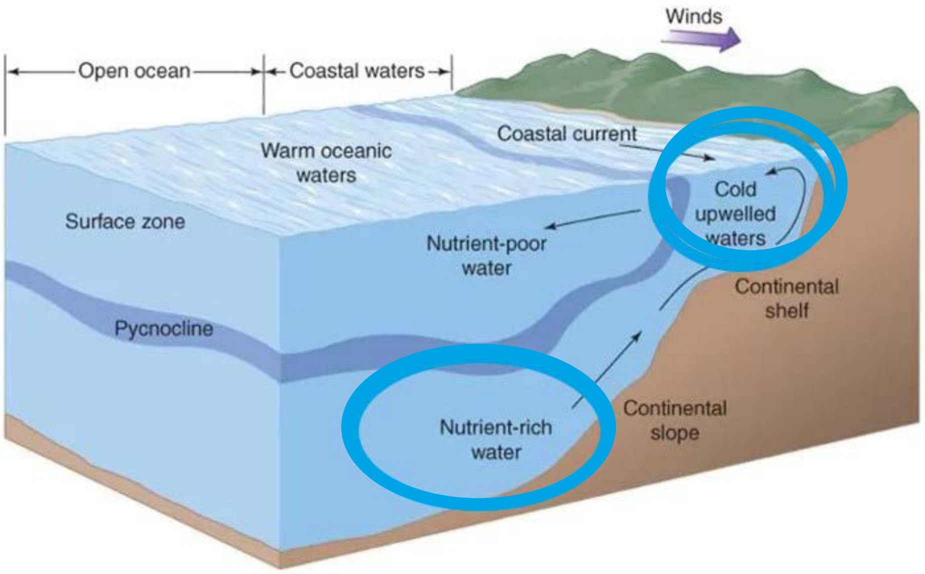
*Photo by Dennis Schroeder, NREL 40462*

# California has abundant fish resources through wind-driven coastal upwelling



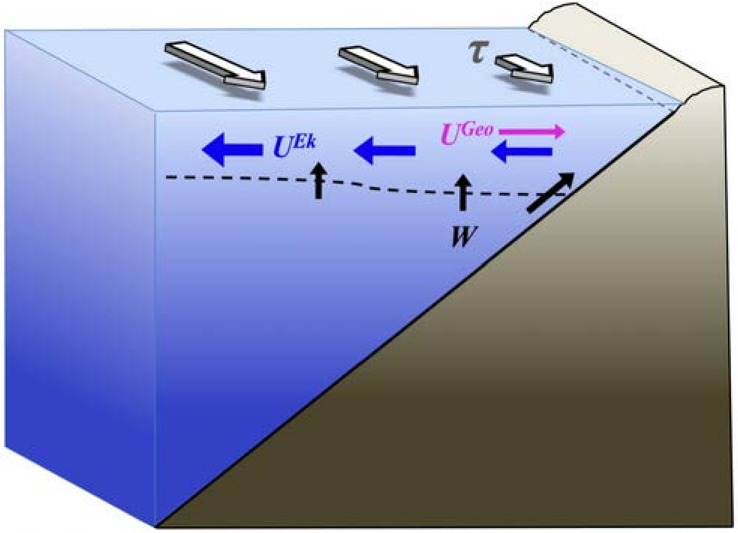
Coastal upwelling in the Northern Hemisphere

- Will upwelling strength change through future offshore wind farms?
- A first step to answer this question is **describing the naturally occurring coastal upwelling in California through observations.**

https://medium.com/geekculture/classifying-coastal-upwelling-using-environmental-variables-8e648d909170

# Quantifying coastal upwelling

- Quantifying the vertical velocity of the Ocean is hard (and very few measurements available)
- Therefore, **upwelling indices** have been developed
- Basic principle: near-surface offshore water transport ($U^{Ek} + U^{Geo}$) equals upwelled water transport $W$




Jacox 2018: doi 10.1029/2018JC014187

# Quantifying coastal upwelling

Benchmark: **Upwelling index CUTI** (Jacox, 2018) **based ocean reanalysis data**

$$\mathrm{CUTI} = U^{\mathrm{Ek}} + U^{\mathrm{Geo}}$$

$U^{\mathrm{Ek}}$: Ekman transport, cross-shore
$U^{\mathrm{Geo}}$: Geostrophic transport, cross-shore

$$U^{\mathrm{Ek}} = \frac{\tau^{\mathrm{along}}}{\rho_0 \cdot f}$$

$$U^{\mathrm{Geo}} = \mathrm{MLD} \cdot u^{\mathrm{geo,\ cross}}$$

$\tau^{\mathrm{along}}$: Wind stress, along-shore
$\rho_0$: Ocean density
$f$: Coriolis parameter
MLD: Mixed layer depth

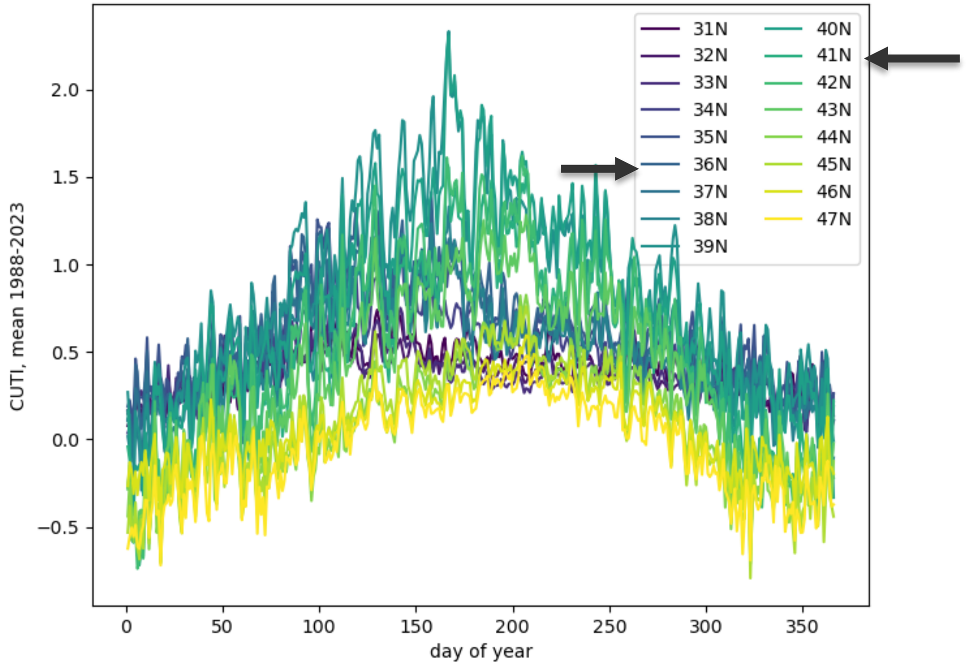
CUTI: **C**oastal **U**pwelling **T**ransport **I**ndex, unit: $\frac{m^2}{s} = \frac{volume}{time * costline}$

Jacox 2018: doi 10.1029/2018JC014187, CUTI: Coastal Upwelling Transport Index

# Model CUTI: Upwelling is strongest in summer and between 34$^o$N and 44$^o$N

- CUTI is available from reanalysis data at 1$^o$ resolution along the California coastline 1988-2023.
- **Can we characterize coastal upwelling with satellite observations?**

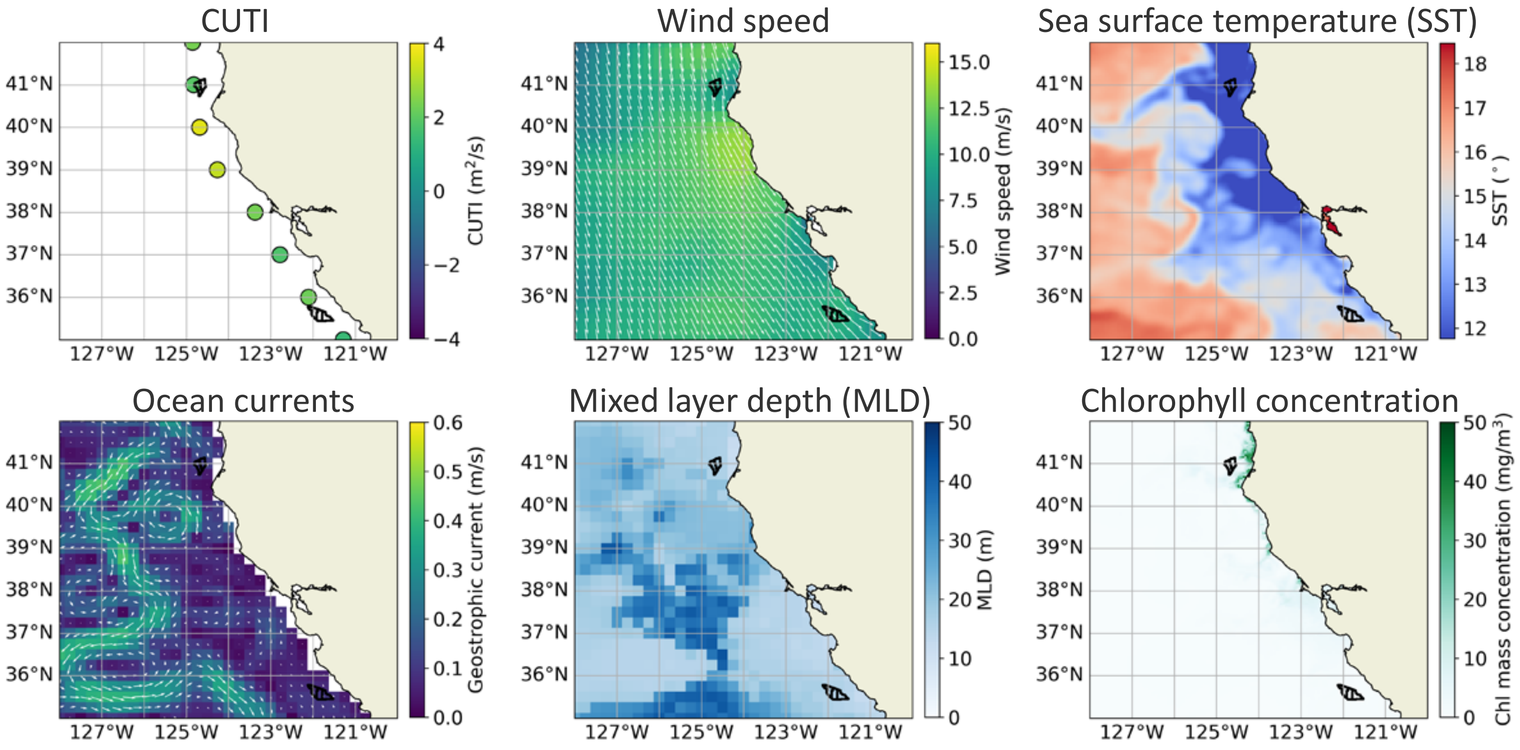
Model CUTI at the California coast




Jacox 2018: doi 10.1029/2018JC014187

# Satellite observations: example day with strong upwelling

**July 23, 2021: CUTI of 1.9$m^2/s$ @ Humboldt, 2.2$m^2/s$ @ Morro**




CUTI: https://mjacox.com/upwelling-indices/
Wind speed: NBSv2 from NOAA Coastwatch
SST: OSTIA from NASA PODAAC
Ocean currents: OSCAR from NASA PODAAC
MLD: Multi Observation ARMOR3D from Copernicus Marine
Chlorophyll: Copernicus-GlobColour

# Can we calculate CUTI with satellite datasets?

$$\text{CUTI} = U^{\text{Ek}} + U^{\text{Geo}}$$

$$U^{\text{Ek}} = \frac{\tau^{\text{along}}}{\rho_0 \cdot f}$$

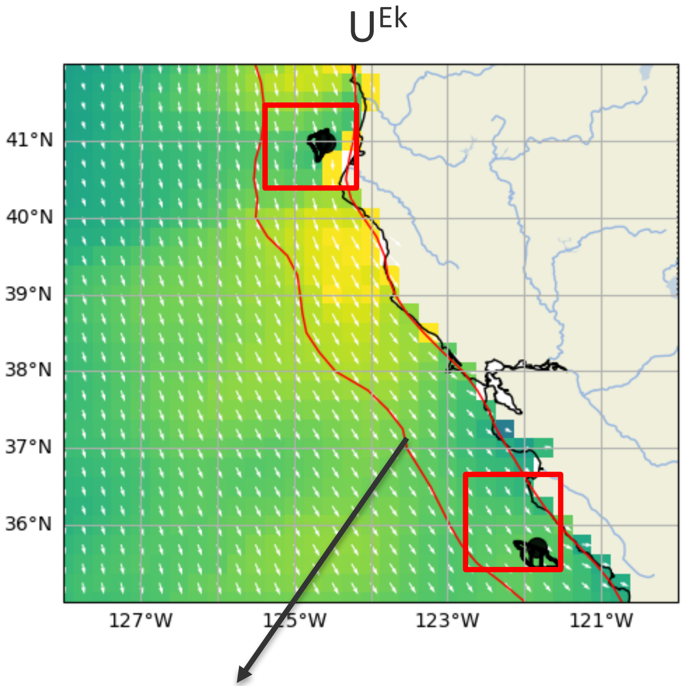
$$U^{\text{Geo}} = \text{MLD} \cdot u^{\text{geo, cross}}$$

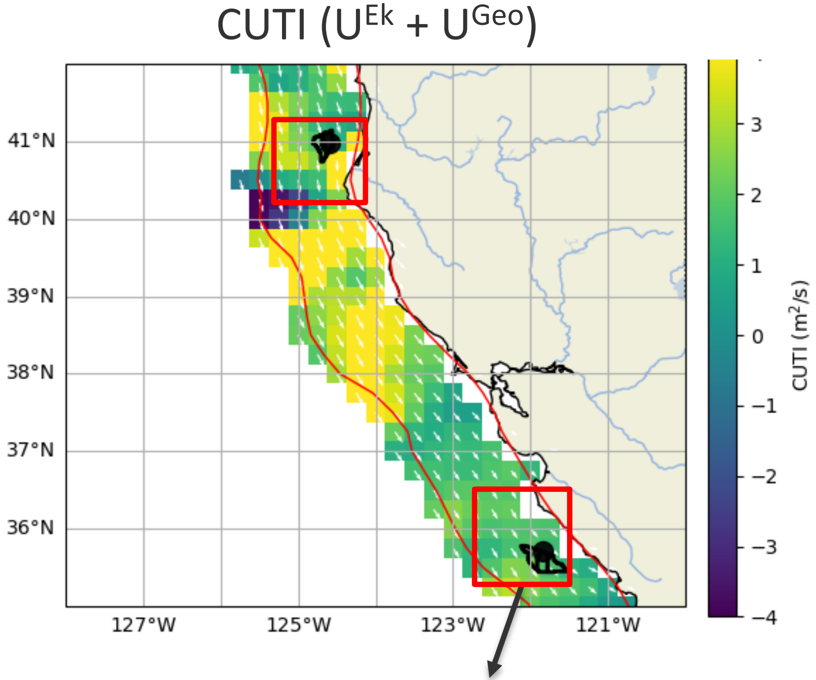
| **Satellite dataset** | **Blended Sea Surface Wind (NBS)** | **OSCAR Surface Currents** | **Multi Obs Global MLD** |
|---|---|---|---|
| Provider | NOAA NCEI | NASA | Copernicus Marine |
| Parameters | wind $U$, $V$, wind stress $\tau_x$, $\tau_y$ | Total & geostrophic surface currents in the upper 30m | 3D Temperature, Salinity, SLA, Geostrophic Currents, MLD |
| Processing level | 4, multi-satellite | 4, multi-satellite | 4, multi-observation |
| Temporal resolution | 6h | daily averaged | weekly averaged |
| Spatial resolution | 0.25° | 0.25° | 0.25° |
| Temporal availability | 1987-present | 1993 - present[1] | 1993 - present |
| Spatial coverage | Global ocean | Global ocean | Global ocean |

NBS wind data: https://coastwatch.noaa.gov/cwn/products/noaa-ncei-blended-seawinds-nbs-v2.html
OSCAR Surface Current data: https://podaac.jpl.nasa.gov/dataset/OSCAR_L4_OC_FINAL_V2.0
MLD Multi Observation dataset: https://doi.org/10.48670/moi-00052

# CUTI from satellite data: example day

July 23, 2021: CUTI of 1.9 m²/s @ Humboldt, 2.2 m²/s @ Morro



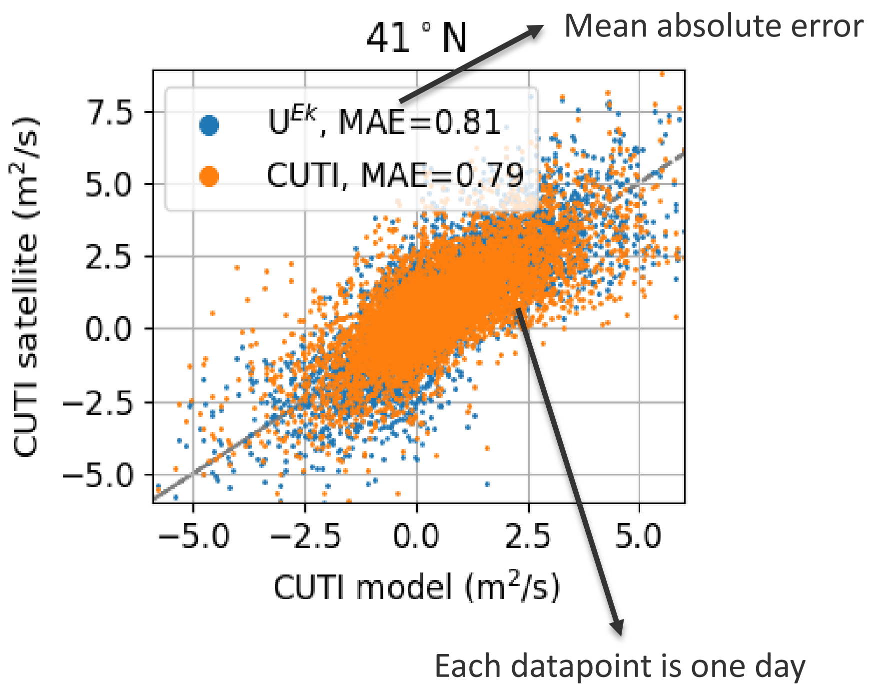




Upwelling index meaningful close to the coast

Compare area average to model CUTI

# CUTI from satellite data - validation

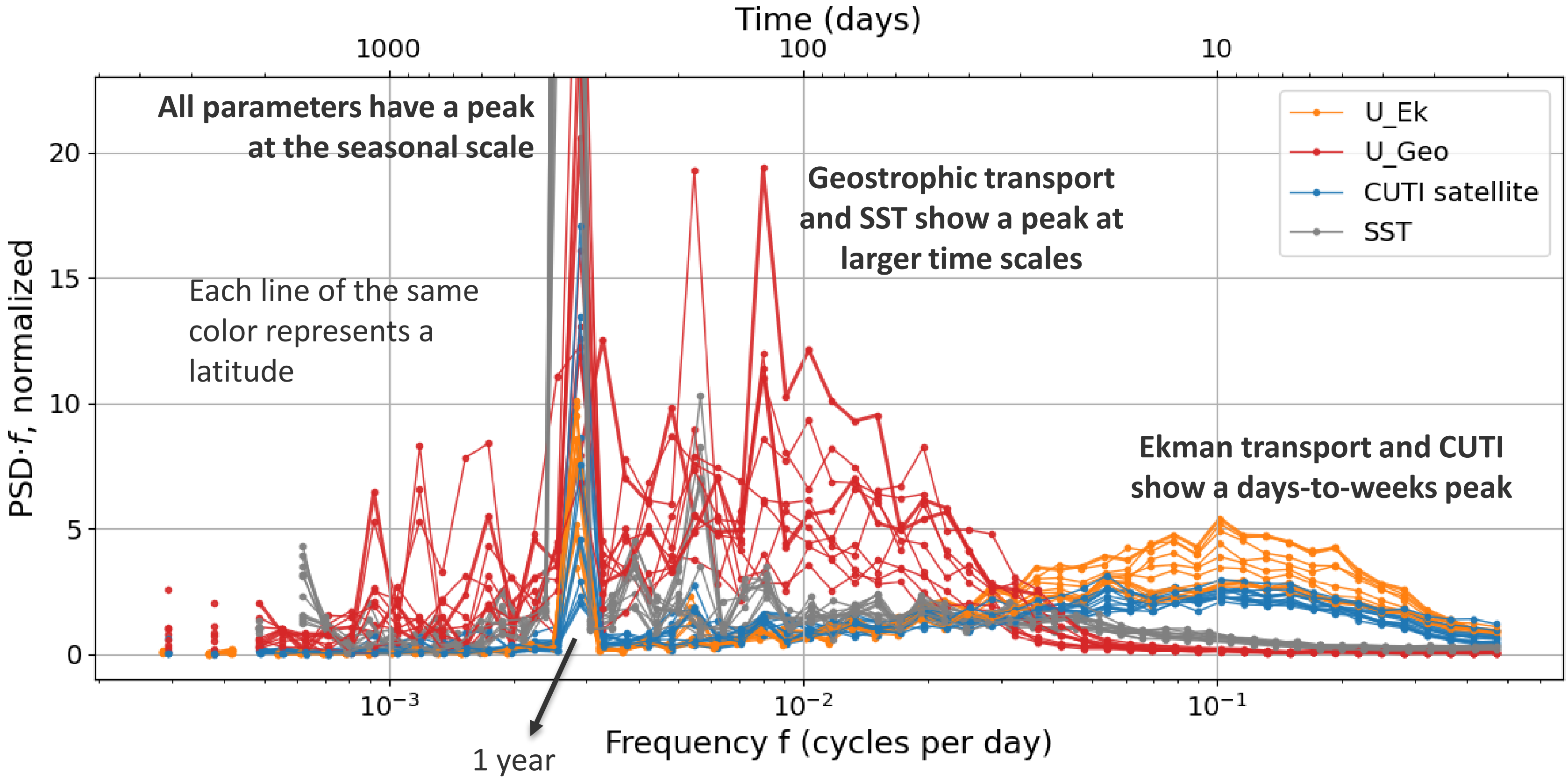
Correlation with original model CUTI at Humboldt, 1993-2023




- Ekman transport contributes most to CUTI.
- Geostrophic transport should still be considered.

➢ **CUTI from three satellite datasets provides results for time period 1993-2023 that agree well with the model CUTI.**

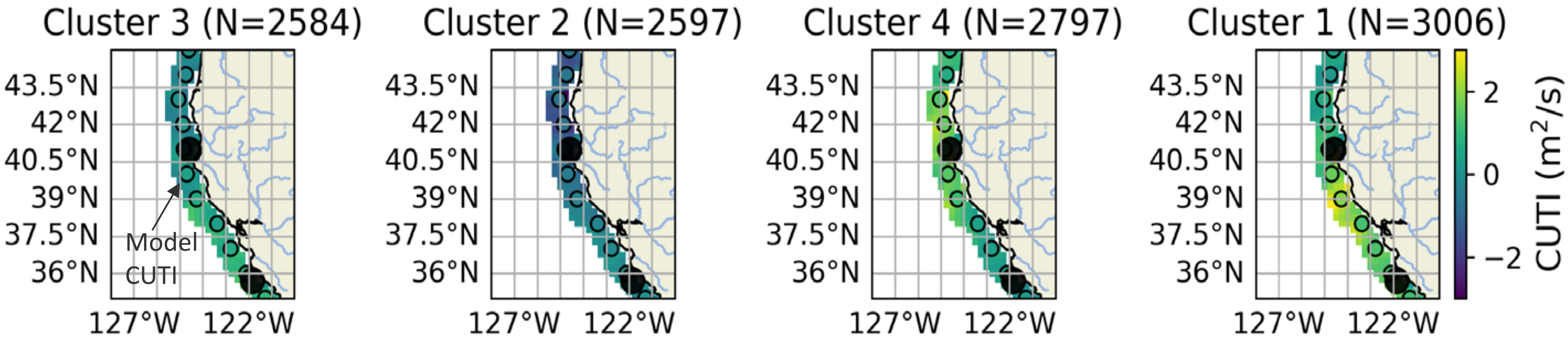
# Temporal scales of upwelling and related parameters



# Spatial patterns and large-scale forcing

**Aim: find typical spatial patterns of CUTI and related parameters in 30 years of satellite data**

→ K-means clustering reveals 4 typical upwelling patterns

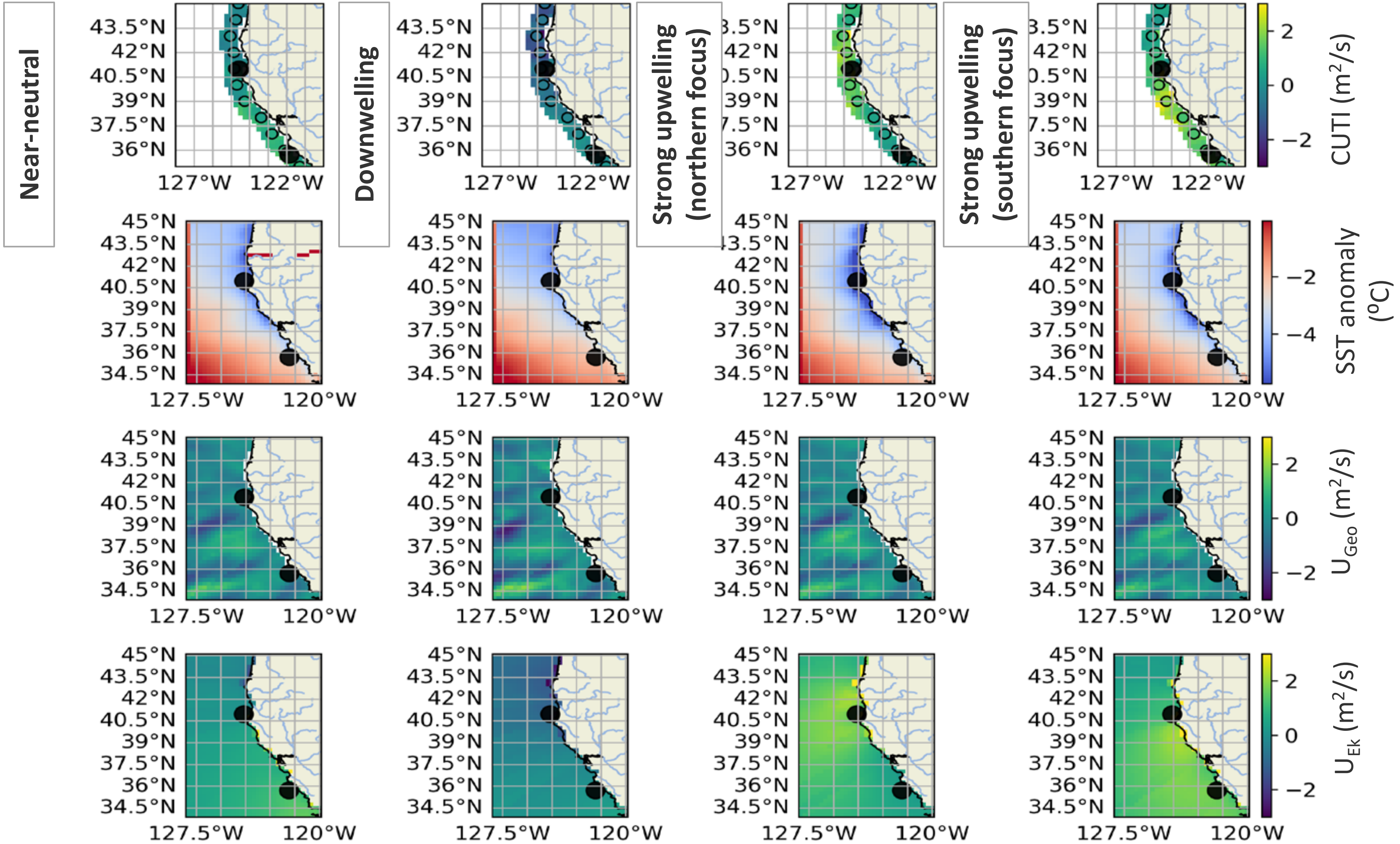



**Near-neutral**

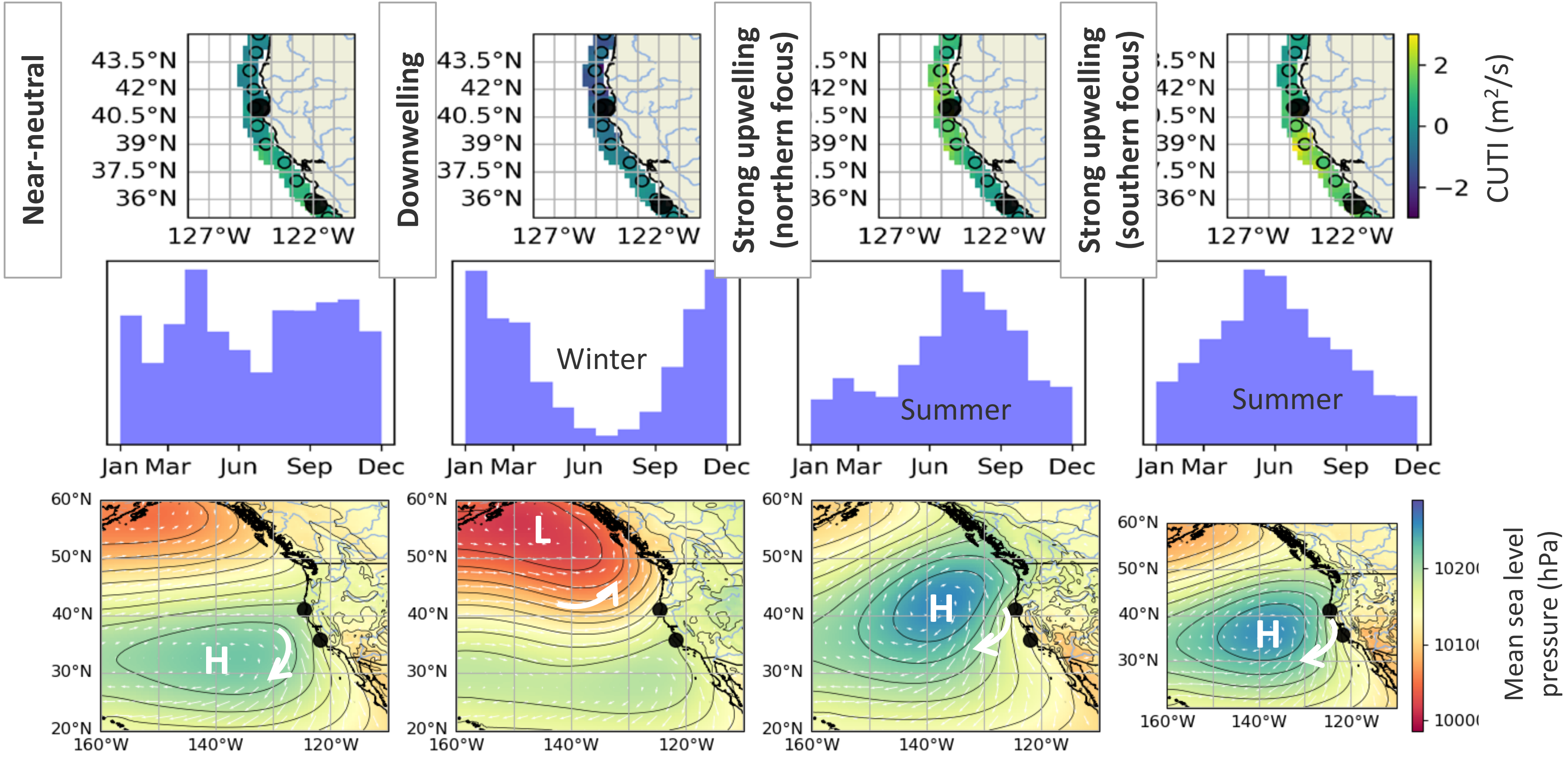
**Downwelling**

**Strong upwelling (northern focus)**

**Strong upwelling (southern focus)**


Near-neutral
Downwelling
Strong upwelling (northern focus)
Strong upwelling (southern focus)
CUTI (m2/s)
SST anomaly (ºC)
UGeo (m2/s)
UEk (m2/s)
45°N
43.5°N
42°N
40.5°N
39°N
37.5°N
36°N
34.5°N
127°W
122°W
127.5°W
120°W
2
0
−2
−4

# Seasonality of spatial patterns and large-scale atmospheric forcing (ERA5)



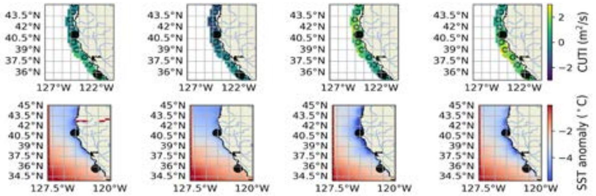

**Upwelling patterns can be attributed to large-scale pressure patterns.**

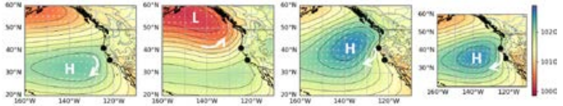
ERA5 data: https://doi.org/10.24381/cds.adbb2d47

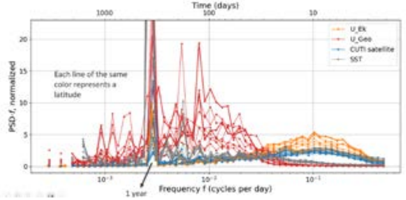
# Summary

Satellite data can describe coastal upwelling at the California coast:

- We found **four characteristic upwelling patterns** that vary seasonally.
- Coastal upwelling is mainly driven by the **large-scale atmospheric forcing** that determines wind patterns.
- Most upwelling **variability is seasonal and at the days-to-weeks scale**, following along-shore winds.



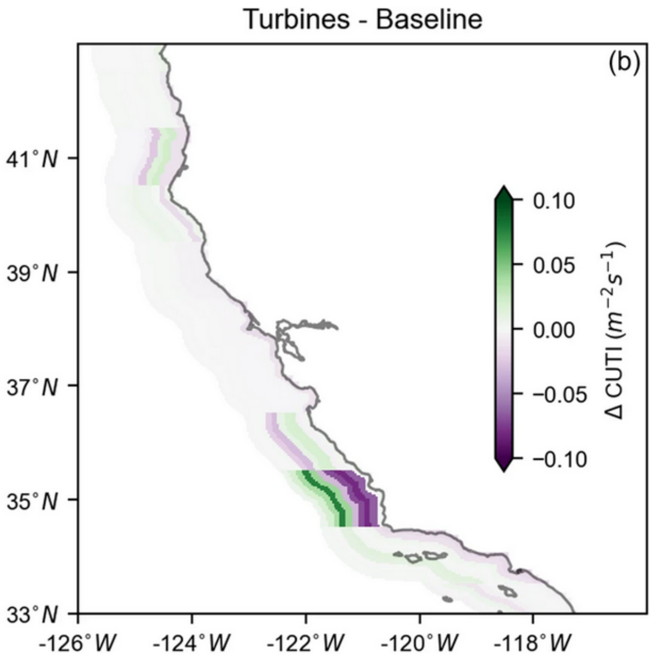



# Future work: Can satellite data explain the impact of wind farms on coastal upwelling?

- It is difficult: **Wind farm wakes primarily cause curl-driven upwelling.**
- In this study, we characterized the natural phenomenon of coastal upwelling for model validation.
- Future research: **Can satellite data reveal changes in curl-driven and coastal upwelling due to wind farms?**

**Model results (Raghukumar 2023):**




https://doi.org/10.1038/s43247-023-00780-y

# Thank you!

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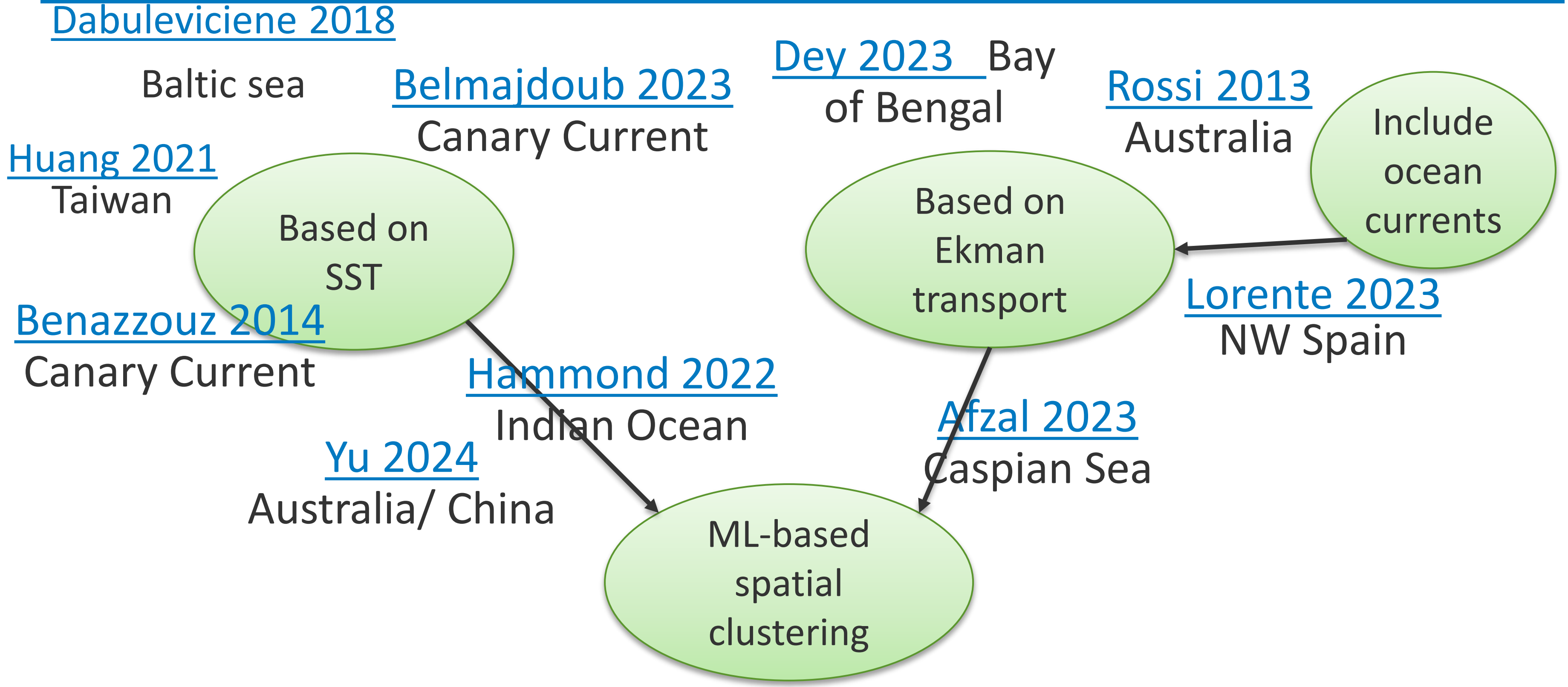
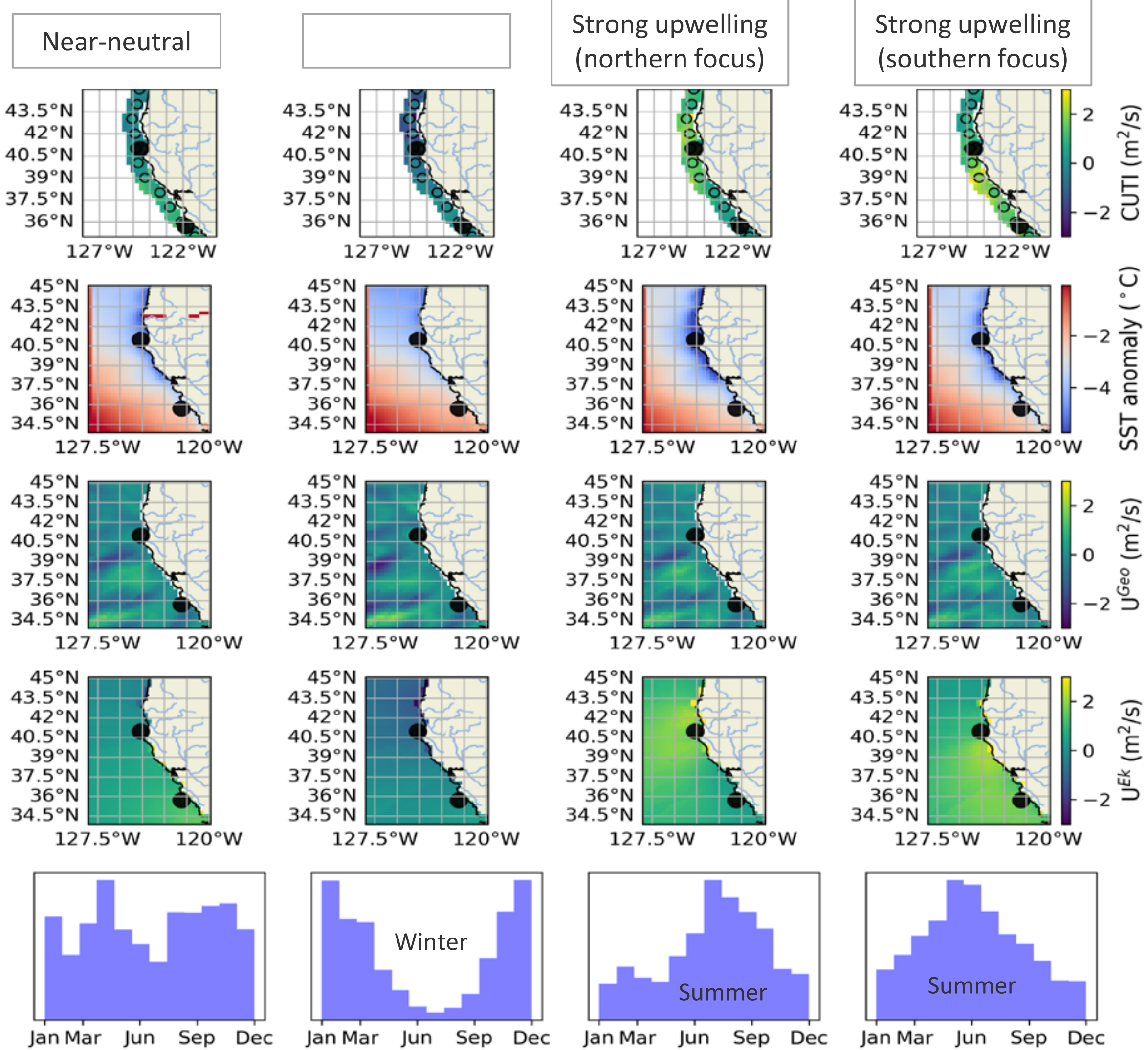
# Backup slides

# Quantifying coastal upwelling from satellite data





Near-neutral
Strong upwelling (northern focus)
Strong upwelling (southern focus)
CUTI (m²/s)
SST anomaly (°C)
$U^{Geo}$ (m²/s)
$U^{Ek}$ (m²/s)
Winter
Summer
Summer
Jan Mar Jun Sep Dec

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$$U^{\mathrm{Geo}} = \mathrm{MLD} \cdot u^{\mathrm{geo,\ cross}}$$

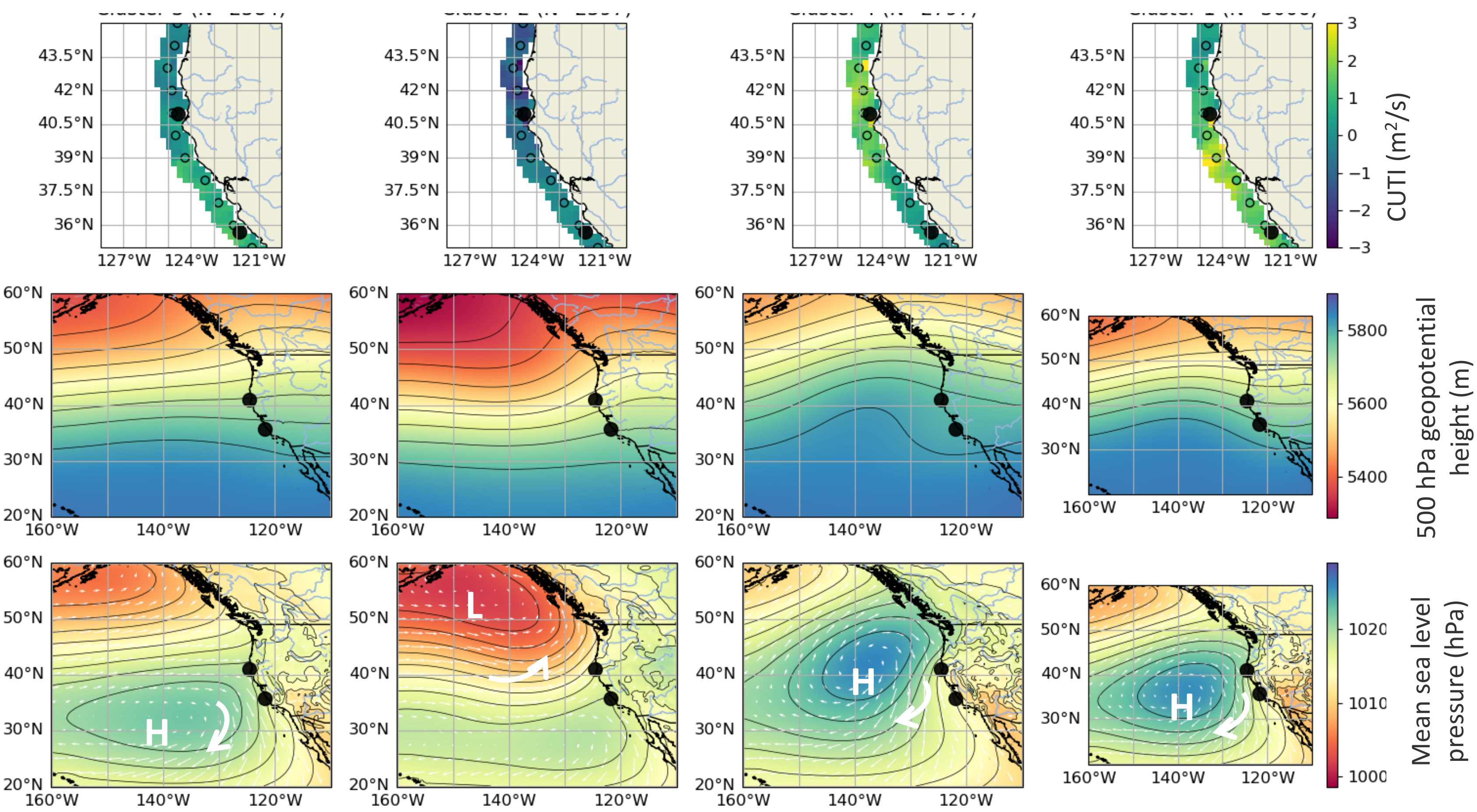
$$U^{\mathrm{Geo}} = \mathrm{MLD} \cdot \frac{g}{f} \cdot \frac{\Delta\mathrm{SSH}}{d_{\mathrm{coast}}}$$

$U^{\mathrm{Ek}}$: Ekman transport, cross-shore
$U^{\mathrm{Geo}}$: Geostrophic transport, cross-shore
$\tau^{\mathrm{along}}$: Wind stress, along-shore
$\rho_0$: Ocean density
$f$: Coriolis parameter
MLD: Mixed layer depth
SSH: sea surface height
$d$: distance along coast

Unit: $\frac{m^2}{s} = \frac{volume}{time * costline}$

Jacox 2018: doi 10.1029/2018JC014187, CUTI: Coastal Upwelling Transport Index

# Upwelling patterns can be attributed to large-scale pressure patterns from ERA 5 reanalysis data

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