Sub(Inter)-seasonal variability in driving physical and biogeochemical dynamics in the Southern Ocean

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Southern Ocean Circulation and Biogeochemistry

Strong westerly winds

+ Circulation
+ Solubility pump
+ Biological pump

Heat and carbon uptake

Morrison et al. (2015)
Southern Ocean Circulation and Biogeochemistry

Highly dynamic region

+ Synoptic-storm activity
+ Weak stratification
+ Vigorous eddy field
+ Flow strongly influenced by topography

Rintoul (2018)
Sources of Subseasonal Variability:

1. Atmospheric weather: externally forced
   
2. Oceanic weather: internally forced
   
3. Ocean-atmosphere weather interactions
Synoptic Storms

500 – 1000 km

2 - 10 days

500 – 1000 km
Sources of Subseasonal Variability:

1. Atmospheric weather: externally forced

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3. Ocean-atmosphere weather interactions
Oceanic Weather

Mesoscale eddies
$O(10-100)\text{ Km,}$
$\sim\text{ weeks to months}$

Submesoscale filaments
$O(1-10)\text{ Km,}$
$\sim\text{ few days}$

South Atlantic Summer Bloom

Envisat’s MERIS Ocean Color (300 m), ESA
Oceanic Weather

- **Mesoscale:**
  - $O(10-100 \text{km})$, $\sim$ weeks to months
  - Flow largely horizontal,
  - $w \sim O(1-10 \text{ m d}^{-1})$

- **Submesoscale:**
  - $O(1-10) \text{ Km}$, $\sim$ few days
  - Large vertical velocities
  - $w \sim O(10-100 \text{ m d}^{-1})$

*Mahadevan (2016)*
Sources of Subseasonal Variability:

1. Atmospheric weather: externally forced

2. Oceanic weather: internally forced

3. Ocean-atmosphere weather interactions
Ocean-Atmosphere Weather Interactions

Wind forcing

- Up-front wind
- Down-front wind
- Ekman flux
- \( b_y \)
- \( u \)
- \( \psi_w \)
- Eddy-driven circulation
- Wind-driven circulation

Heat fluxes

- Cooling
- Mixing
- Eddy-driven circulation

Mahadevan (2016)
Why do we care?

- Interesting phenomena per se...

- Weather timescales (~days) resonate with the life cycle of phytoplankton

- Weather perturbations (short/small time/space scales) can influence climate (longer/larger scales)
Small-scale Impacts on the Carbon System

- CARIOCA drifters (hourly, 1-3km)  

Small-scale Variability:

Small spatial-scale structures (~100 km) are a non-negligible source of variability for DIC, with amplitudes of about a third of the variations associated with the seasonality

Resplandy et al. (2014)
Subseasonal Impacts on the Carbon System

Seasonal cycle reproducibility:

- Satellite Chl-a based
- Quasi-fixed location

SO Seasonal Cycle (SOSCEEx II) Glider Experiment (1h, 1km)

Uncertainties in seasonal mean CO2 fluxes may arise from undersampled/unresolved dynamics

Thomalla et al. (2011), Monteiro et al. (2015)
Atmospheric Weather
Stormy Seas

very deep mixed-layer depths (MLD) and gloomy conditions
Phytoplankton Blooms

The mixed layer controls:
+ exposure to light
+ nutrient supply
+ grazing pressure
+ ...

Net growth rates:
\[ r = \mu - g - s - p - f \]

- phytoplankton specific growth
- sinking
- grazing
- parasitism
- physical flushing

Gille (2010)
High winds deepen the mixed layer and enhance satellite Chl-a

Carranza and Gille (2015), JGR
Storm-driven mixing enhances summer primary production

1. Entrainment of Fe impacting growth rates?

Storm-driven mixing enhances summer primary production (by 60%)

Chl-a response to high winds

High winds enhance satellite Chl-a through the summer

Chl-a vs wind speed, 3-day lag

1. Entrainment of Fe impacting growth rates?

de Baar et al. (2015)
Chl-a response to high winds

High winds enhance satellite Chl-a through the summer

Chl-a vs wind speed, zero lag (daily data)

1. Entrainment of Fe impacting growth rates?
2. Entrainment of Chl-a from a deep Chl-a maximum?
1. Reduced grazing pressure on phytoplankton due to dilution effects?
New Tools: Bio-optical profiles

Seals (Guinet et al. 2013):
- Chl-a fluorescence
- twice daily
- 10 m vertical resolution
- up to 200 m depth

BGC Argo floats (SOCCOM):
- Chl-a and Bpb profiles
- 5-7 days
- variable resolution: 2m, 5m, and 10m
- greater depths

EM-APEX floats (DIMES):
- Chl-a and Bpb profiles
- 5-10 days
- ~ 2.5 m vertical resolution
- 200 m, 500 m

~ 6300 fluorescence
> 3000 nighttime profiles
Chl-a vertical structure

1) Chl-a fluorescence variability

2) Presence of Deep Chl-a Maxima (DFM)
Chl-a and Bpb unevenness within mixed layer: seasonal variability

Unlike temperature, Chl-a fluorescence and Particle Backscatter show consistently large variance within the mixed layer in all seasons.

Standard Deviation Index (SDI): compares variability within the mixed layer with spatial variability across SO mixed layers.

Carranza et al. (2018), in revision for JGR Oceans
Bio-optical profile fits

σ: potential density (rescaled)

MLD
Δσ = 0.005

MLD
Δσ = 0.125

Chl-a Fluorescence

Particle Backscattering

Best fit selected based on a Chi-square goodness of fit test

Carranza et al. (2018), in revision for JGR Oceans
Gaussian vs non-Gaussian

Year-round NIGHTTIME:

Chl-a fluorescence mirroring potential density

Chl-a shows Gaussian structure

Carranza et al. (2018), in revision for JGR Oceans
Nighttime DM are more frequent in summer, but may occur in all seasons and are generally well-correlated with maxima in particle backscattering.

*Carranza et al. (2018), in revision for JGR Oceans*
DFMD vs Mixed-layer Depth (MLD)

MLD Definition: $\Delta \sigma = 0.03$

DFM below the MLD

DFM above the MLD

DFM are more often found close to the MLD

Carranza et al. (2018), in revision for JGR Oceans
DFM above the MLD: Sensitivity to MLD definition

Fraction of DFM in mixed layer depends on mixed layer definition:
- $\Delta \sigma = 0.005$ (mixing layer)
- $\Delta \sigma = 0.03$ (canonical)

At least $\sim 20\%$ of profiles with DFM show subsurface maxima above the MLD

Carranza et al. (2018), in revision for JGR Oceans
Mixed layers vs Mixing Layers

- The mixing layer (i.e. actively turbulent) is fundamentally different from the mixed layer (i.e. homogenous in density from a past mixing event).

- Light decreases exponentially with depth and turbulence stirs phytoplankton through the light gradient.

- The trade-off between timescales of mixing and photo-adaptation determine whether gradients in Chl-a fluorescence can form within a hydrographic mixed layer:
  \[
  \tau_{bio} > \tau_{mix} \quad \rightarrow \quad \text{Uniform Chl-a}
  \]
  \[
  \tau_{bio} < \tau_{mix} \quad \rightarrow \quad \text{Vertical gradients in Chl-a can exist}
  \]
Homogeneous vs Heterogeneous

WINTER (JJA):
~49%

SUMMER (DJF):
~29%

~51%

~71%

Carranza et al. (2018), in revision for JGR Oceans
The existence of gradients and variance in Chl-a fluorescence and Bpb within mixed layers homogeneous in density suggest that the biological timescales of photo-adaptation to light (i.e. growth/photo-acclimation) are shorter than mixing timescales:

$\tau_{bio} < \tau_{mix}$

$\tau_{photacclimation}$ (~ few hours) < $\tau_{growth}$ (~ >3-4 days)

Synoptic Storms (2-10 days)

Oceanic submesoscale (~few days)

Or mesoscale (weeks)
Storm events deepen and homogenize the mixed layer.

When storm ends, density remains mixed and the top of the mixed layer might continue mixing.

Phytoplankton grow where mixing is minimal?

MLD ~100 m

MLD ~70 m

wind-driven turbulence

Storm events deepen and homogenize the mixed layer.

When storm ends, density remains mixed and the top of the mixed layer might continue mixing.

Phytoplankton grow where mixing is minimal?
Can we constrain $T_{bio}$?

$T_{bio}$ is a biological timescale of restratification.

$T_{recurrence}$ is the recurrence time.

$T_{storm}$ is the storm time.

$T_{interstorm}$ is the interstorm time.

MLD ~ 100 m

MLD ~ 70 m

Wind-driven turbulence

$T_{mix}$ ~ 1 day

(i.e. time it takes to homogenize a gradient)

$T_{bio}$

Satellite (CCMP) winds

Profile structure statistics from floats

$f_{homogeneous} \sim \frac{T_{storm} - T_{mix} + T_{bio}}{T_{recurrence}}$
Storm-mixing Timescales

One storm arrival every week, that will last ~ 3 days

Storm:
wind speeds >10 m s\(^{-1}\)

Exhibit seasonality:
slightly less frequent storms in summer, lasting ~ 1 day shorter, allowing for longer periods of quiescence (~ 5 days)

Storm timescales imply biology restratifies in less than 1-3 days
Wind-profile matchups

MLD increases as winds get stronger

Bio-optics get homogenized within the mixed layer
Wind-profile matchups: What happens after a storm?

MLD shoals within 1-2 days

Mixed layer bio-optical variance and peak prominence increase

\[ \mu = 0.31 \text{ day}^{-1} \]

Biological restratification timescales of < 3 days
Implications

- Hydrographic mixed layers are not mixed in bio-optical properties

- Biological timescales for growth might be shorter than previously thought, i.e. SO’s phytoplankton is well adapted to cold temperatures, low light and Fe conditions

- Seasonality/Asymmetry in storm-mixing timescales suggests atmospheric weather can have a net effect on annual means and longer-term biogeochemical properties
Oceanic Weather
Hotspots for Eddy Activity

- Downstream of topographic features

Brazil-Malvinas Confluence

Aghulas Retroflection

Kerguelen Plateau

Mesoscale eddies’

Frenger et al. (2015)
Submesoscale patchiness linked to topography

Kerguelen Plateau

1/20° horizontal resolution (mesoscale-resolving)

1/80° horizontal resolution (submesoscale-resolving)

Rosso et al. (2015), Rosso et al. (2016)
Iron fluxes are enhanced by a factor of 2 by the sub-mesoscales, though differences in mean [Fe] are small.

Rosso et al. (2015), Rosso et al. (2016)
Submesoscale Observations...

Southern Drake Passage (ChinStrAP)
Glider observations (1-3km, hr) crossing fronts

PWP: 1-D bulk mixed layer model
mPWP: PWP + parameterized submesoscale

Ekman buoyancy flux and BCI are at least as important as the surface wind and buoyancy forcing in setting mixed layer variability in the Southern Ocean

Viglione et al. (2018)
Submesoscale Impacts on Subduction of Chl-a

Evidence of submesoscale-driven subduction of Chl-a, contributing to the formation of deep Chl-a maxima in summer.

Erickson et al. (2016)
Wind modulation of upwelling at a SBF

Patagonian Shelf

Wind-driven currents and high tidal energy

Chl-a amplitude

Chl-a is uniformly sustained at fronts

Carranza et al. (2017), JGR
Satellite Chl-a response to along-front winds at the SBF

Composites of satellite Chl-a by along-front wind direction

(a) Southerly winds (from the south)       high Chl-a onshore
(b) Northerly winds (from the north)       high Chl-a offshore

Southerly winds (down-front)  Northerly winds (up-front)
Evidence of isopycnal tilting due to changing winds: synoptic evidence

Siedlecki et al. (2011)
Conclusions

✓ Synoptic winds impact MLD and Chla variance within the ML: enhanced ML variance during periods of quiescence between high wind events. Seasonal asymmetry in storm timescales (longer interstorm periods in summer) could impact annual means.

✓ Mesoscale eddies modulate MLD variability. Asymmetric contribution of eddies to MLD variability (greater for anticyclones vs cyclones). Stronger signal in winter vs summer, and over localized regions. Impacts on surface Chl-a through changes in light and nutrient supply.

✓ Highly energetic submesoscale dynamics downstream of topography that can be active in the summertime!, enhance Fe supply and support along-isopycnal subduction of Chla below the seasonal MLD.

✓ Wind-mesoscale interactions can potentially enhance nutrient fluxes.. and modulate Chla (e.g. at a shelf-break front).
Winds and Currents Mission (WaCM)

- Ka-band rotating pencil beam Doppler scatterometer
- Winds measured from Ka or Ka/Ku s0 measurements at multiple azimuth angles or jointly with Doppler for direction ambiguity removal.
- Surface currents from Doppler measurements
- Temporal coverage > 1/day

- Wide-swath and fast sampling result in less aliasing of time-averaged currents and derivatives (D. Chelton)
  - Mitigates noisier single-pass measurements
  - True surface currents (ageostrophic & surface)

Mark Bourassa (FSU), Ernesto Rodriguez (JPL), Sarah Gille (SIO)
References