Phytoplankton Thin Layers Simulated by Large-Eddy Simulation

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Plankton live near the surface of the ocean.

They are subjected to wind, wave and convection driven turbulence.

Despite turbulent mixing, spatial structures in the plankton are common in the surface waters.

One commonly observed structure is the phytoplankton thin layer.

We use a Large-eddy simulation model coupled to a simple biological model to investigate this phenomenon.
Thin layer observation, Mcmanus et. al (2003)

Fig. 3. (A) $\sigma_t$ along transect from Rosario Point to RV 'Henderson'. (B) Time-series of $\sigma_t$ measured from RV 'Henderson'. $\sigma_t$ contours (21.4, 21.5, 21.6, 21.7) are drawn in black in (A) and (B). (C) Chlorophyll concentration (µg L$^{-1}$) along transect from Rosario to RV 'Henderson'. (D) Chlorophyll concentration (µg L$^{-1}$) at RV 'Henderson'. Chlorophyll concentration estimated from $(a_r, 676 - a_r, 650)/0.012$ (where $a_r$ = phytoplankton absorption); red = chlorophyll concentrations $>12$ µg L$^{-1}$. 'Third Love' was next to RV 'Henderson' at approximately 14:30 h on June 18; non-plotted values at bottom of graphs are due to sediments for which $a_r, 676 - a_r, 650 < 0$. 
Thin layer observations, Ryan et. al (2008)
Proposed Mechanisms, Durham and Stocker (2012)
Thin layer models, Birch et al. (2007)
ness from 0.12 m to 3.61 m (mean 1.20 m). Roughly 44% of layers were <1 m in thickness, and 80% of

and strength of the pycnocline. Roughly 62% of all thin

layers were at the base of the pycnocline (Fig. 6a). This

72% of the thin layers had absorption intensities that

ranged from 0.25 to 1.5 m\(^{-1}\) (Fig. 4c).

There is a second class of thin optical layer adjacent
to the bottom. These bottom layers were found in 31
(26%) of the profiles. They ranged from 0.23 to 3.11 m
in thickness (mean 1.30 m). Bottom layer intensities
ranged from 0.26 to 2.24 m\(^{-1}\) (mean 0.80 m\(^{-1}\)). Thus,
bottom layers had similar thickness to and slightly
lower intensities than water column thin layers. We
do not include bottom layers in these

Thin phytoplankton layers and the pycnocline

Thin layer depth was closely associated with depth

and strength of the pycnocline. Roughly 62% of all thin

layers were at the base of the pycnocline (Fig. 6a). This

pattern was observed on all cruises, but was strongest in

May. Approximately 9% of thin layers were distributed
Model description

- Physical model: Large-Eddy Simulation (LES)
- PALM 5.0

\[
\frac{\partial u}{\partial t} + u \cdot \nabla u + f \times u = -\frac{\nabla p}{\rho_0} + \nabla \cdot \nu_t \nabla u - \frac{\rho g}{\rho_0}
\]

\[\nabla \cdot u = 0\]

- Filtered Navier-Stokes equations
- Fully 3-dimensional
- Turbulence resolving
Model description

- Biological model: Nutrient-Phytoplankton model (NP)
- Phytoplankton are treated as Lagrangian particles
- Each particle is representative of a number of phytoplankton cells, denoted by a weighting factor $W$.
- This weighting factor varies with the net growth rate of the phytoplankton i.e.

$$W_{t+\delta t} = W_t \times (1 + \delta t \times \text{Net growth rate})$$

Net growth rate = \( Ge^{Kz} \frac{N}{N_0} - \hat{D} \)
Model description

- Biological model: Nutrient-Phytoplankton model (NP)

- Nutrient is treated as an Eularian scalar

\[
\frac{\partial N}{\partial t} + u \cdot \nabla N = \nabla \cdot D_t \nabla N - P \times \text{Net growth rate}
\]
Model setup

80m

No Nutrient

Nutrient
Model setup

- Domain size: $L_x = L_y = 300\text{m} \quad L_z = 80\text{m}$
- Domain resolution: $\delta x = \delta y = \delta z = 1\text{m}$
- Period horizontal boundary conditions
- Wind forcing: $4\text{ms}^{-1} - 12\text{ms}^{-1}$
- Initial surface mixed layer: $30\text{m}$
- Initial stratification: $0.1\text{Kelvin/m}$
- Initial Nutrient: $10\mu\text{mol l}^{-1}$
- Amount of particles: $9,000,000$
- Phytoplankton size: $50\mu\text{m}$
Simulation design
Nutrient response to wind

Low wind ($4ms^{-1}$)

High wind ($6ms^{-1}$)

($8ms^{-1}$)
Plankton response to wind

Low wind \((4ms^{-1})\)

High wind \((6ms^{-1})\)

\((8ms^{-1})\)

(10ms^{-1})
Plankton (Scaled by max) response to wind

Low wind (4ms\(^{-1}\))

High wind (10ms\(^{-1}\))
Stratification

Low wind ($4\text{ms}^{-1}$)

High wind ($6\text{ms}^{-1}$)

($8\text{ms}^{-1}$)

High wind ($10\text{ms}^{-1}$)
Thin Layer Intensity = Maximum Phytoplankton concentration / Surface Phytoplankton concentration
Quick Summary I

- Thin layers form at the pycnocline
- Low wind = Low concentration in thin layer
- High wind = Low thin layer intensity
Phytoplankton (particle) injection

Low wind ($4ms^{-1}$) (6$ms^{-1}$)

High wind ($8ms^{-1}$) (10$ms^{-1}$)
Nutrient Entrainment <N’w’>

Low wind (4ms\(^{-1}\))

High wind (10ms\(^{-1}\))
Quick Summary II

- Low wind = Small amount of particles injected into pycnocline
- High wind = Lots of nutrient entrainment into surface water
Proposed Mechanisms, Durham and Stocker (2012)
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A thin layer should form if the timescale of growth is much larger than the timescale of vertical mixing.

\[
\frac{\partial < P >}{\partial t} = \frac{\partial}{\partial z} < wP > + Ge^{-Kz} < PN > - D < P >
\]

\[
< F > = \frac{1}{XY} \int_0^y \int_0^x F \, dx \, dy
\]

Which term is dominant?
Dynamics breakdown - Plankton

\[
\frac{\partial \langle P \rangle}{\partial t} = \frac{\partial}{\partial z} \langle wP \rangle + Ge^{-Kz} \langle PN \rangle - D \langle P \rangle
\]
Quick Summary III

- Results show that in-situ growth is taking place

- Timescale of biological growth outweighs timescale of vertical mixing

- Why do they grow here?

- As we are using particles, we can trace the journey of the thin layer plankton back through time.
Thin layer particles at the pycnocline
Conclusions

- We demonstrated thin layer formation with simple passive particles.

- Thin layers always occur in the pycnocline

- Model results reveal patterns observed in the field

- Once particles reach the pycnocline, they are trapped for a sustained period, giving them time to feed in the nutrient rich water.

- The thin layer is strongest when a compromising level of wind is realised.
  - If wind is too weak, less particles are injected into the pycnocline
  - If wind is too strong, too many nutrients are brought to the surface to feed the competing surface plankton