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Observations of radiatively driven convection plumes in a deep, unstratified, ice-free lake

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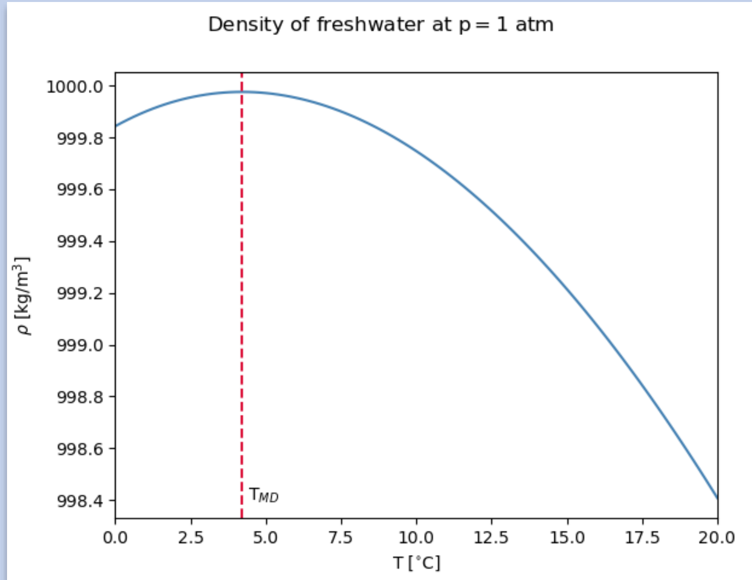
I. Background and Motivation

- Freshwater below temperature of maximum density (~4℃ at 1 atm) has a negative thermal expansion coefficient
- Forcing by radiative heat flux at the surface creates density instabilities that lead to convective motion and turbulent mixing
- This can be the dominant process driving mixing of phytoplankton and nutrients in temperate lakes during the spring and serves as the only convective mixing process in ice-covered lakes



II. Study Site

- western arm of Lake Superior
- ice free
- depth: 170 m
- mid-latitude: $f = 1.04 \times 10^{-4}\ \mathrm{s}^{-1}$
- unstratified: $N^2 \leq 10^{-8}\ \mathrm{s}^{-2}$
- light to moderate wind: $u_{10} = 2 - 10\ \mathrm{m/s}$

III. Research Questions

- What dynamical processes control the formation, size and structure of radiatively driven convective plumes?
- How does turbulence vary inside vs. outside convective plumes?
- Are phytoplankton preferentially observed in downwelling or upwelling regions?

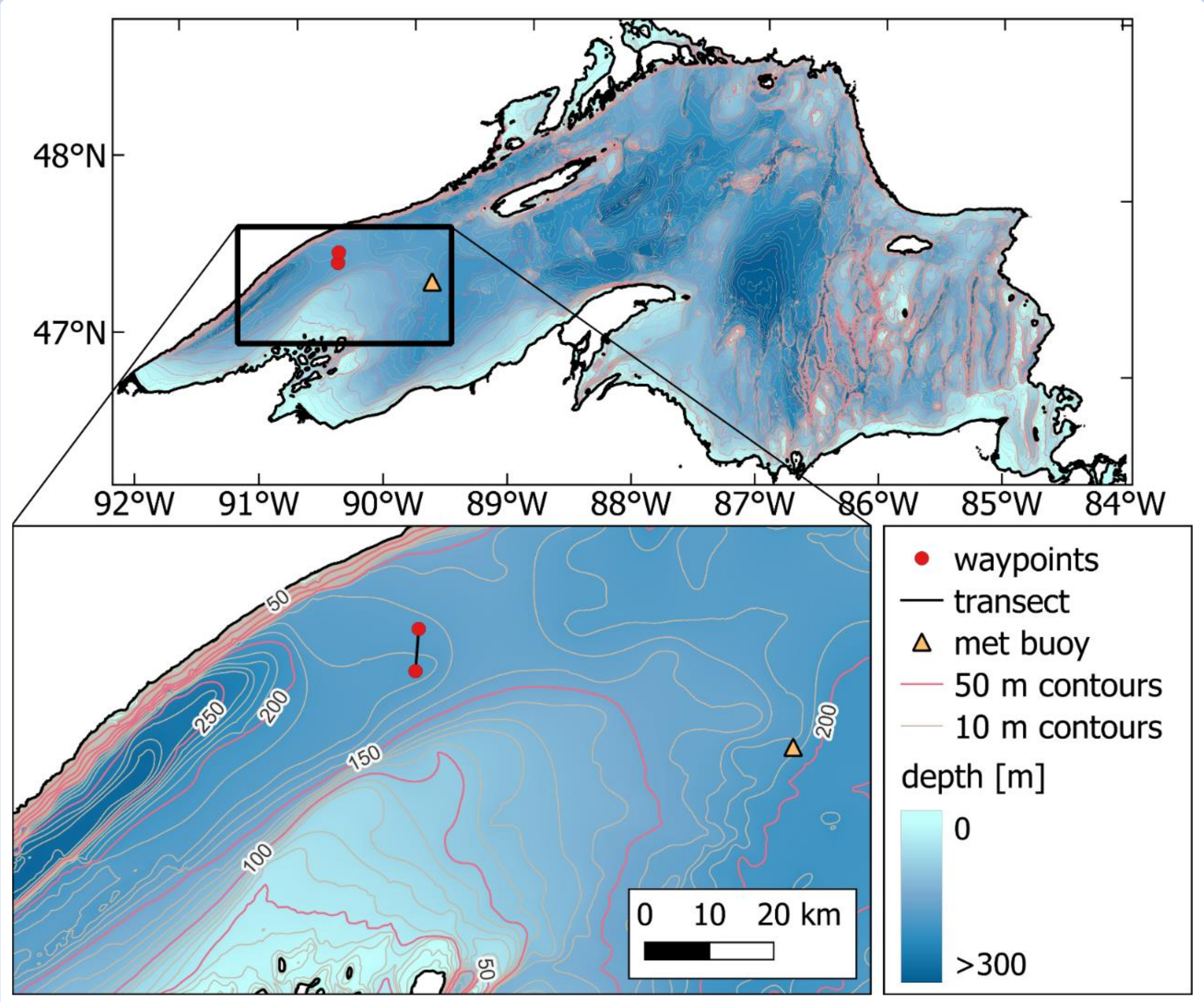


Figure 1: Study location in the western arm of Lake Superior.

IV. Methods

- Three days of continuous profiling in western Lake Superior with an autonomous underwater glider (AUV)

- Continuously measured CTD, chlorophyll-a fluorescence, and shear microstructure
- Sawtooth flight pattern (26° dive angle) resolved both vertical and lateral variability
- Meteorological buoy measured relevant surface forcing: air and water temperature, incident shortwave/longwave radiation, relative humidity, wind speed/direction.

Distributed buoyancy flux characterizes convective forcing resulting from shortwave radiation (taking z as positive downward)[1]:

$$B_* = \frac{1}{h_{CML}} \int_0^{h_{CML}} B(z)dz = \frac{1}{h_{CML}} \int_0^{h_{CML}} \frac{g}{\rho}\frac{\alpha}{C_p}\frac{dI(z)}{dz}\,(h_{CML} - z)dz$$

assuming irradiance has exponential decay from surface:

$$I(z) = I_0 e^{-kz}$$

B_* acts as a source of TKE that is subsequently dissipated by viscous forces (ε). Dissipation rate can be inferred from measured shear spectrum components (assuming locally homogeneous and isotropic turbulence):

$$\varepsilon = \frac{15}{2}\nu\overline{\left(\frac{\partial u}{\partial s}\right)^2}$$

where u is the velocity component perpendicular to the glider path along s.

Downwelling convective plumes were delineated as regions with positive temperature anomalies >0.02 °C above the value corresponding to neutral stability. Plume widths and statistics were computed based on this method.

V. Results

Buoyancy/Wind Forcing

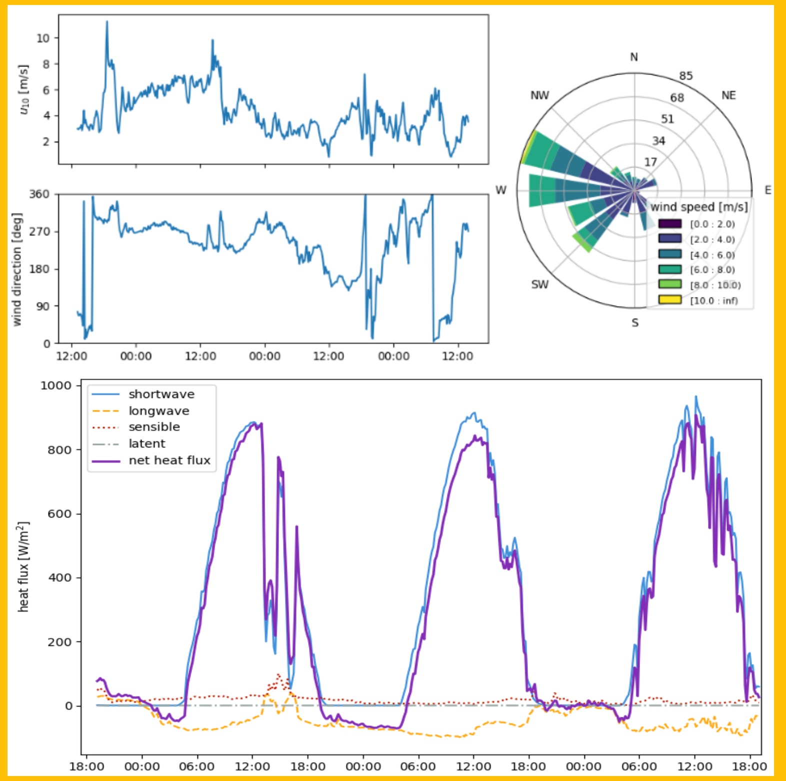


Figure 2: Surface heat flux and wind forcing estimated from met buoy data.

TKE dissipation

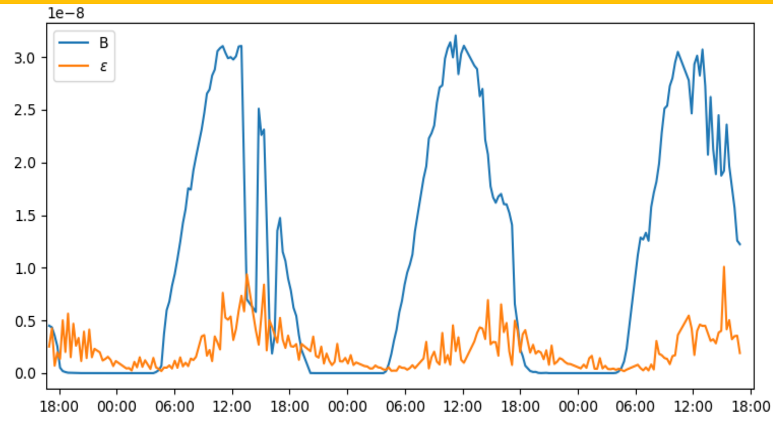


Figure 3: Distributed buoyancy flux (B_*) and vertically averaged TKE dissipation (ε).

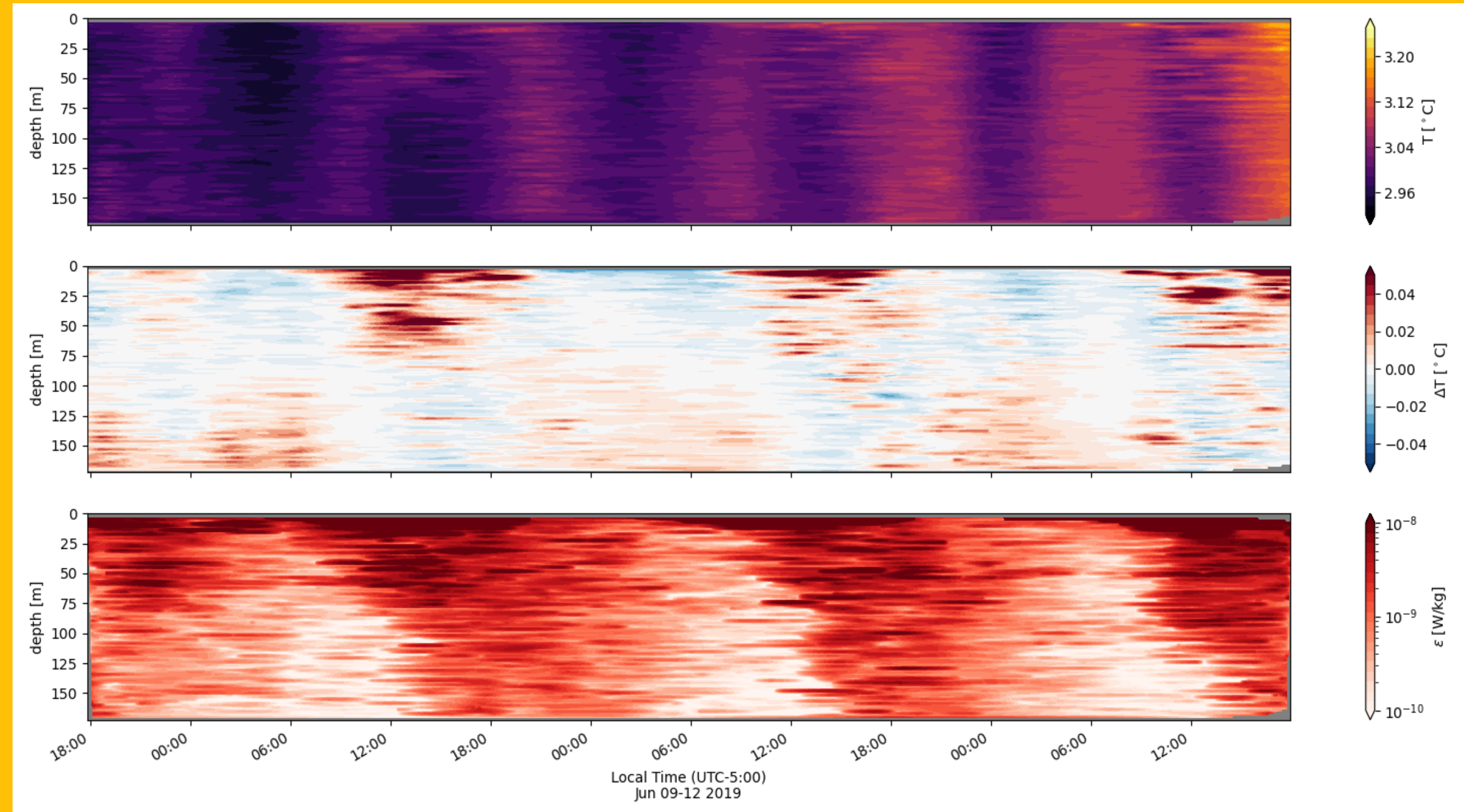


Figure 4: Temperature, temperature anomaly, and turbulence kinetic energy dissipation.

Convective Plume Scaling

Deardorff scales: characteristic convective vertical velocity and turnover time[2]

$$w_* = (h_{CML} B_*)^{1/3} \approx 1\ \mathrm{cm/s}$$

$$\tau_* = \frac{h_{CML}}{w_*} \approx 3\ \mathrm{hr}$$

Applying the same width scaling used for convective plumes formed by ocean surface cooling in unstratified conditions[3] yields:

$$\begin{aligned} l &\sim (B_* t^3)^{1/2}, && t < f^{-1} \\ l &\sim \left(\frac{B_*}{f^3}\right)^{1/2}, && f^{-1} \leq t < \tau_* \\ l &\sim h_{CML}\ , && t \geq \tau_* \end{aligned}$$

where the distributed buoyancy flux (B_*) replaces the original surface buoyancy flux.

This implies rotation controls plume structure in sufficiently deep lakes or lakes with low buoyancy flux (e.g., ice covered), while the water depth is the primary constraint on plume width for shallow lakes with larger buoyancy fluxes. The rotationally-controlled maximum plume width for Lake Superior during the study period is:

$$\left(\frac{B_*}{f^3}\right)^{1/2} = \left(\frac{3 \times 10^{-8}\ \mathrm{m^2/s}}{(1.07 \times 10^{-4}\ \mathrm{s^{-1}})^3}\right)^{1/2} \approx 173\ \mathrm{m}$$

Convective Plume Structure

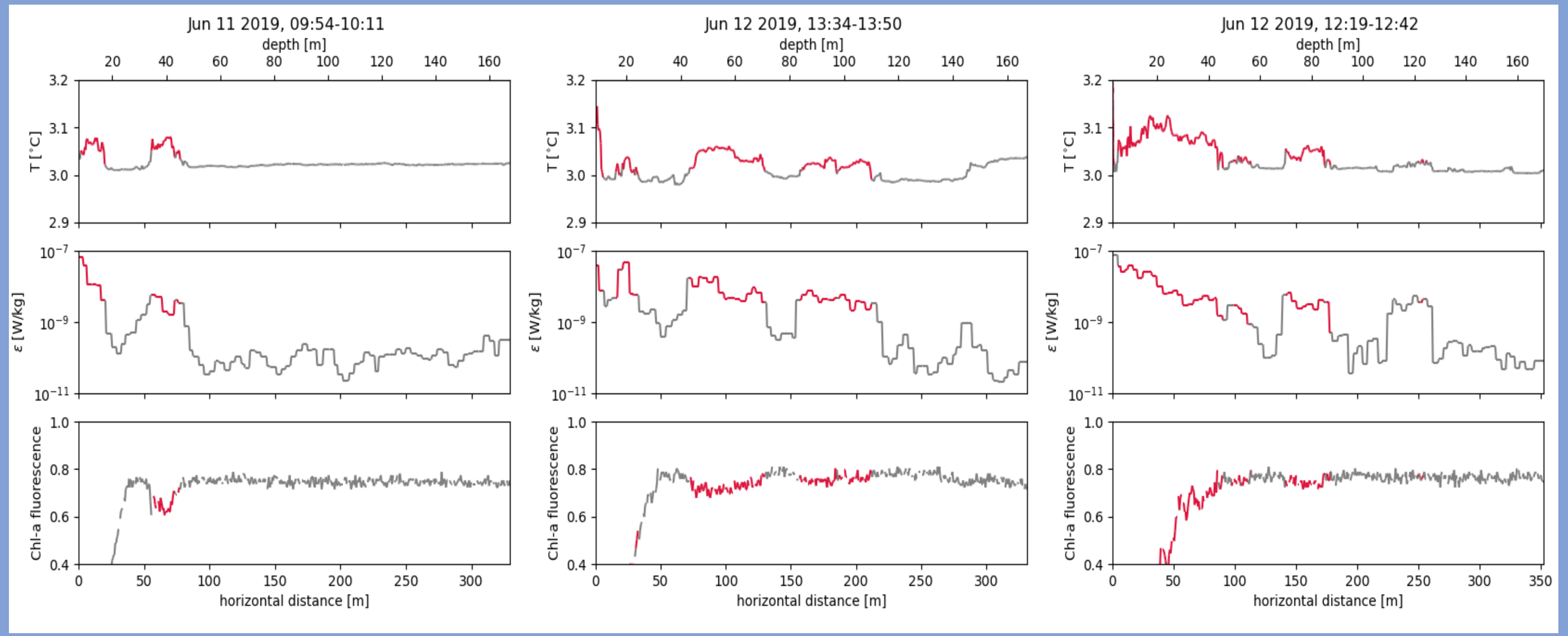


Figure 5: Individual profiles of temperature, TKE dissipation rate, and chlorophyll-a fluourescence. Convective plumes are delineated in red.

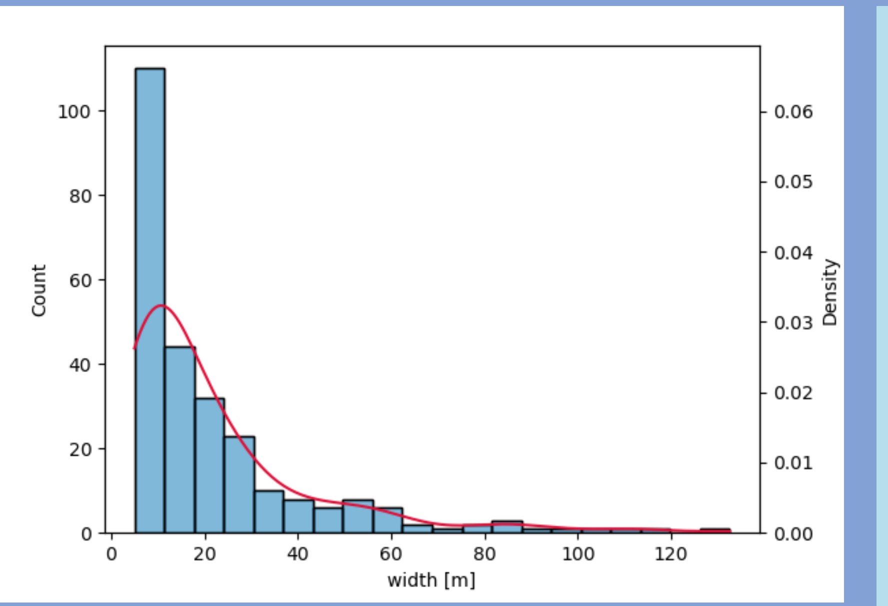


Figure 6: Histogram and kernel density estimate of observed convective plume widths.

VI. Conclusions

- Observed plume sizes consistent with theoretical scales imposed by rotation and depth, both likely exert control on limiting plume width
- Lag between start of buoyancy forcing and increase in TKE dissipation is consistent with Deardorff turnover time scale
- Radiative forcing primarily controls springtime turbulence and vertical mixing, despite moderate wind shear
- TKE dissipation rates are 1-2 orders of magnitude greater inside convective plumes
- Photoquenched phytoplankton are transported to depth by downwelling convective plumes

References

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