OVERLAPPING TURBULENT BOUNDARY LAYERS IN A STRONGLY-FORCED COASTAL SEA

INTERNATIONAL UNDERWATER GLIDER CONFERENCE, IUGC 2024

13 JUNE 2024 - GÖTEBORG, SVERIGE

arnaud@oceanlyscience.com* @CookStMonster*

Arnaud Valcarcel* – Oceanly Science / U. Otago
Craig Stevens – U. Auckland / NIWA
Joe O'Callaghan – Oceanly Science / U. Auckland
Ata Suanda – U. North Carolina Wilmington

oceanly · University of Otago, Te Whare Wānanga o Otāgo, New Zealand · NIWA Taihoro Nukurangi · The University of Auckland, New Zealand, Te Whare Wānanga o Tāmaki Makaurau · UNCW University of North Carolina Wilmington

Overview

What was the motivation ?

How did we approach the problem ?

What did we find ?

What are we following up on ?

Overview

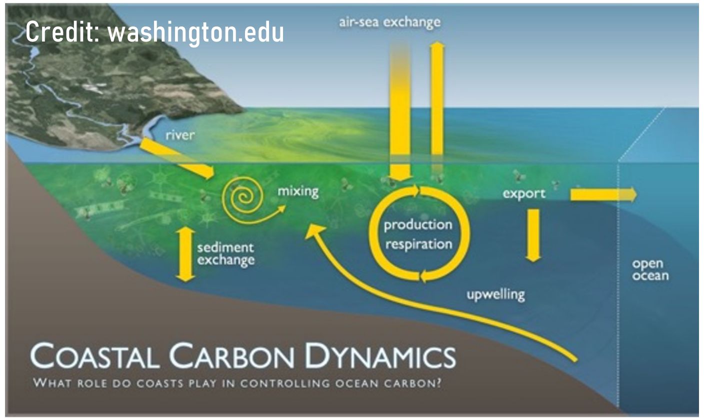
What was the motivation ?

How did we approach the problem ?

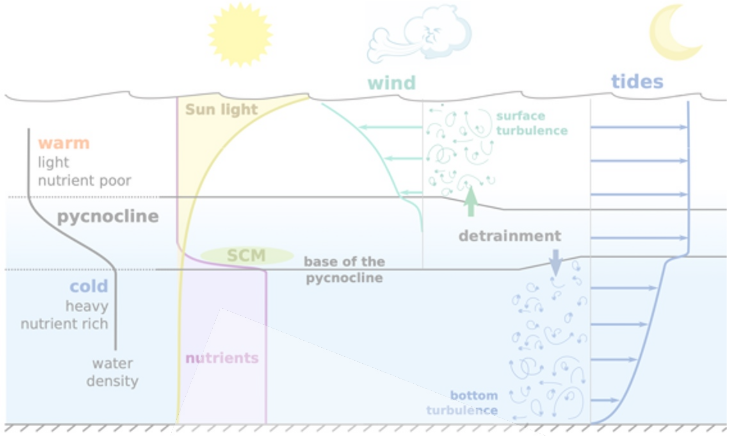
What did we find ?

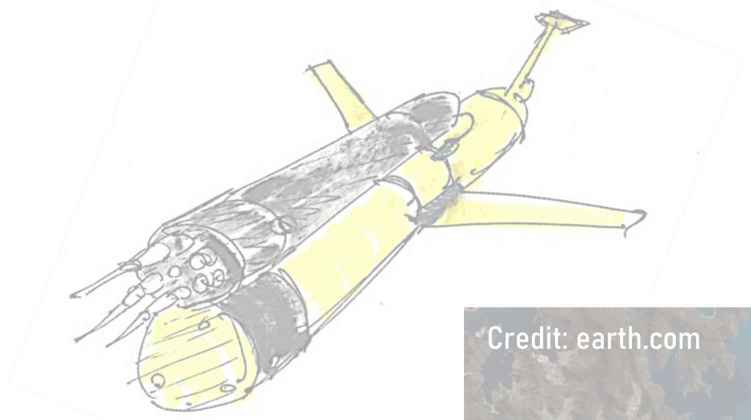
What are we following up on ?

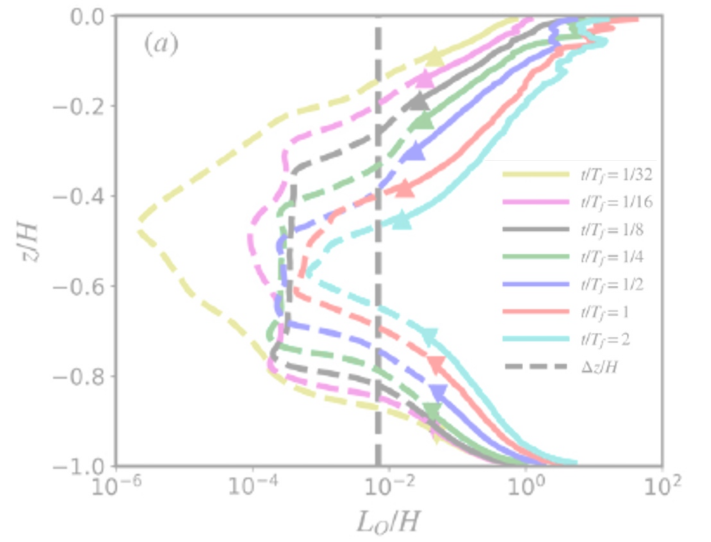
Background – Global influence of coastal ocean dynamics



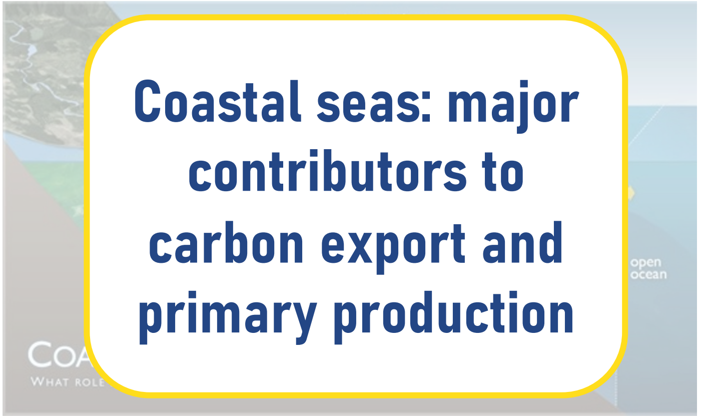
Bianchi (2005)
Simpson and Sharples (2012)





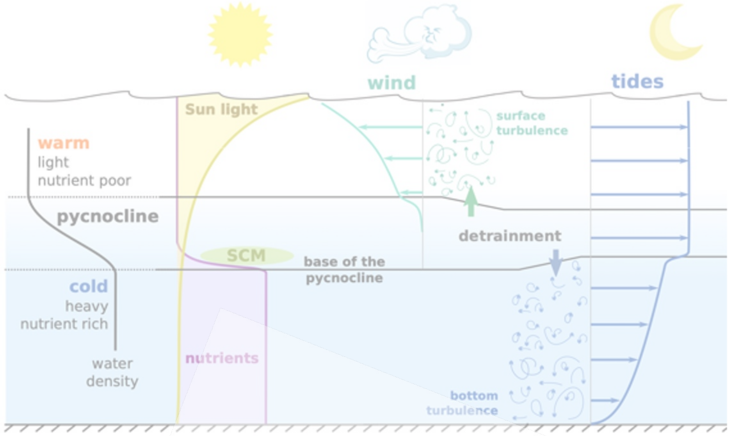


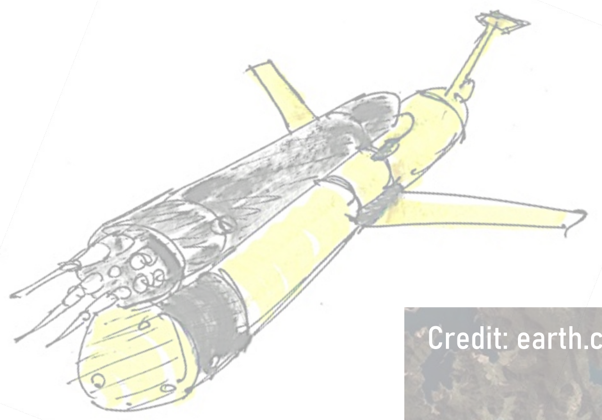
Background – Global influence of coastal ocean dynamics

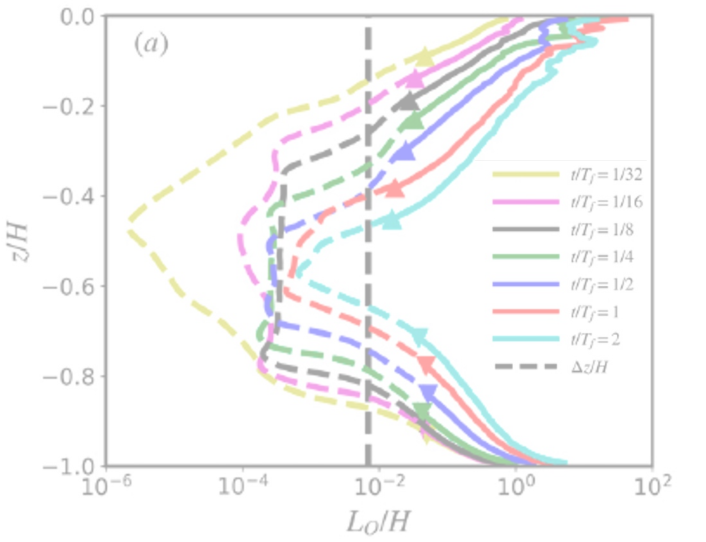


Coastal seas: major contributors to carbon export and primary production

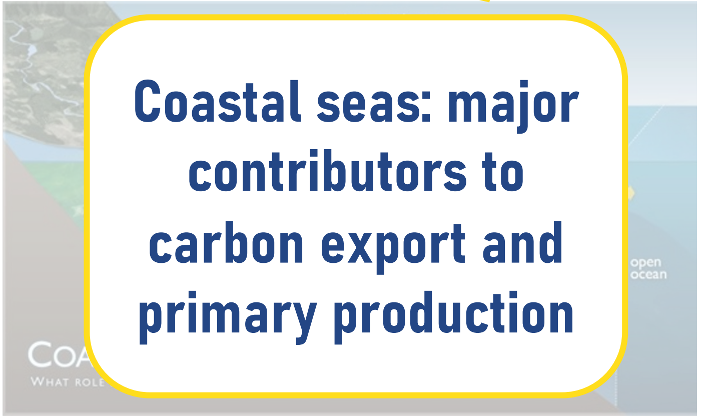
[Bianchi (2005)]
[Simpson and Sharples (2012)]





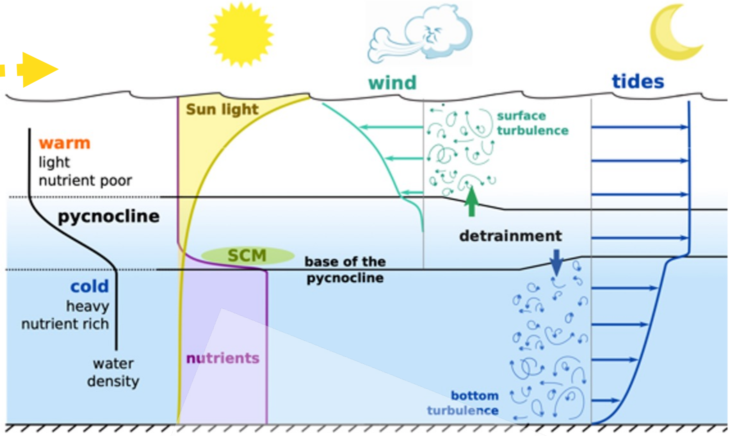


Background – Boundary layers growth impact interior mixing in shallow seas

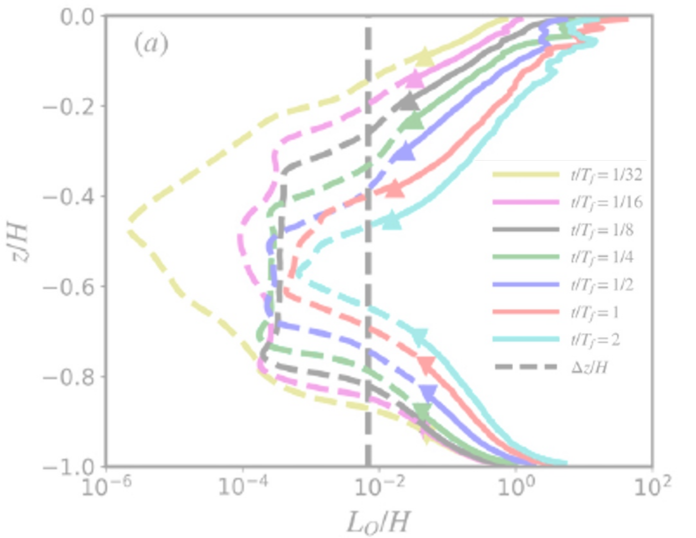


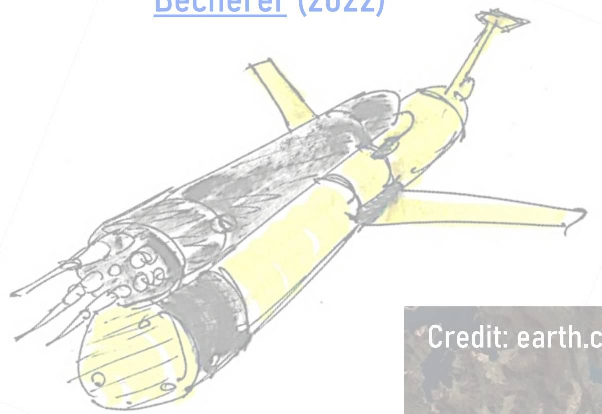
Coastal seas: major contributors to carbon export and primary production

Bianchi (2005)
Simpson and Sharples (2012)

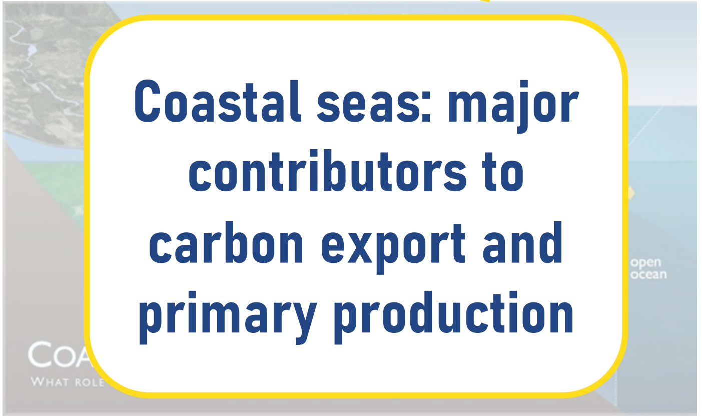


Becherer (2022)



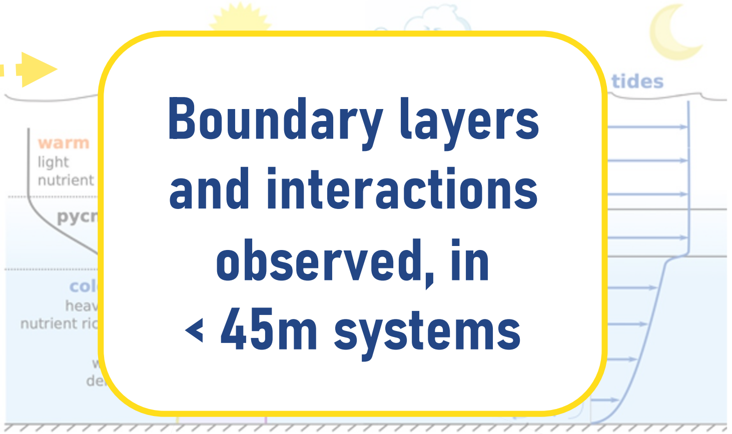


Background – Boundary layers growth impact interior mixing in shallow seas



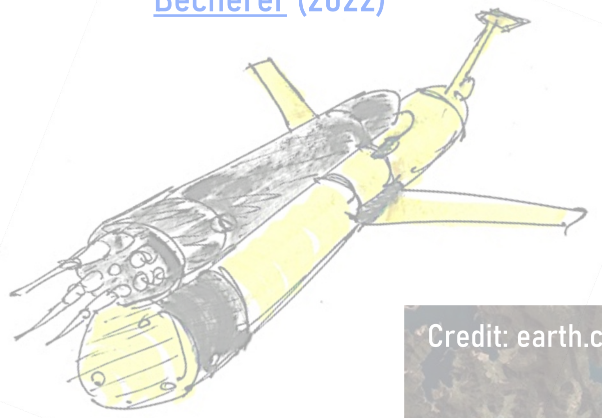
Coastal seas: major contributors to carbon export and primary production

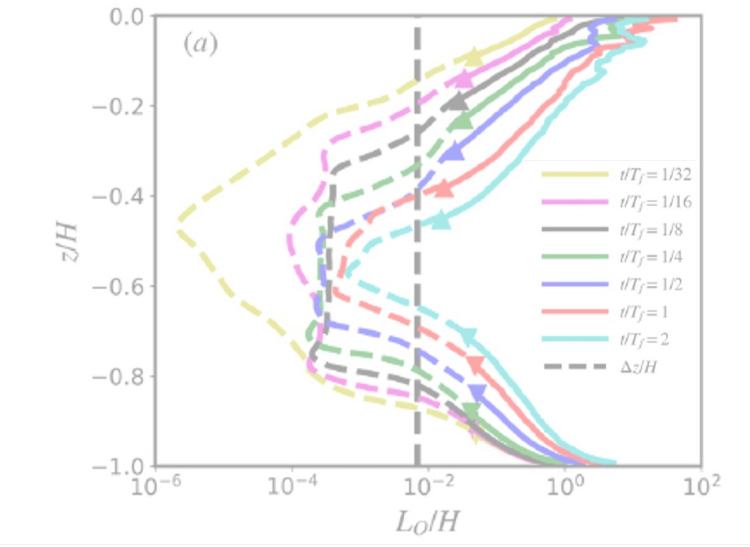
Bianchi (2005)
Simpson and Sharples (2012)



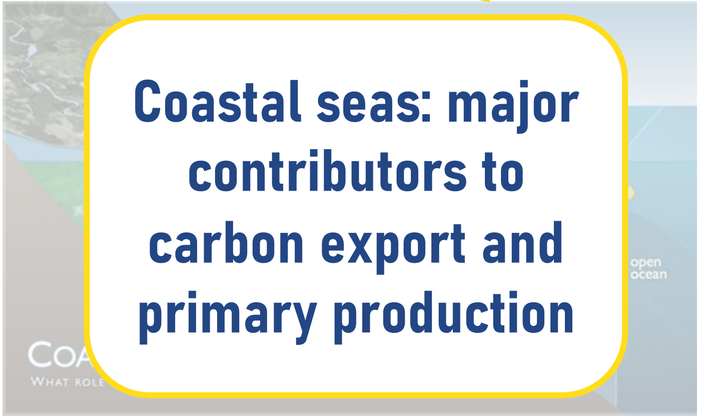
Boundary layers and interactions observed, in < 45m systems

Becherer (2022)



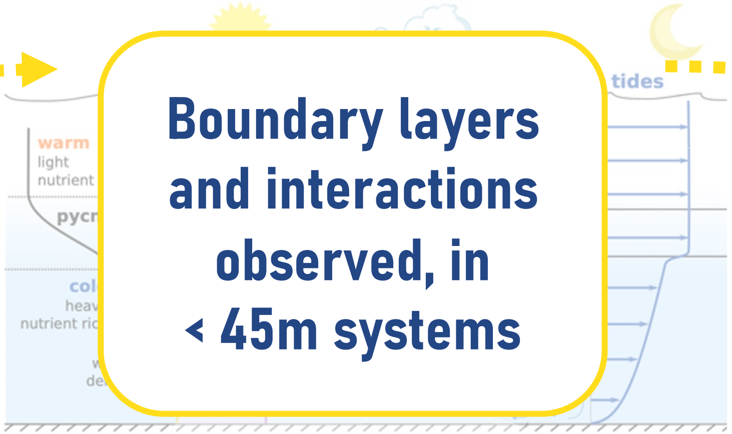


Background – Boundary layer interactions remain challenging to observe



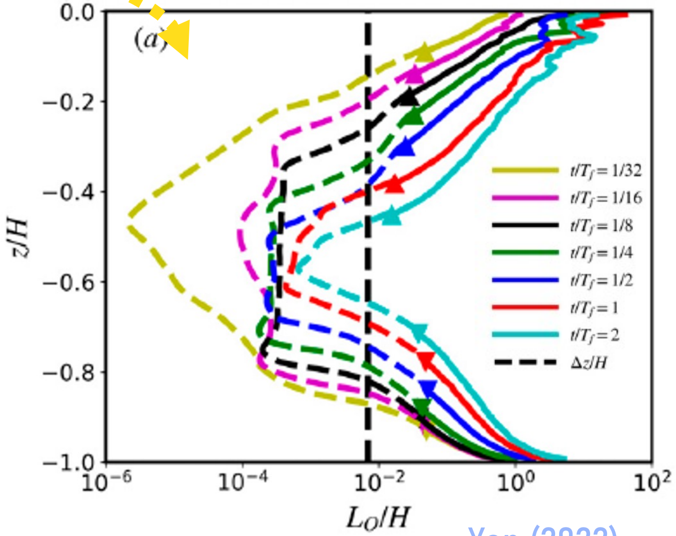
Coastal seas: major contributors to carbon export and primary production

Bianchi (2005)
Simpson and Sharples (2012)



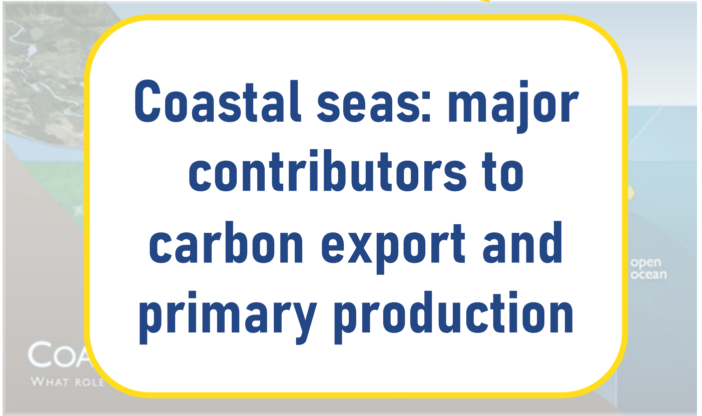
Boundary layers and interactions observed, in < 45m systems

Becherer (2022)



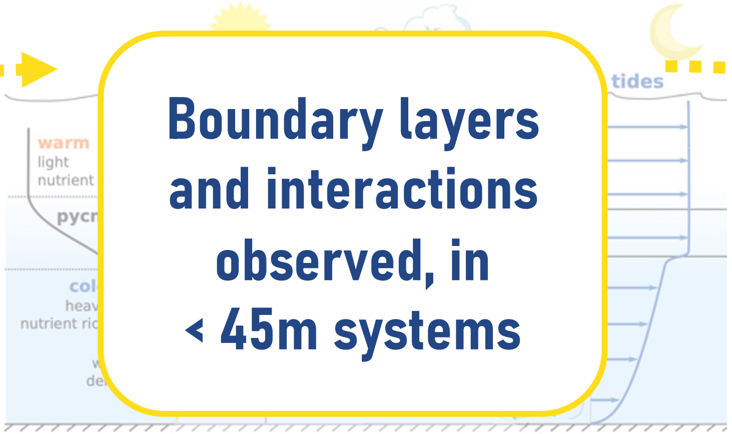
Yan (2022)
Jabbari (2021)

Background – Boundary layer interactions remain challenging to observe



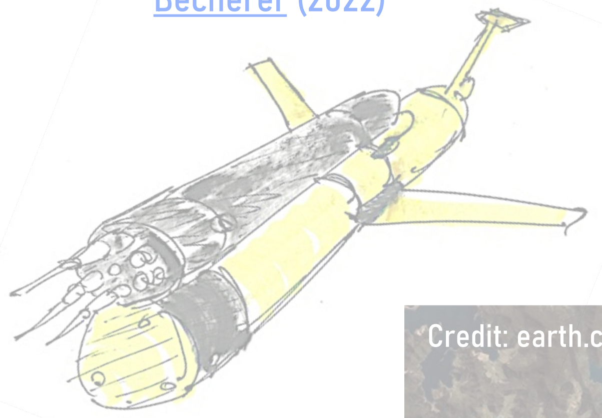
Coastal seas: major contributors to carbon export and primary production

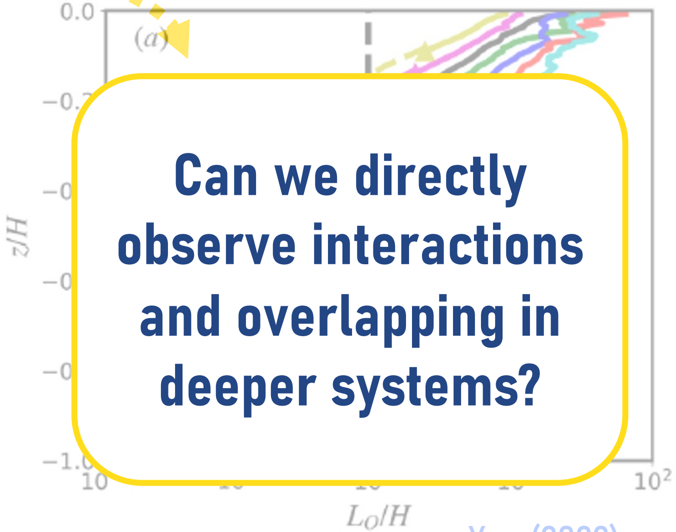
Bianchi (2005)
Simpson and Sharples (2012)



Boundary layers and interactions observed, in < 45m systems

Becherer (2022)

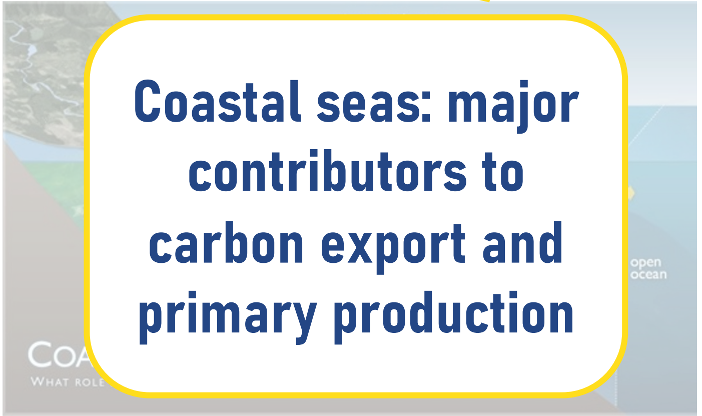




Can we directly observe interactions and overlapping in deeper systems?

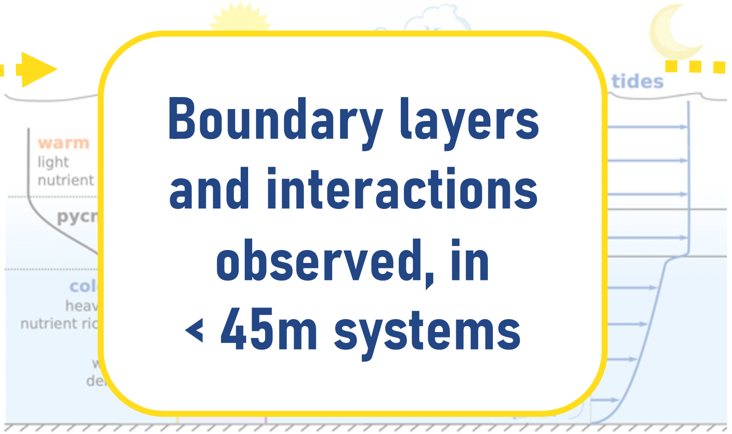
Yan (2022)
Jabbari (2021)

Background – Te Moana o Raukawa / Cook Strait: ideal laboratory?



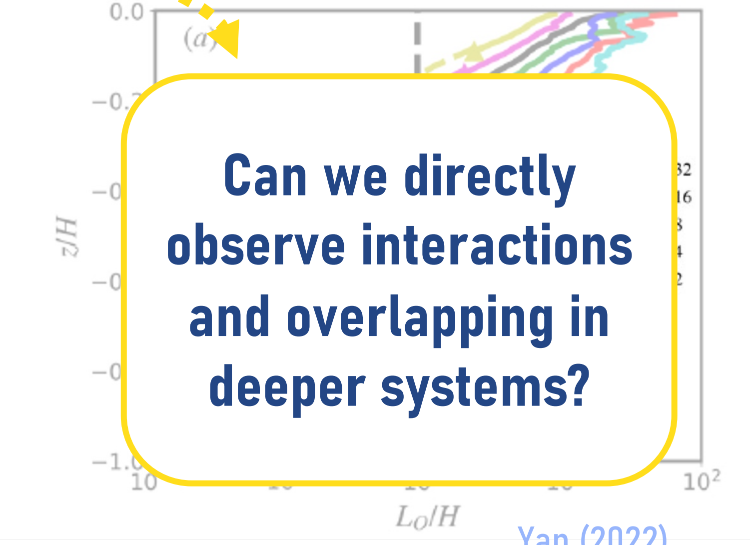
Coastal seas: major contributors to carbon export and primary production

Bianchi (2005)
Simpson and Sharples (2012)



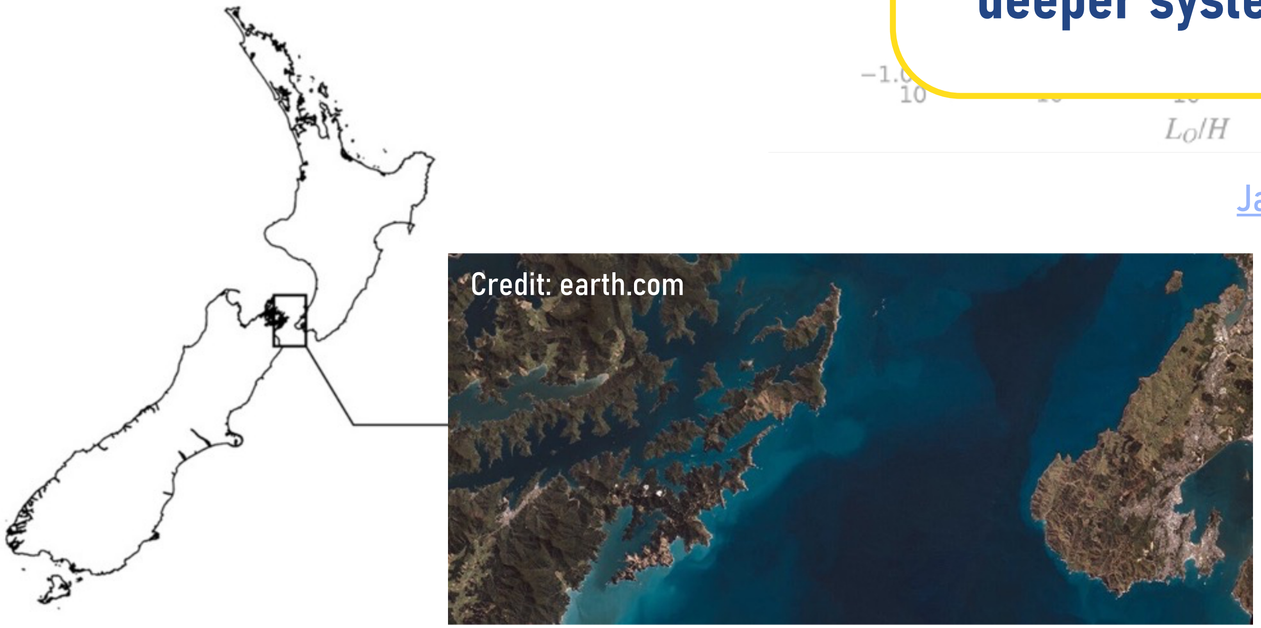
Boundary layers and interactions observed, in < 45m systems

Becherer (2022)



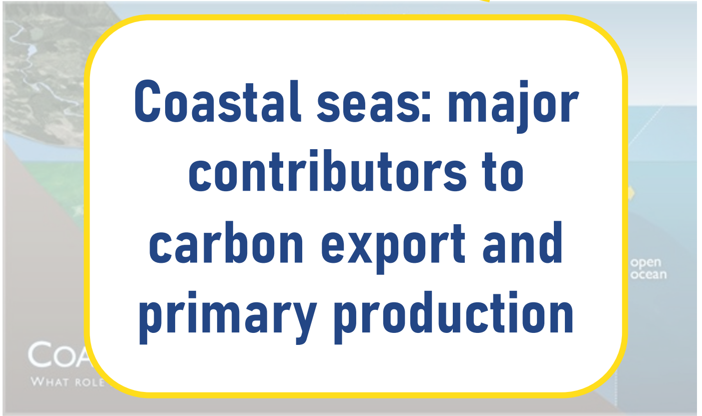
Can we directly observe interactions and overlapping in deeper systems?

Yan (2022)
Jabbari (2021)



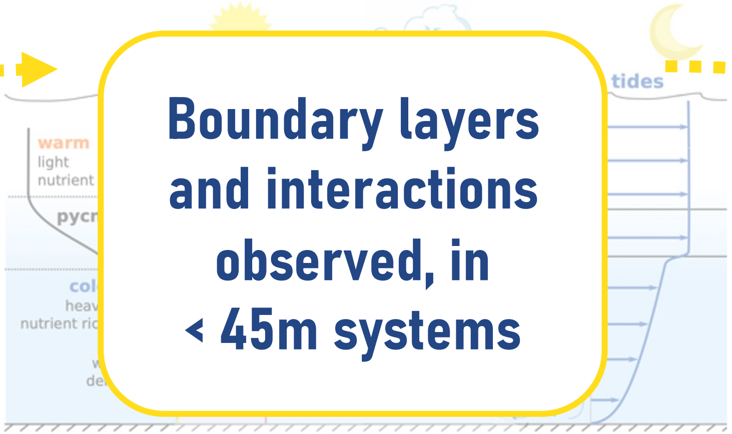
Stevens (2018)
Schultze (2020)

Background – Boundary layer interactions remain challenging to observe



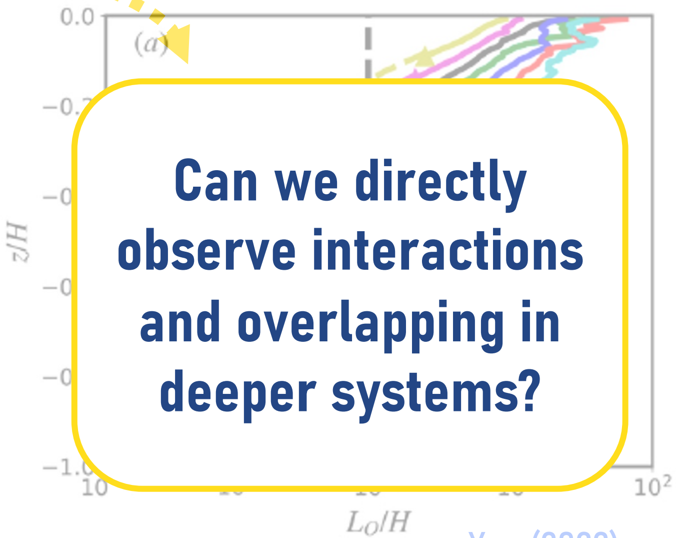
Coastal seas: major contributors to carbon export and primary production

Bianchi (2005)
Simpson and Sharples (2012)



Boundary layers and interactions observed, in < 45m systems

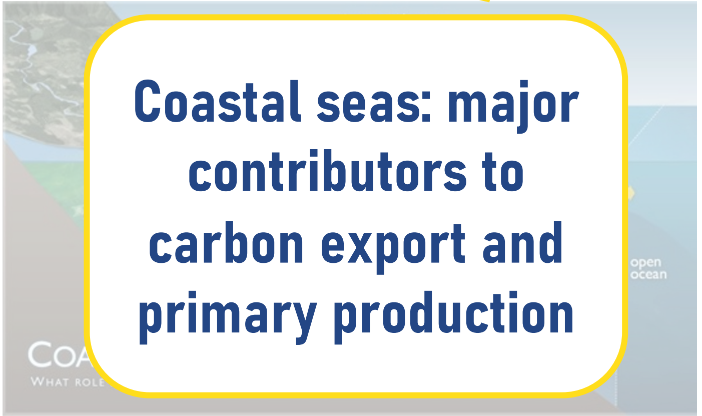
Becherer (2022)



Can we directly observe interactions and overlapping in deeper systems?

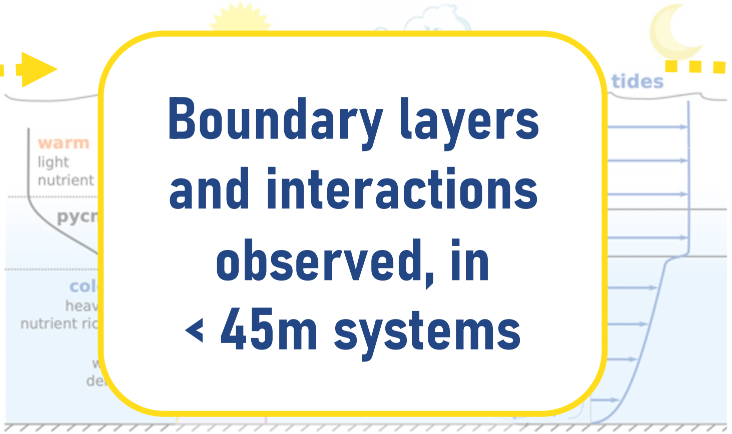
Yan (2022)
Jabbari (2021)

Background – Te Moana o Raukawa / Cook Strait: ideal laboratory?



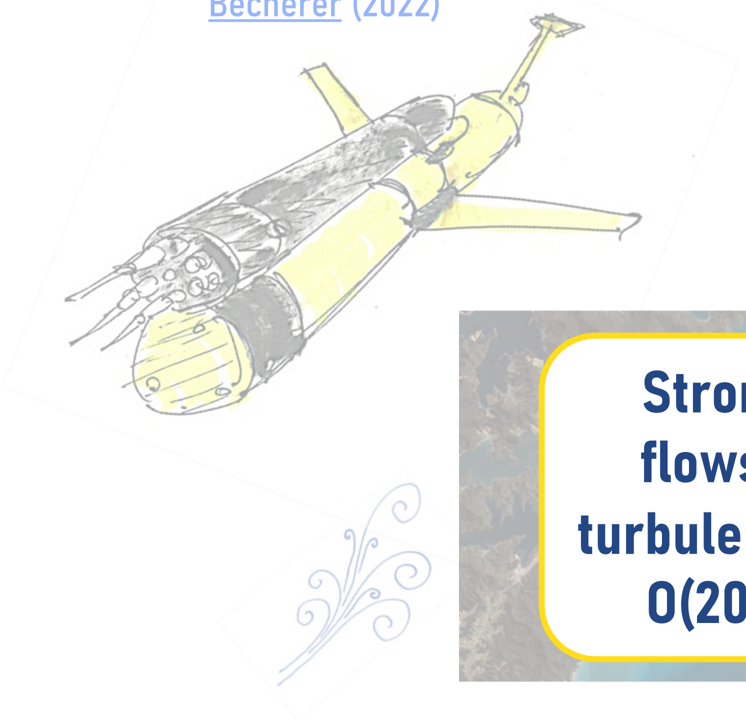
Coastal seas: major contributors to carbon export and primary production

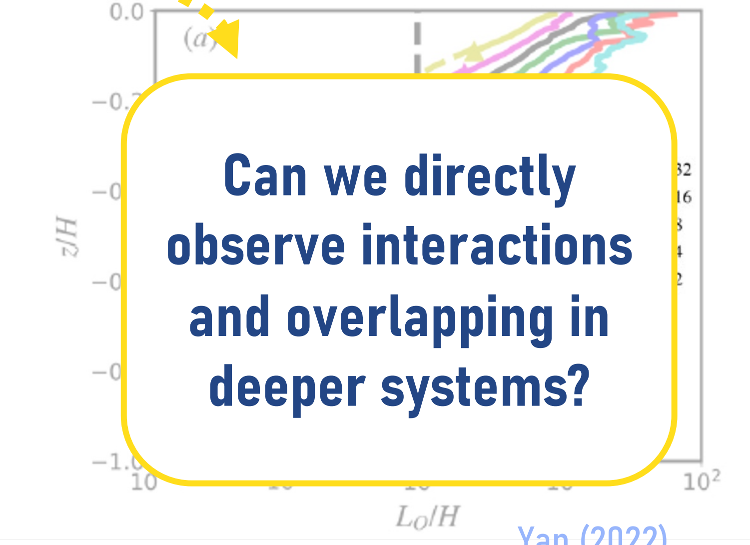
Bianchi (2005)
Simpson and Sharples (2012)



Boundary layers and interactions observed, in < 45m systems

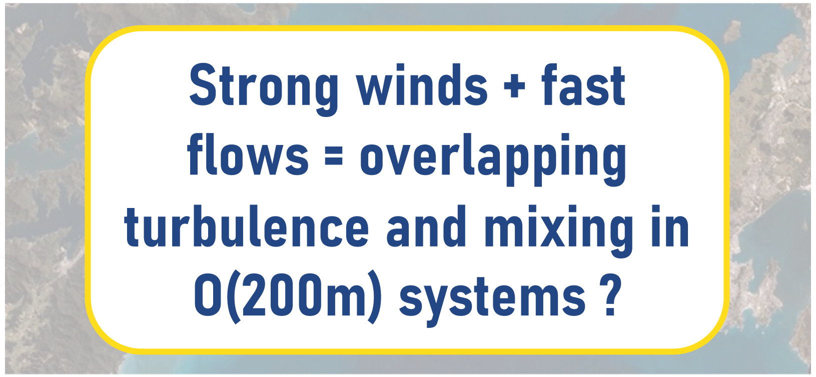
Becherer (2022)





Can we directly observe interactions and overlapping in deeper systems?

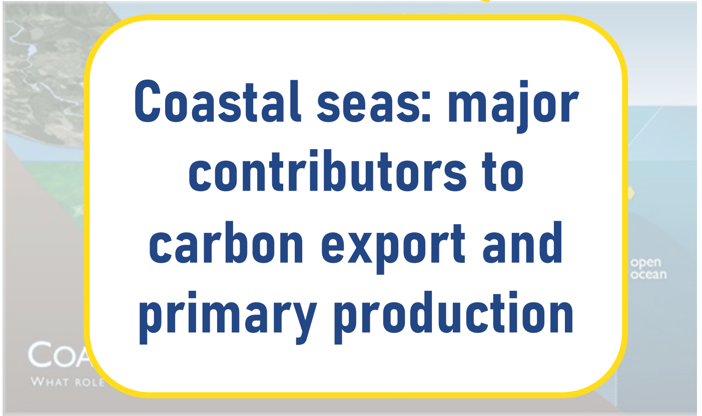
Yan (2022)
Jabbari (2021)



Strong winds + fast flows = overlapping turbulence and mixing in O(200m) systems ?

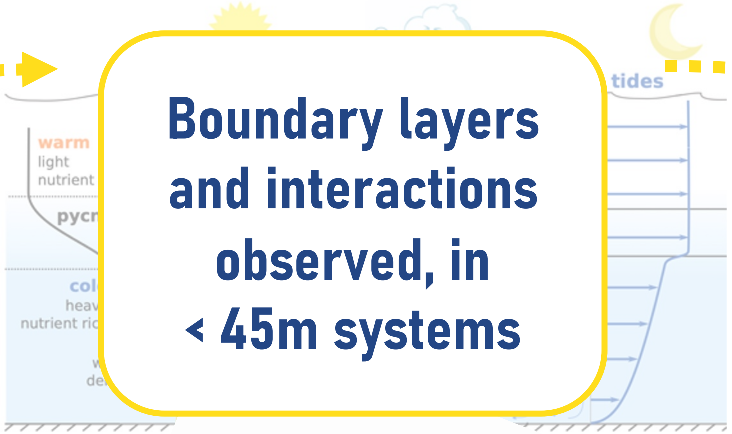
Stevens (2018)
Schultze (2020)

Background – Continuous sampling with an Ocean Microstructure Glider (OMG)



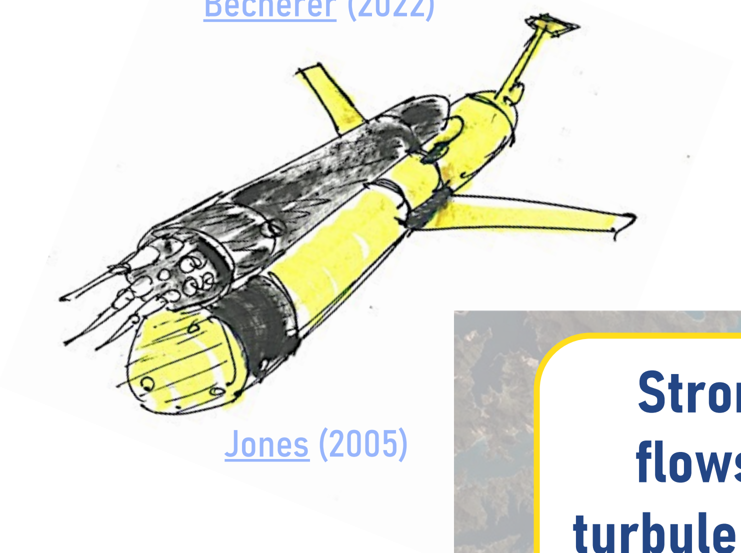
Coastal seas: major contributors to carbon export and primary production

Bianchi (2005)
Simpson and Sharples (2012)



Boundary layers and interactions observed, in < 45m systems

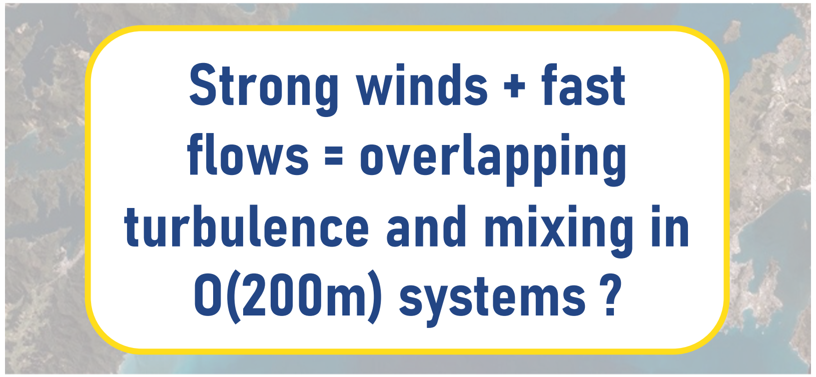
Becherer (2022)



Jones (2005)

Can we directly observe interactions and overlapping in deeper systems?

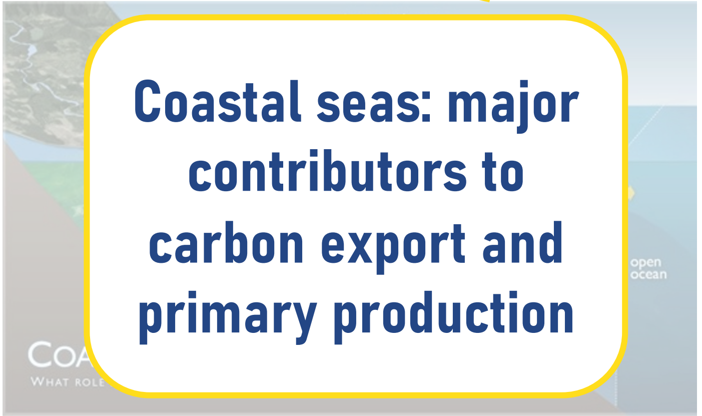
Yan (2022)
Jabbari (2021)



Strong winds + fast flows = overlapping turbulence and mixing in O(200m) systems ?

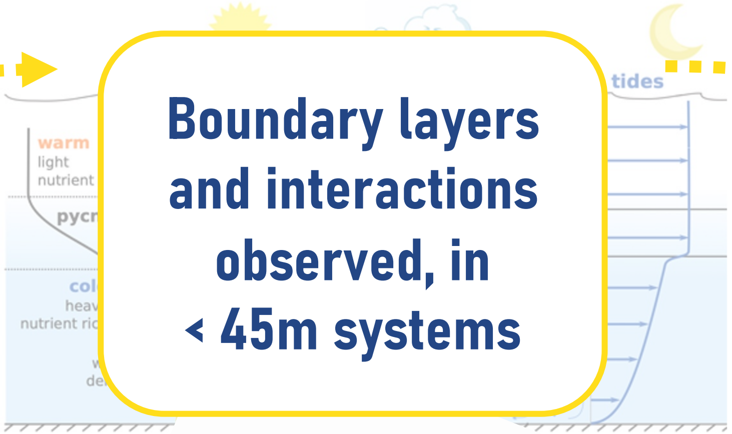
Stevens (2018)
Schultze (2020)

Background – Conductivity Temperature Depth (CTD) payload for stratification



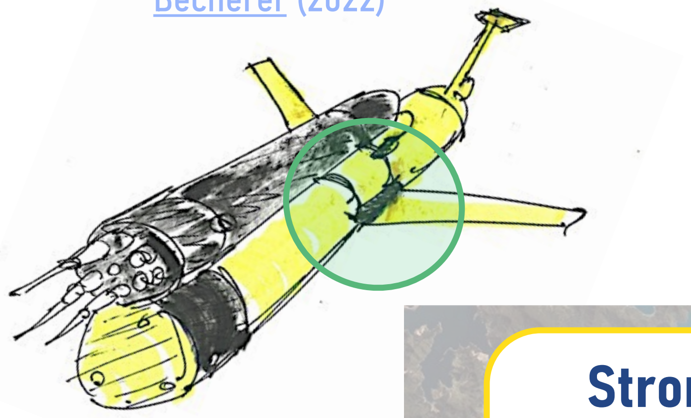
Coastal seas: major contributors to carbon export and primary production

Bianchi (2005)
Simpson and Sharples (2012)



Boundary layers and interactions observed, in < 45m systems

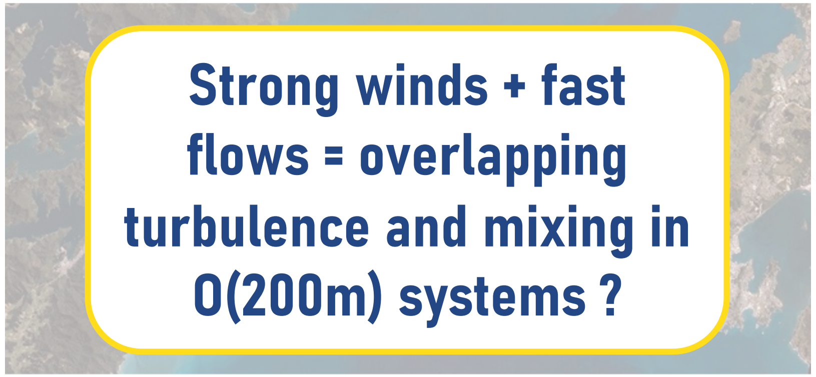
Becherer (2022)



Jones (2005)

Can we directly observe interactions and overlapping in deeper systems?

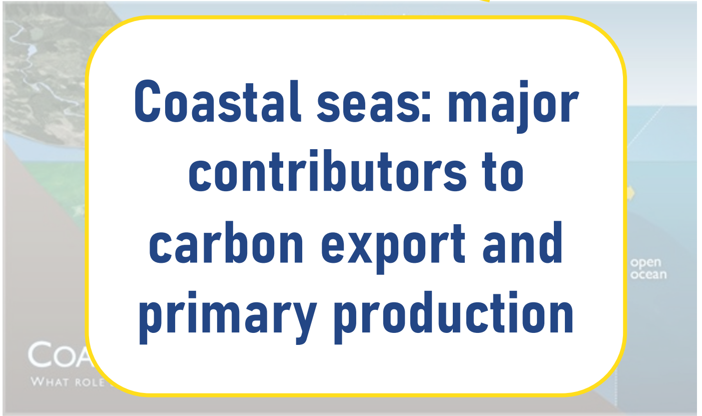
Yan (2022)
Jabbari (2021)



Strong winds + fast flows = overlapping turbulence and mixing in O(200m) systems ?

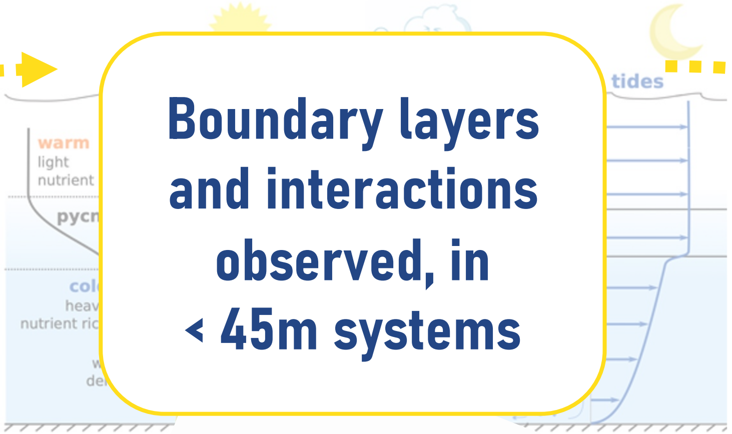
Stevens (2018)
Schultze (2020)

Background – Rockland MicroRider to sample turbulence microstructure



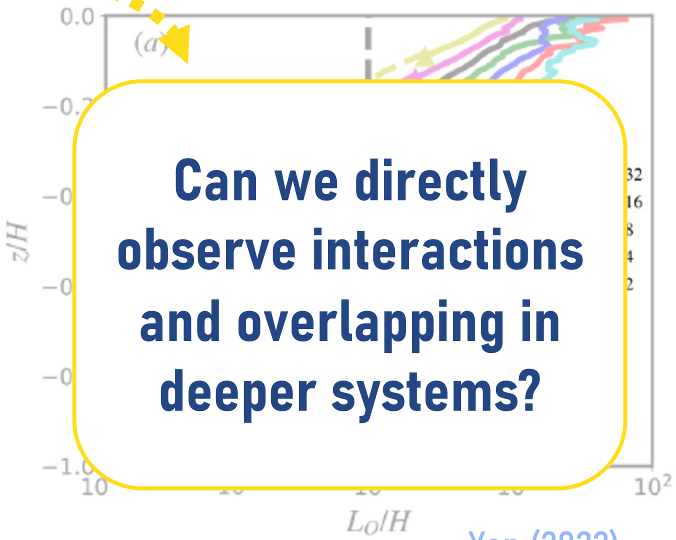
Coastal seas: major contributors to carbon export and primary production

Bianchi (2005)
Simpson and Sharples (2012)



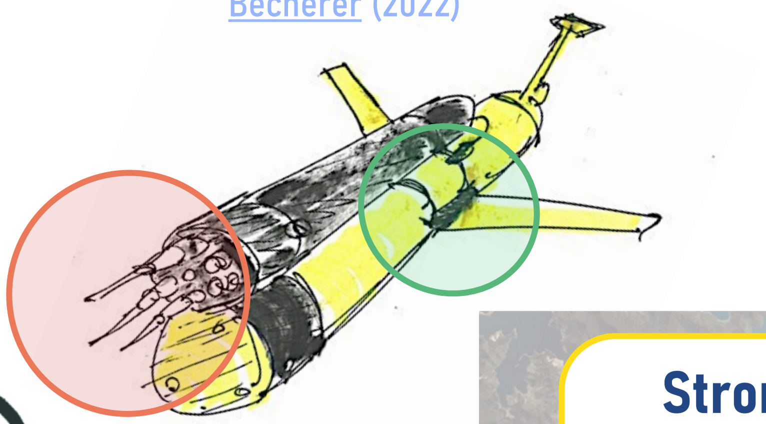
Boundary layers and interactions observed, in < 45m systems

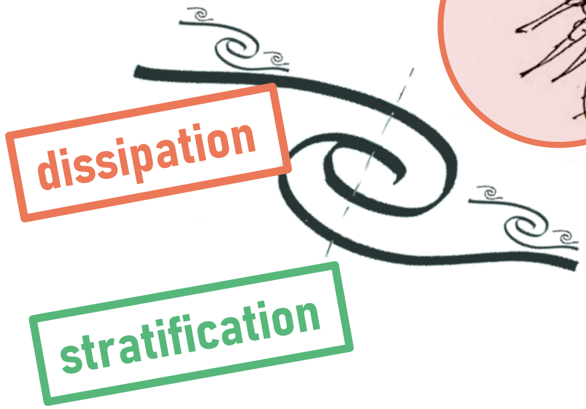
Becherer (2022)



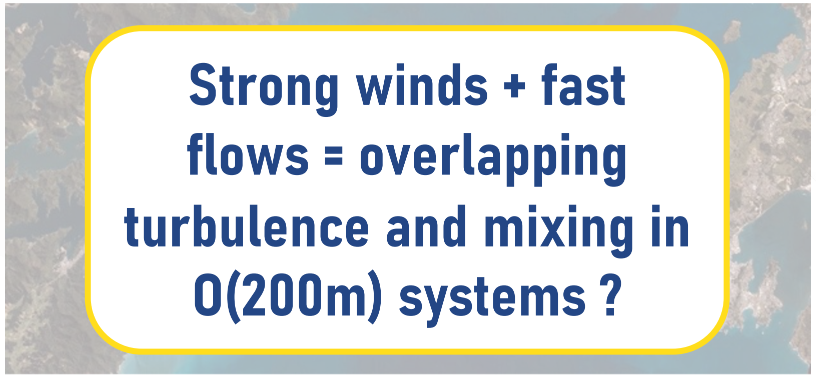
Can we directly observe interactions and overlapping in deeper systems?

Yan (2022)
Jabbari (2021)





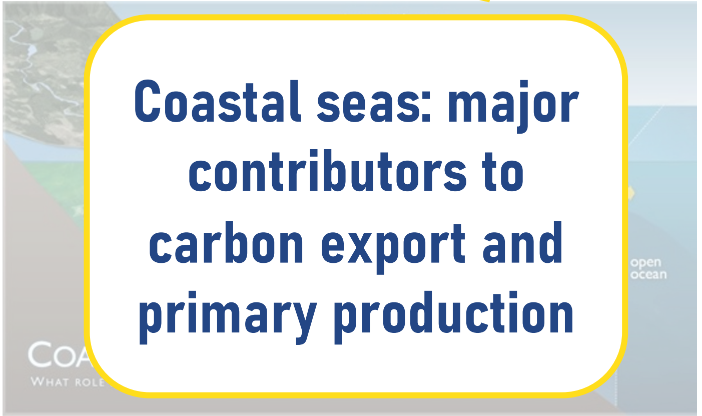
Jones (2005)
Fer (2014)
Peterson (2014)
Oakey (1982)
Lueck (2016)



Strong winds + fast flows = overlapping turbulence and mixing in O(200m) systems ?

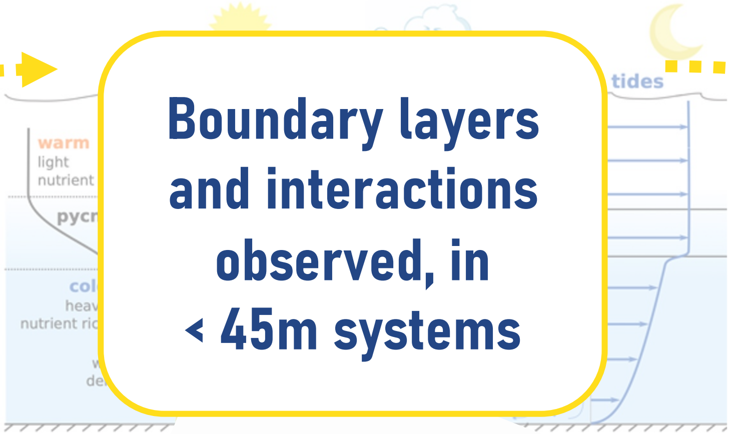
Stevens (2018)
Schultze (2020)

Background – Osborn formula for diapycnal diffusivity



Coastal seas: major contributors to carbon export and primary production

Bianchi (2005)
Simpson and Sharples (2012)

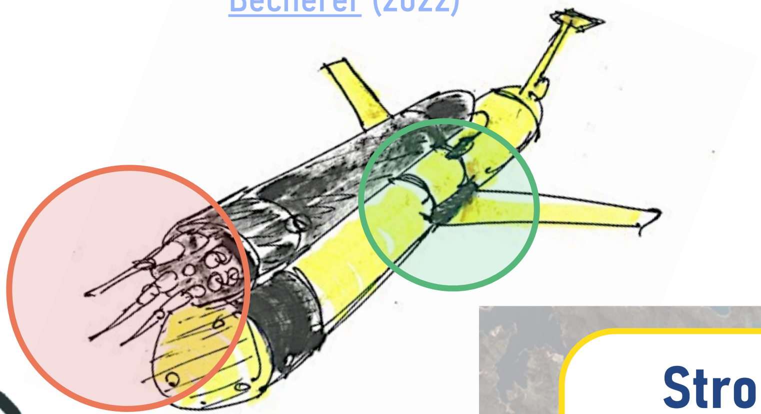


Boundary layers and interactions observed, in < 45m systems

Becherer (2022)

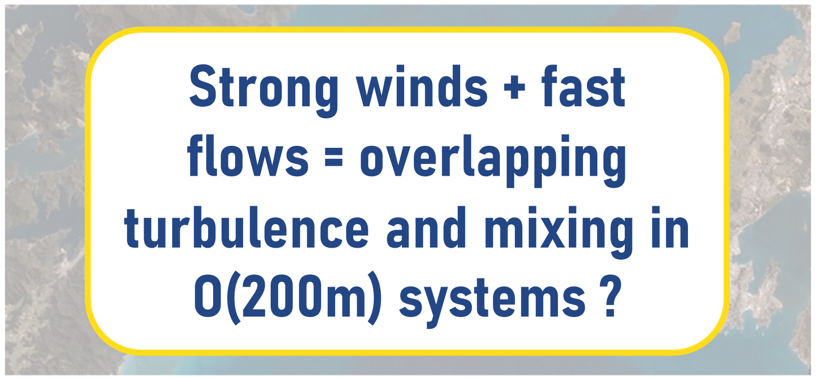
Can we directly observe interactions and overlapping in deeper systems?

Yan (2022)
Jabbari (2021)



Jones (2005)
Fer (2014)
Peterson (2014)
Oakey (1982)
Lueck (2016)
Osborn (1980)

vertical diffusivity of mass ∝ **dissipation** / **stratification**



Strong winds + fast flows = overlapping turbulence and mixing in O(200m) systems ?

Stevens (2018)
Schultze (2020)

Overview

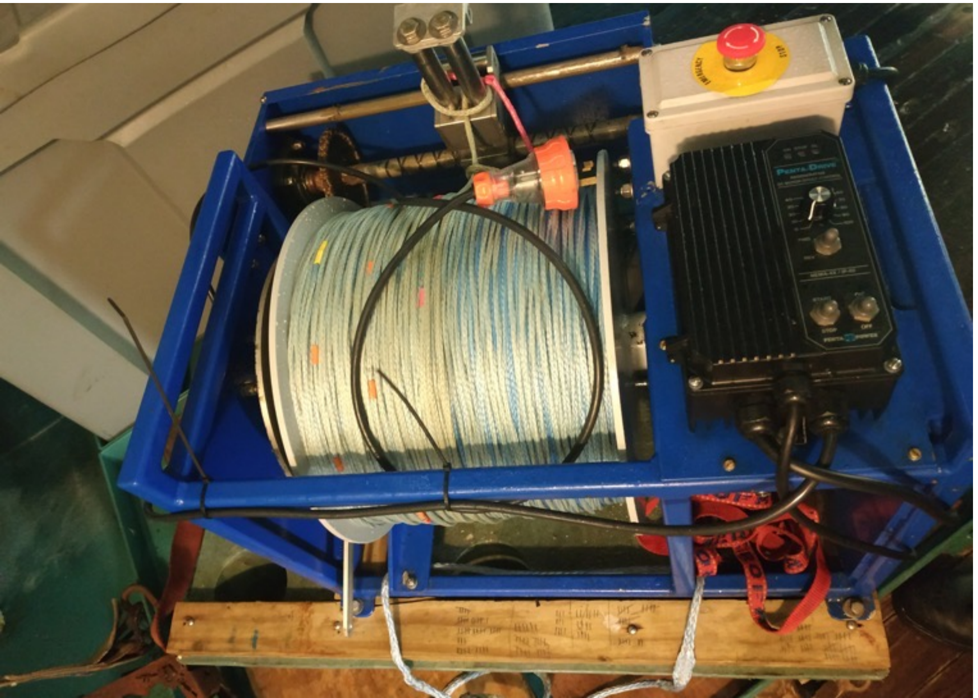
What was the motivation ?

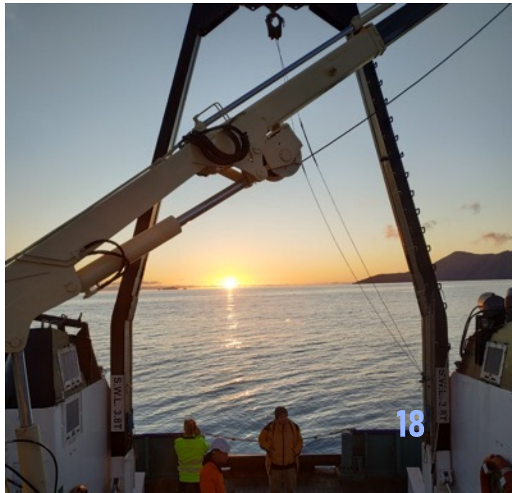
How did we approach the problem ?

What did we find ?

What are we following up on ?

CookieMonster 2020





CookieMonster 2020 – OMG what a journey

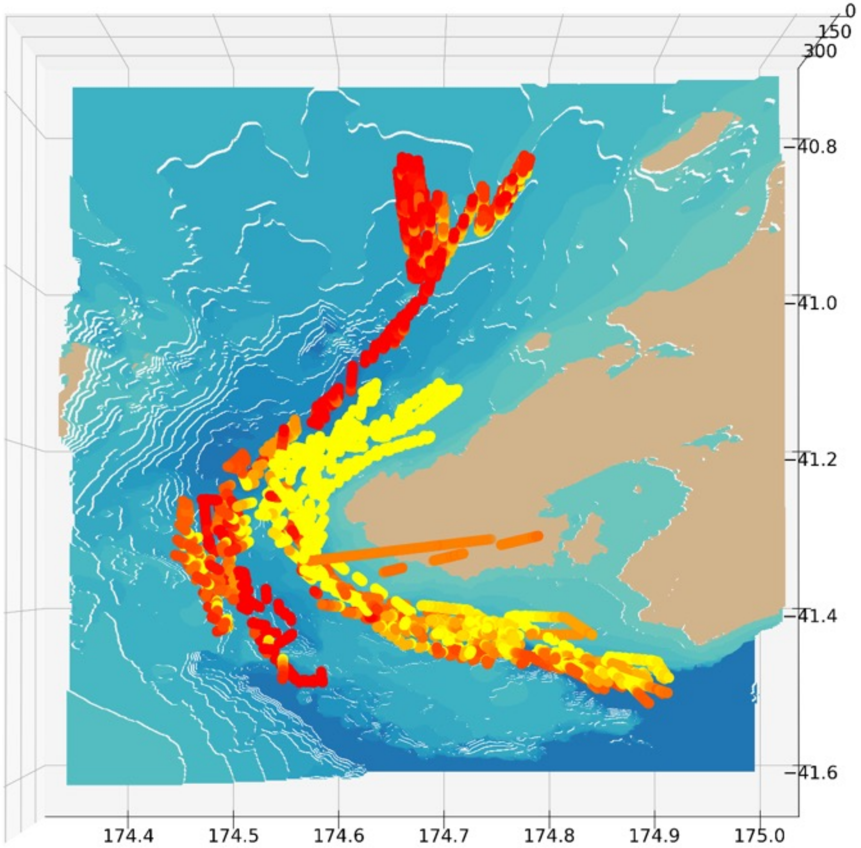
17 days of continuous sampling

~1300 profiles of T & S
x2 for microstructure casts

Sampled depths in 50-650m
As close as 5m from the seabed
As close as 1m from the surface

Handled up to 2 $m.s^{-1}$ integrated tidal flows

Handled up to 120 $km.h^{-1}$ winds



CookieMonster 2020 – OMG what a journey

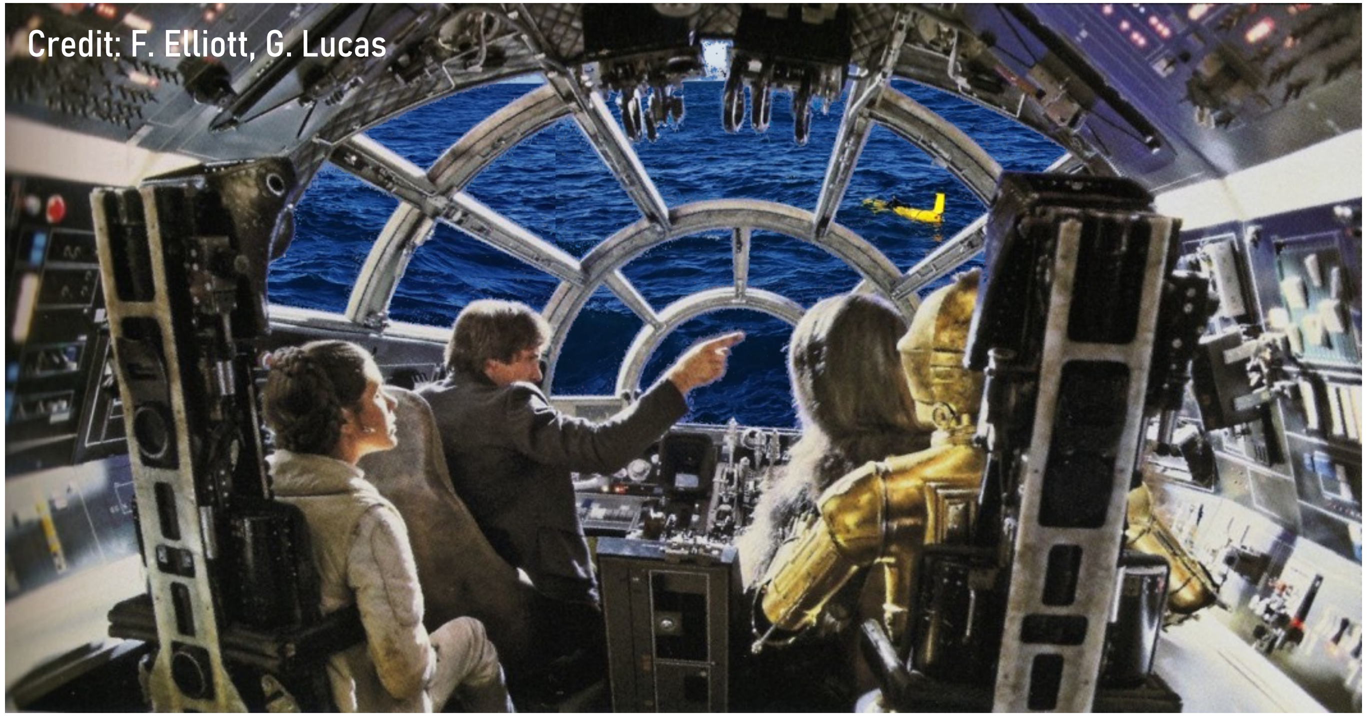
17 days of continuous sampling

~1300 profiles of T & S
x2 for microstructure casts

Sampled depths in 50-650m
As close as 5m from the seabed
As close as 1m from the surface

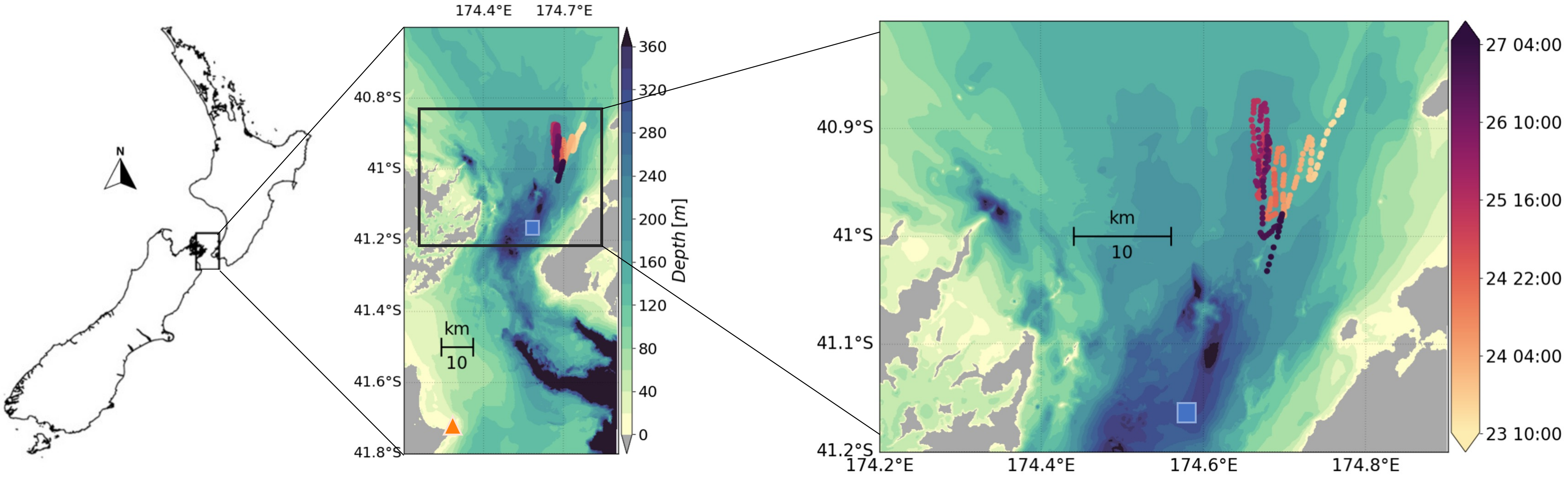
Handled up to 2 $m.s^{-1}$ integrated tidal flows

Handled up to 120 $km.h^{-1}$ winds



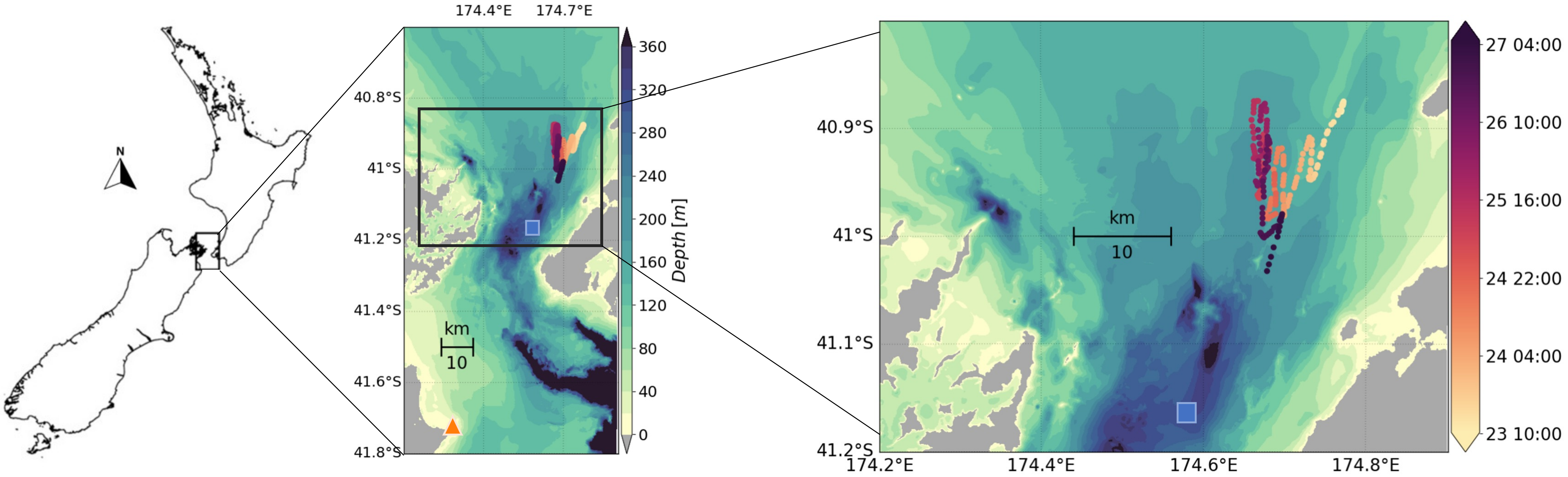
Success of the mission = Joe O'Callaghan + Fiona Elliott

CookieMonster 2020 – 4 days subset, with flow measurements



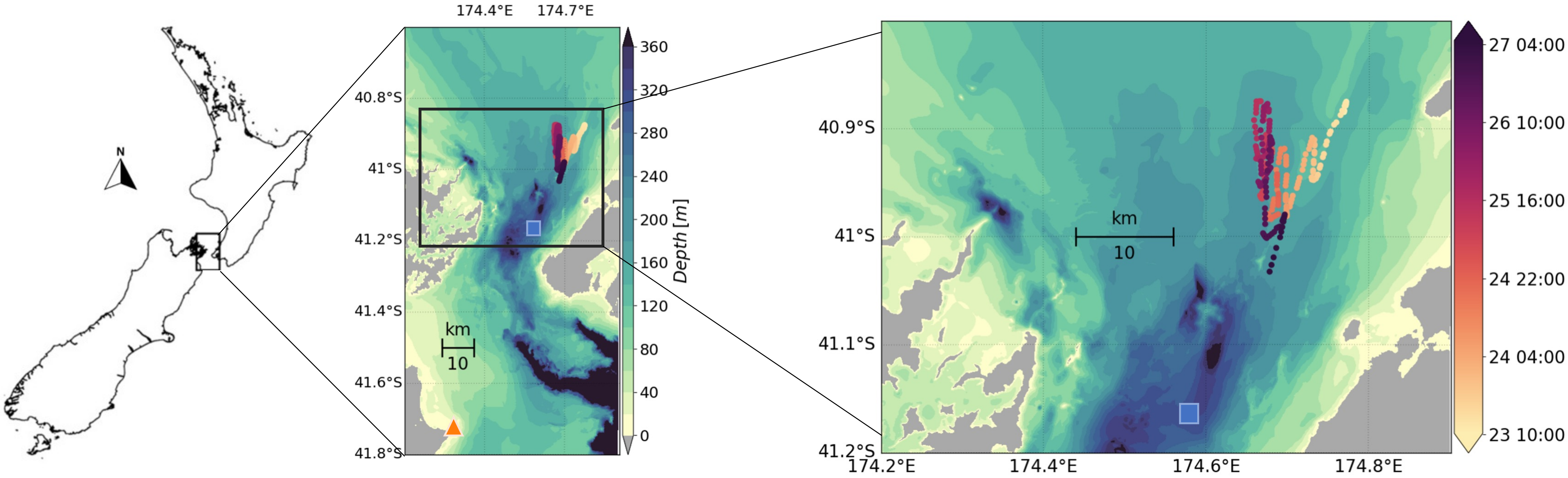
- Acoustic Doppler Current Profiler (ADCP) $\longrightarrow$ 55 Hz flow speeds U,V in 5 m depth bins $\longrightarrow$ tidal shear phases

CookieMonster 2020 – 4 days subset of regional hourly winds



- ■ Acoustic Doppler Current Profiler (ADCP) ⟶ 55 Hz flow speeds U,V in 5 m depth bins ⟶ tidal shear phases
- ▲ Atmospheric Weather Station (AWS) ⟶ hourly wind speeds at 10 m ⟶ surface stress signal

CookieMonster 2020 – 4 days subset of OMG measurements



- Acoustic Doppler Current Profiler (ADCP) → 55 Hz flow speeds U,V in 5 m depth bins → tidal shear phases
- Atmospheric Weather Station (AWS) → hourly wind speeds at 10 m → surface stress signal
- Ocean Microstructure Glider (OMG) → ~1 m resolution state variables θ, S, σ → buoyancy frequency N^2
  → 512 Hz microstructure shear → dissipation rates ϵ

Oakey (1982) Lueck (2016)

Overview

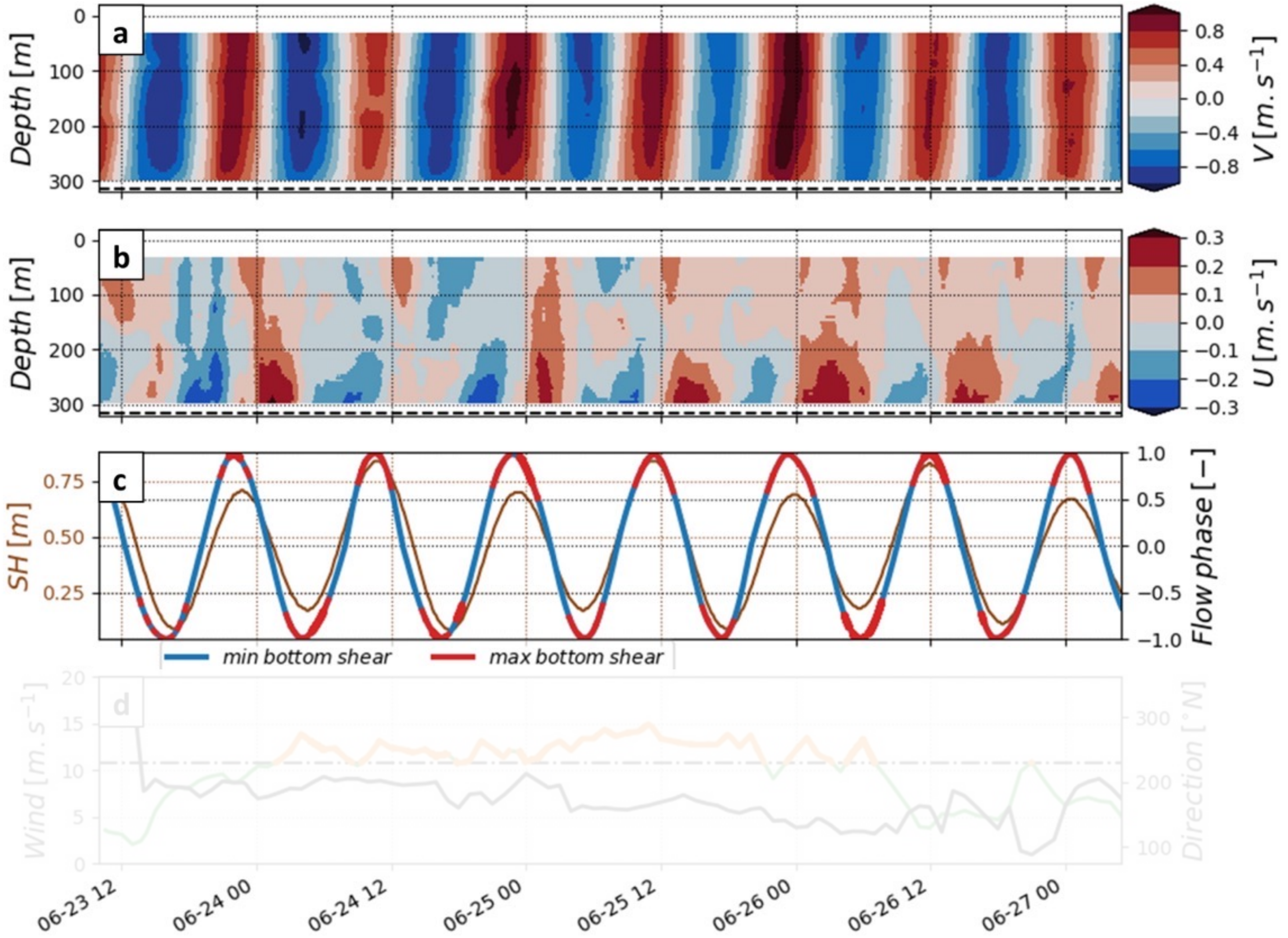
What was the motivation ?

How did we approach the problem ?

What did we find ?

What are we following up on ?

Results – Fast, strongly-sheared tidal flows

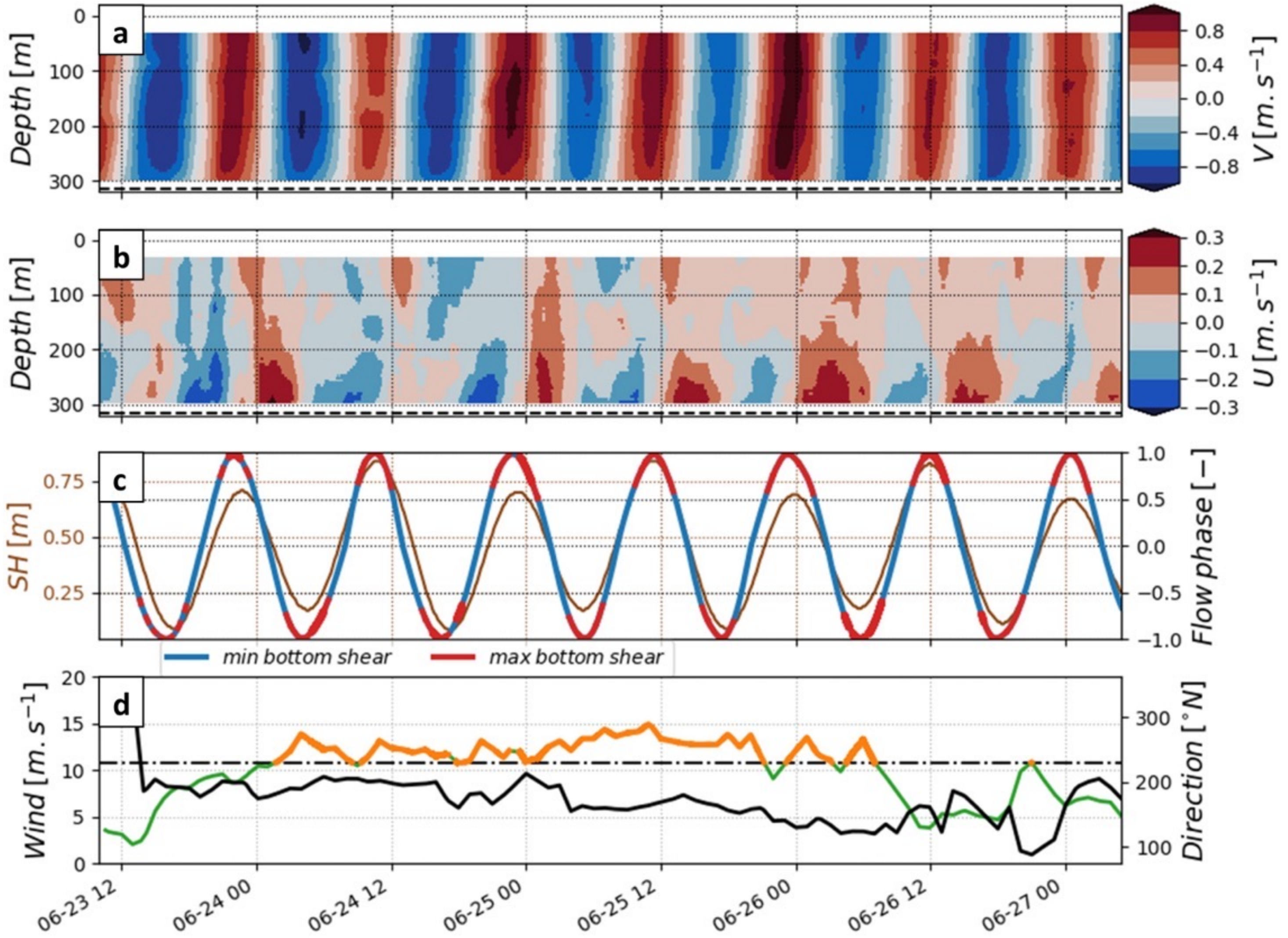


Fast tidally-driven flows
± 1.2 m.s^{-1} along strait primary flows
± 0.3 m.s^{-1} cross strait secondary circulation
$\rightarrow$ Strong bottom drag & velocity shear

Consistent with previous regional studies
Vennell (1998a,b), Stevens (2012, 2014)

Wind speeds mainly in 10-15 m.s^{-1}
Storm-like conditions Schultze (2020)

Results – Strong breeze to moderate gale winds



Fast tidally-driven flows

± 1.2 m.s^{-1} along strait primary flows

± 0.3 m.s^{-1} cross strait secondary circulation

→ Strong bottom drag & velocity shear

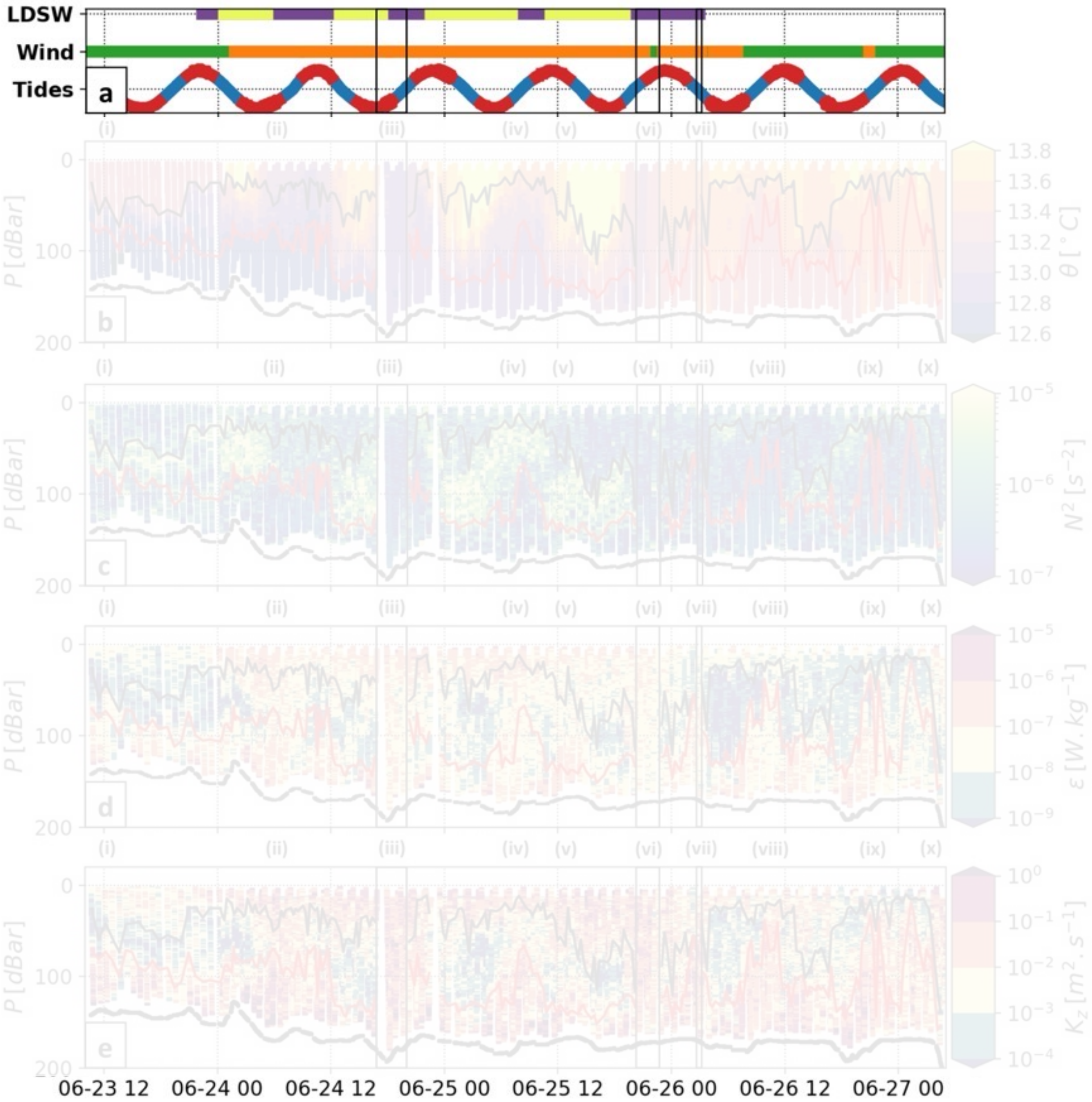
Consistent with previous regional studies

Vennell (1998a,b), Stevens (2012, 2014)

Wind speeds reaching 10-15 m.s^{-1}

Storm-like conditions Schultze (2020)

Results – Three main external forcings



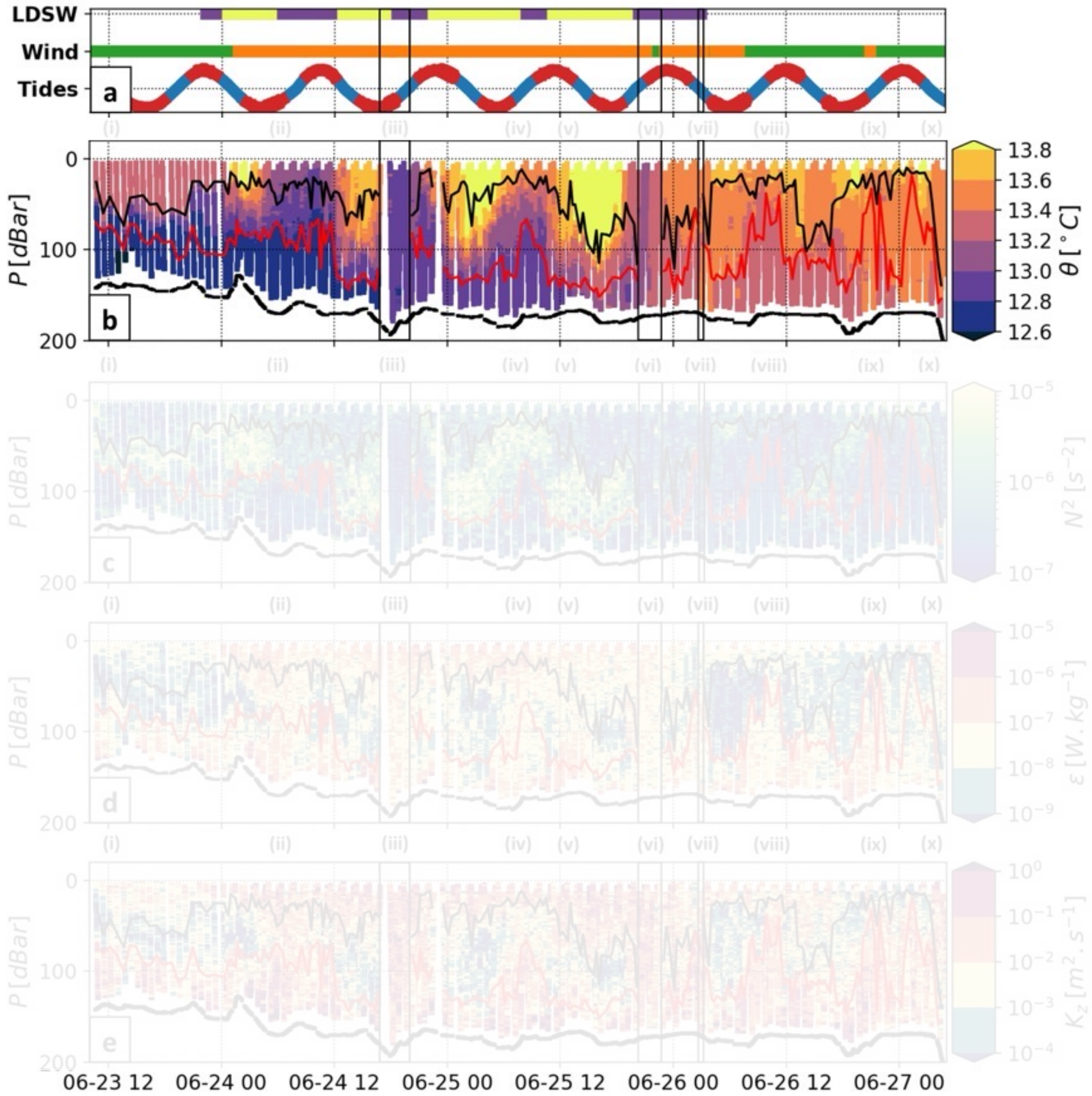
Weak top-bottom θ differences
Overlapping surface and bottom mixed layers in 150-200m depths
Low Density Surface Waters (LDSW), sub-mesoscale signal

Relatively weak stratification, mainly N^2 in 10^{-7} - 10^{-5} s^{-2}
Strengthened interior N^2, at the base of the LDSW
Extending within the bottom and surface layers

Elevated dissipation, mainly ϵ in 10^{-9} - 10^{-5} W.kg^{-1}
Tidal bottom pulses and wind-driven turbulence layer
10 episodes of interior turbulence interactions (i-x)

Strongly enhanced diffusivity, mainly K_z in 10^{-4} - 1 $m^2.s^{-1}$
5 orders of magnitude above similar passages Wesson (1994)
Interior K_z increased 5-30 fold during overlapping, on average

Results – Overlapping of surface and bottom mixed layers



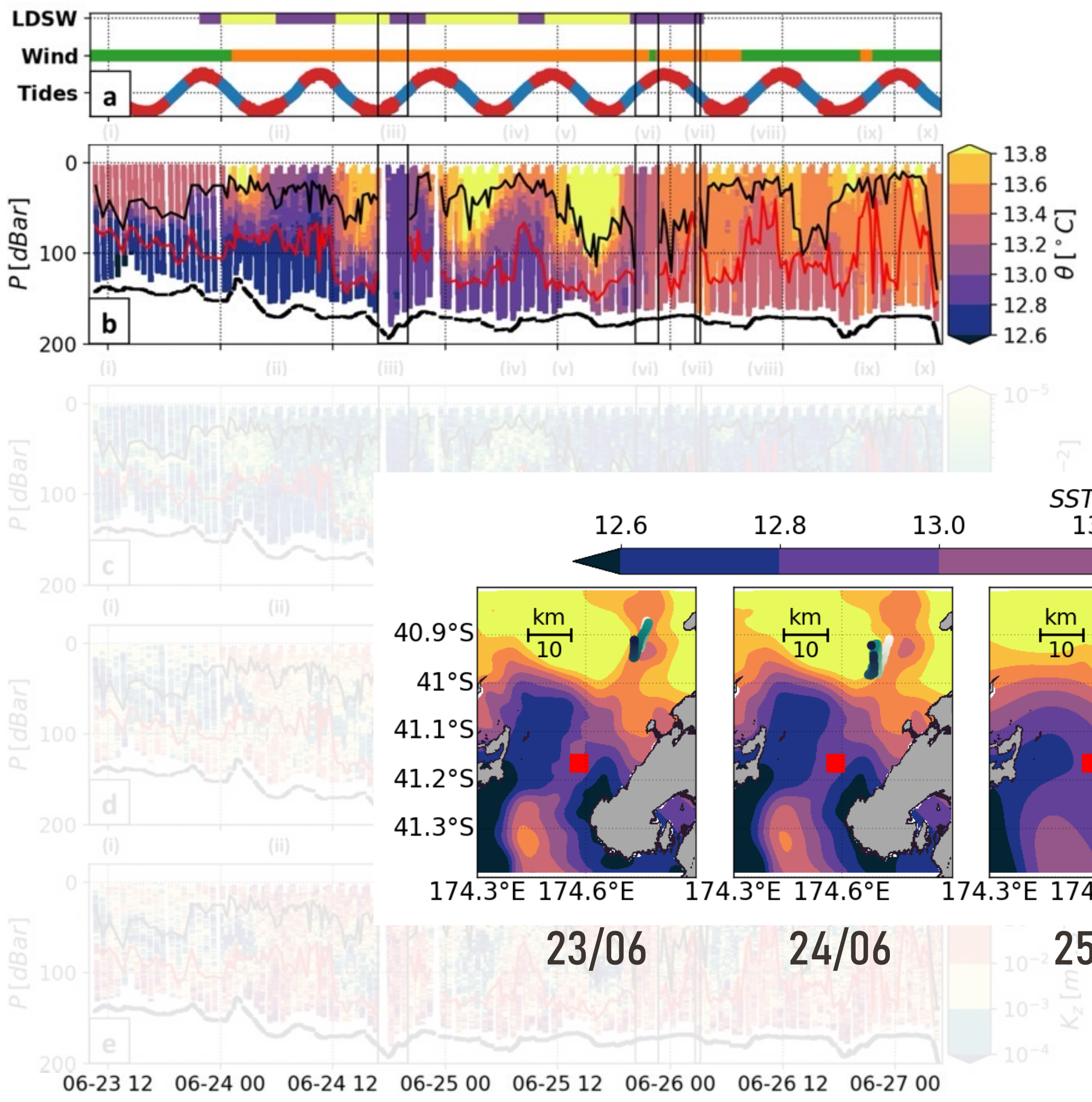
Weak top-bottom θ differences
Overlapping surface and bottom mixed layers in 150-200m depths
Low Density Surface Waters (LDSW), sub-mesoscale signal

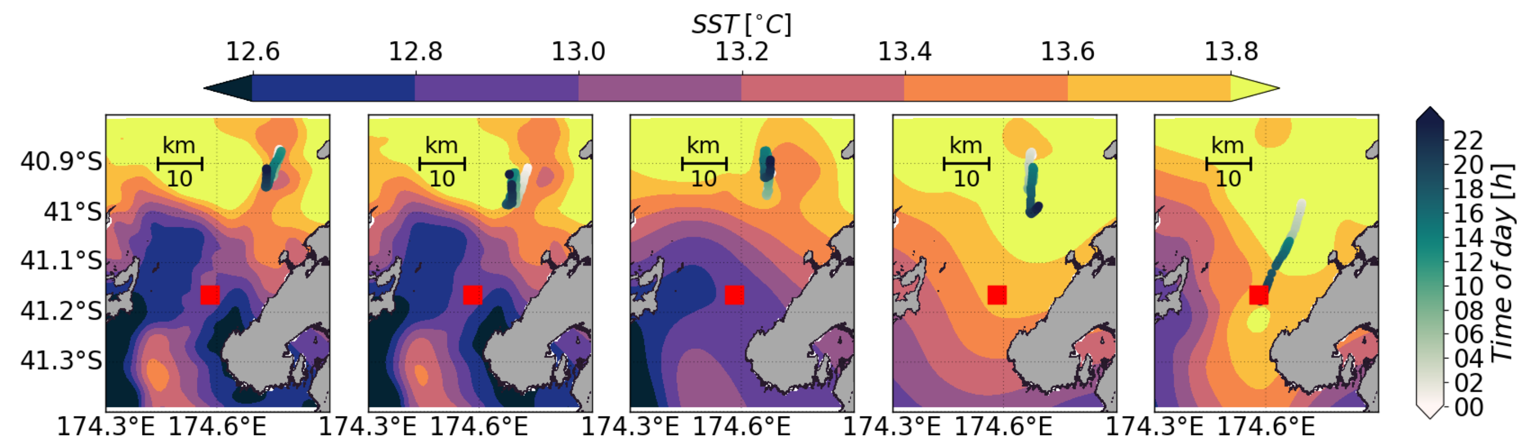
Relatively weak stratification, mainly N^2 in 10^{-7} - 10^{-5} s^{-2}
Strenghtened interior N^2, at the base of the LDSW
Extending within the bottom and surface layers

Elevated dissipation, mainly ϵ in 10^{-9} - 10^{-5} $W.kg^{-1}$
Tidal bottom pulses and wind-driven turbulence layer
10 episodes of interior turbulence interactions (i-x)

Strongly enhanced diffusivity, mainly K_z in 10^{-4} - 1 $m^2.s^{-1}$
5 orders of magnitude above similar passages Wesson (1994)
Interior K_z increased 5-30 fold during overlapping, on average

Results – LDSW from advection of water masses at the sub-mesoscale



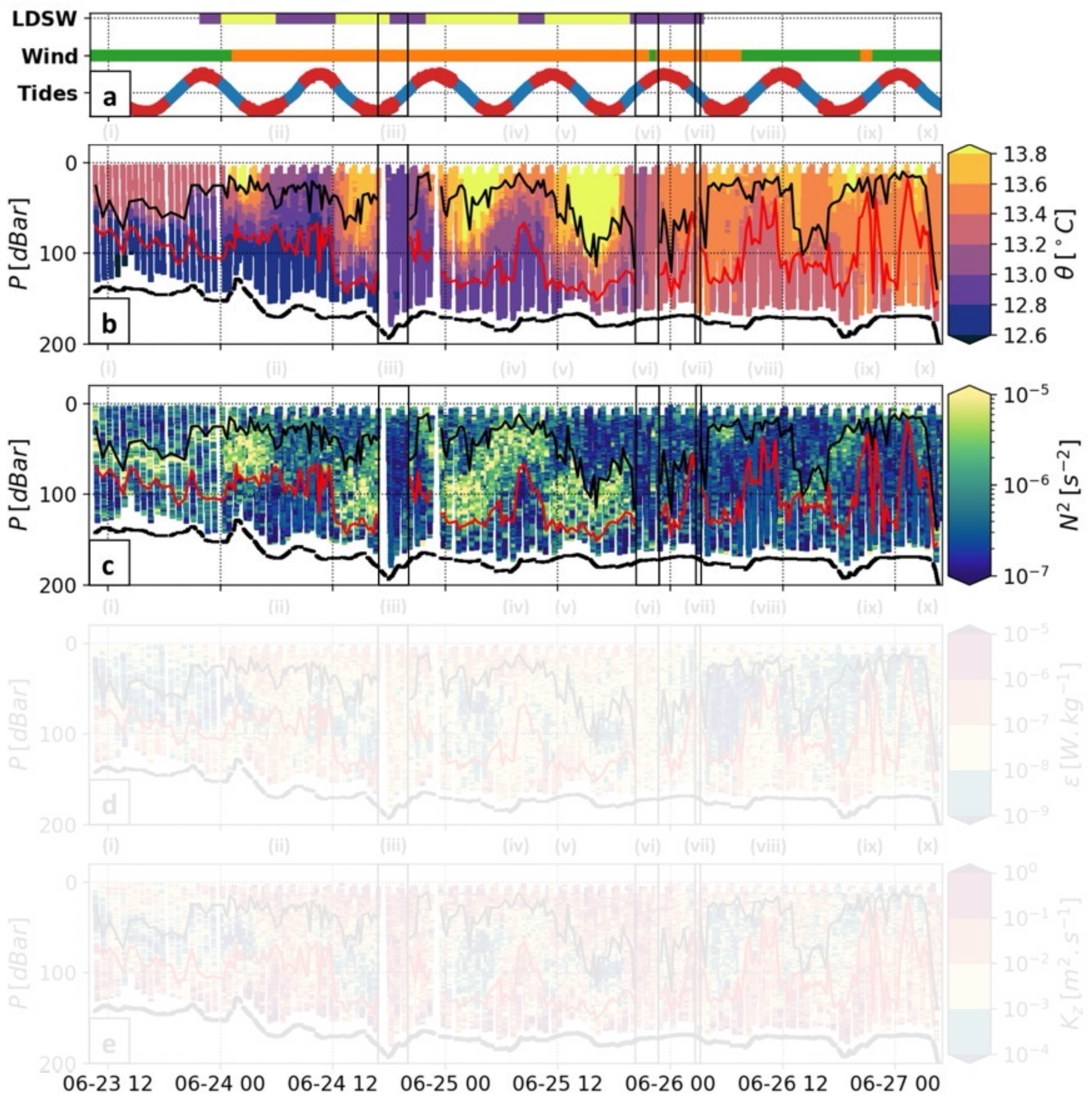


23/06 24/06 25/06 26/06 27/07

Weak top-bottom θ differences
Overlapping surface and bottom mixed layers in 150-200m depths
Low Density Surface Waters (LDSW), sub-mesoscale signal

Relatively weak stratification, mainly N^2 in 10^{-7} - 10^{-5} s^{-2}
the LDSW
e layers
$^{-5}$ W.kg^{-1}
bulence layer
ctions (i-x)
in 10^{-4} - 1 $m^2.s^{-1}$
5 ord... magnitu... ve similar passages Wesson (1994)
Interior K_z increased 5-30 fold during overlapping, on average

Results – Relatively weakly stratification, externally prescribed



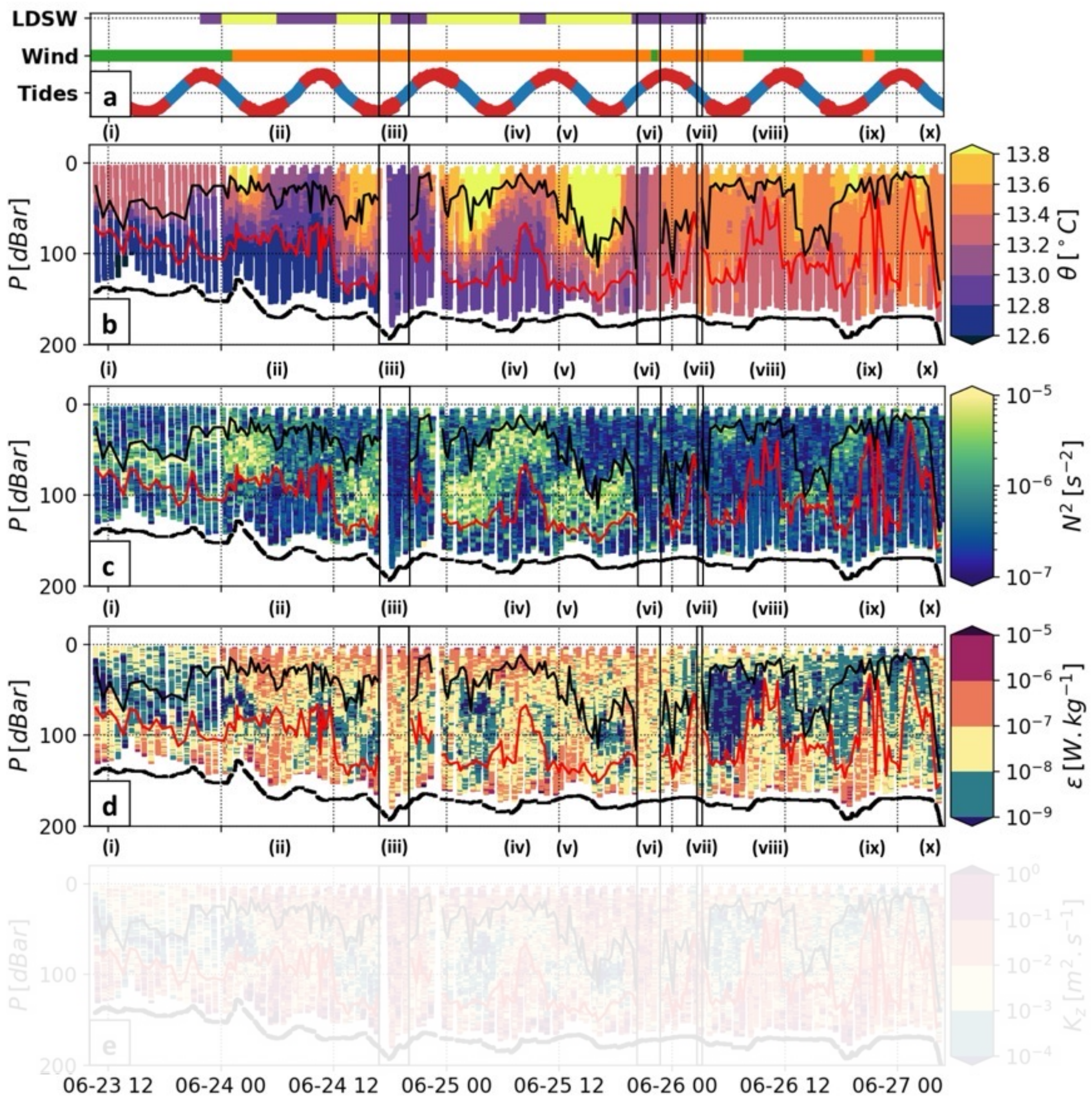
Weak top-bottom θ differences
Overlapping surface and bottom mixed layers in 150-200m depths
Low Density Surface Waters (LDSW), sub-mesoscale signal

Relatively weak stratification, mainly N^2 in 10^{-7} - 10^{-5} s^{-2}
Strengthened interior N^2, at the base of the LDSW
Extending within the bottom and surface mixed layers

Elevated dissipation, mainly ϵ in 10^{-9} - 10^{-5} $W.kg^{-1}$
Tidal bottom pulses and wind-driven turbulence layer
10 episodes of interior turbulence interactions (i-x)

Strongly enhanced diffusivity, mainly K_z in 10^{-4} - 1 $m^2.s^{-1}$
5 orders of magnitude above similar passages Wesson (1994)
Interior K_z increased 5-30 fold during overlapping, on average

Results – Elevated tidal and wind-driven turbulence interacts in the interior



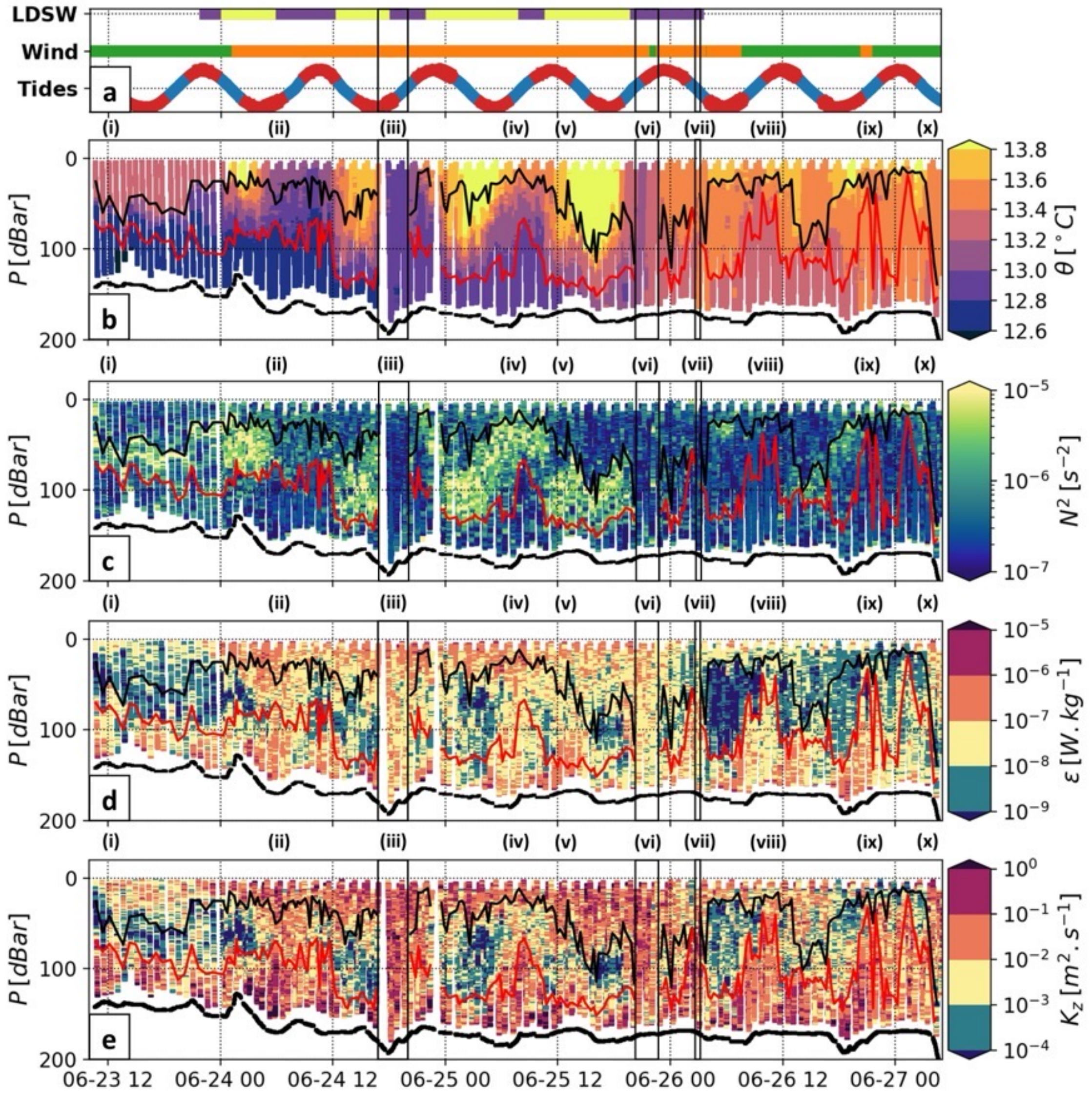
Weak top-bottom θ differences
Overlapping surface and bottom mixed layers in 150-200m depths
Low Density Surface Waters (LDSW), sub-mesoscale signal

Relatively weak stratification, mainly N^2 in 10^{-7} - 10^{-5} s^{-2}
Strengthened interior N^2, at the base of the LDSW
Extending within the bottom and surface mixed layers

Elevated dissipation, mainly ϵ in 10^{-9} - 10^{-5} $W.kg^{-1}$
Tidal bottom pulses and wind-driven turbulence layer
10 episodes of interior turbulence interactions (i-x)

Strongly enhanced diffusivity, mainly K_z in 10^{-4} - 1 $m^2.s^{-1}$
5 orders of magnitude above similar passages Wesson (1994)
Interior K_z increased 5-30 fold during overlapping, on average

Results – Mean diapycnal diffusivity increased 5-30 fold in the interior



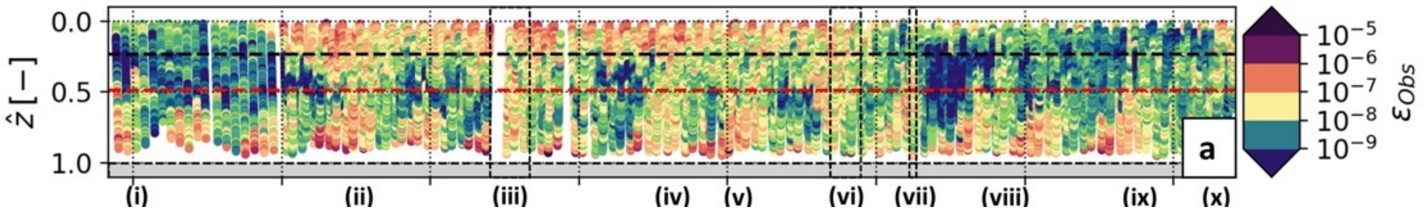
Weak top-bottom θ differences
Overlapping surface and bottom mixed layers in 150-200m depths
Low Density Surface Waters (LDSW), sub-mesoscale signal

Relatively weak stratification, mainly N^2 in 10^{-7} - 10^{-5} s^{-2}
Strengthened interior N^2, at the base of the LDSW
Extending within the bottom and surface mixed layers

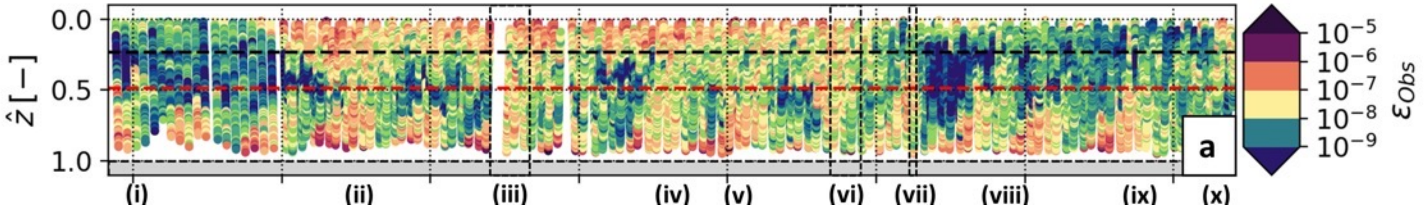
Elevated dissipation, mainly ϵ in 10^{-9} - 10^{-5} $W.kg^{-1}$
Tidal bottom pulses and wind-driven turbulence layer
10 episodes of interior turbulence interactions (i-x)

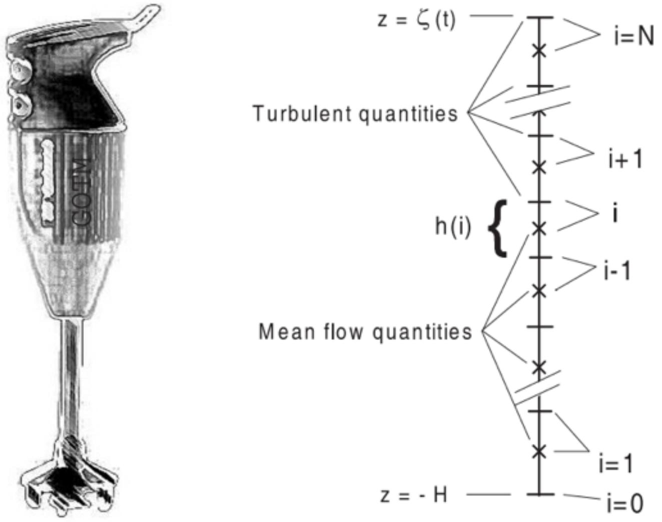
Strongly enhanced diffusivity, mainly K_z in 10^{-4} - 1 $m^2.s^{-1}$
2 orders of magnitude above similar passages Wesson (1994)
Interior K_z increased 5-30 fold during overlapping, on average

Discussion – Turbulence interactions, overlapping and restratification



Discussion – Turbulence interactions, overlapping and restratification

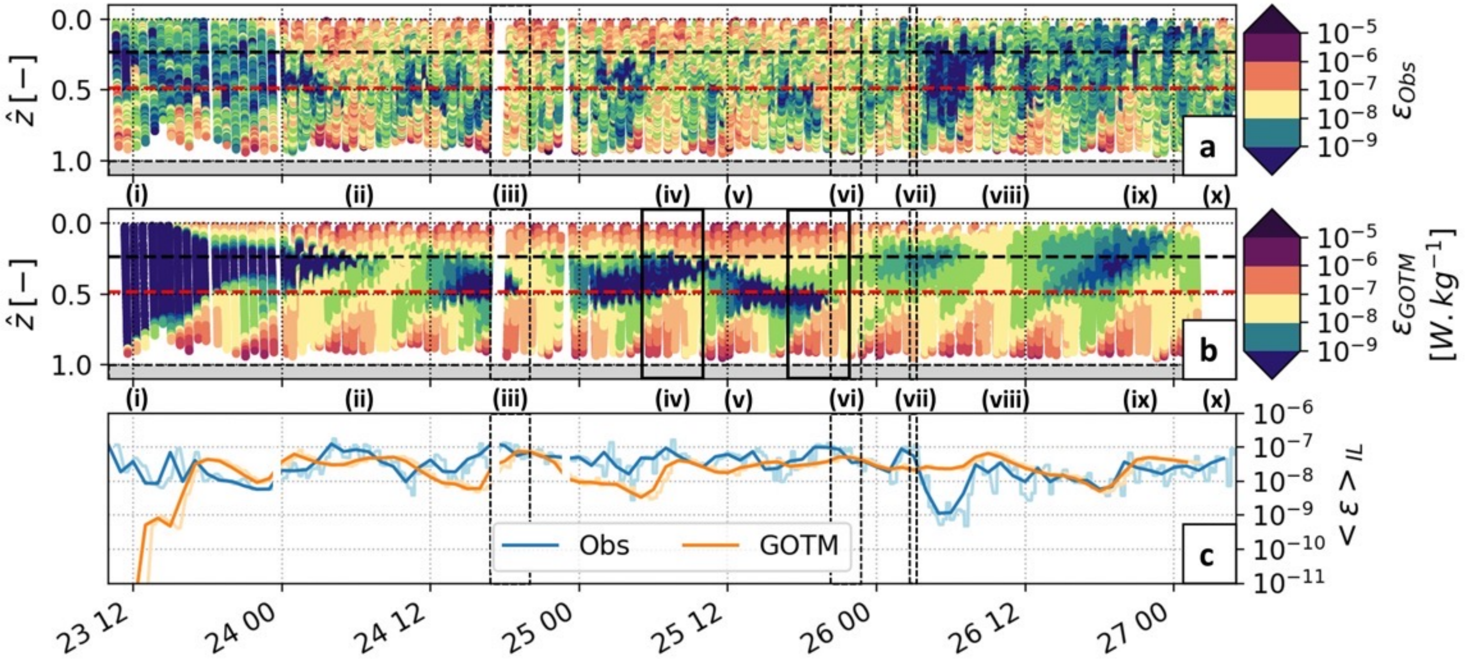


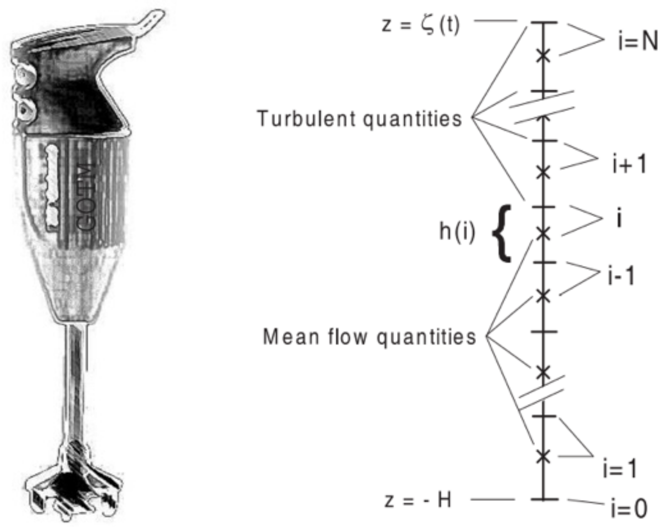


1D turbulence model Umlauf (2012)
Shown success of observation coupling
e.g. Liverpool Bay Rippeth (2001)

Moderately-forced here with obs of:
Mean flow (T-N-tides)
Wind variability (τ_w)

Discussion – Turbulence interactions, overlapping and restratification

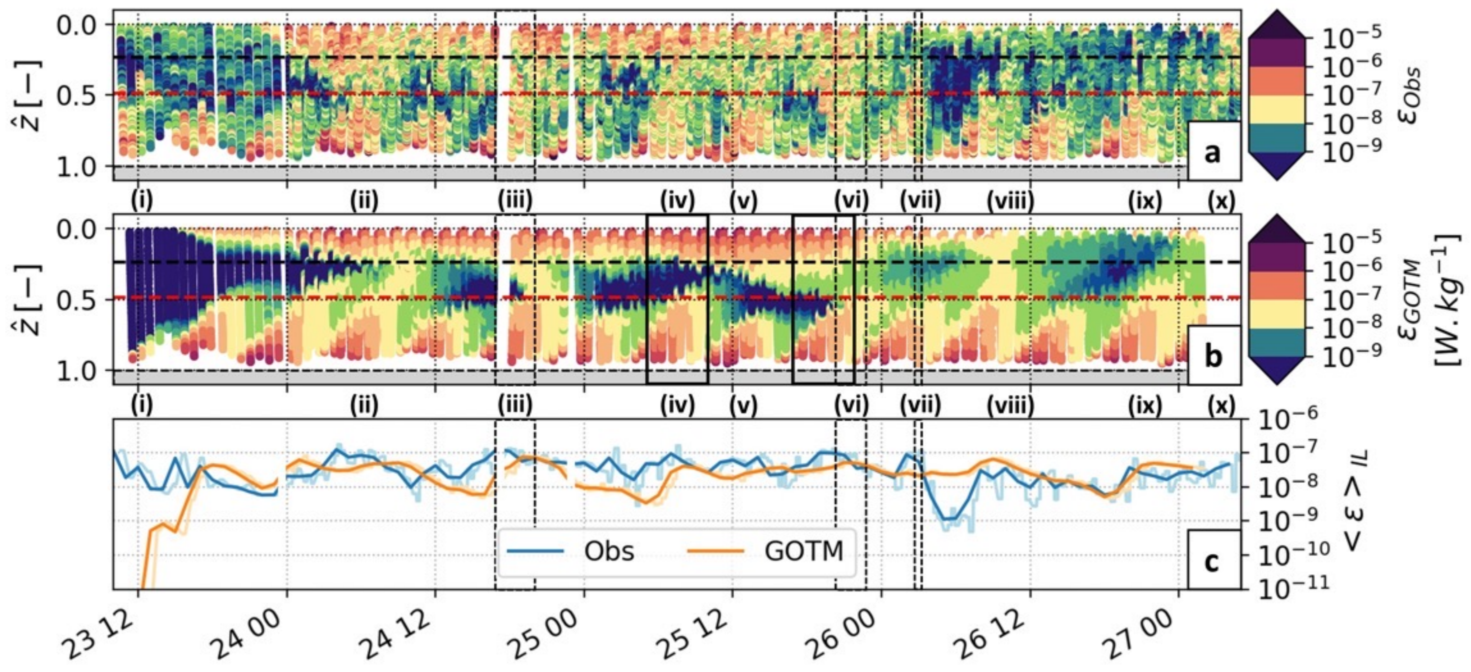


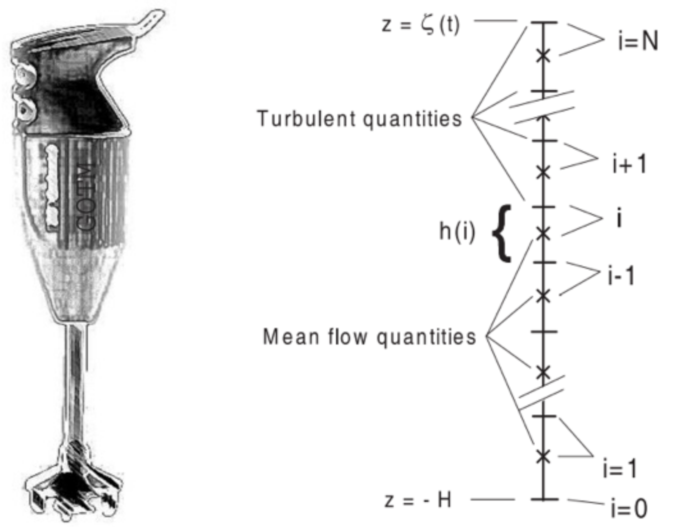


1D turbulence model Umlauf (2012)
Shown success of observation coupling
e.g. Liverpool Bay Rippeth (2001)

Moderately-forced here with obs of:
Mean flow (T-N-tides)
Wind variability (τ_w)

Discussion – Turbulence interactions, overlapping and restratification



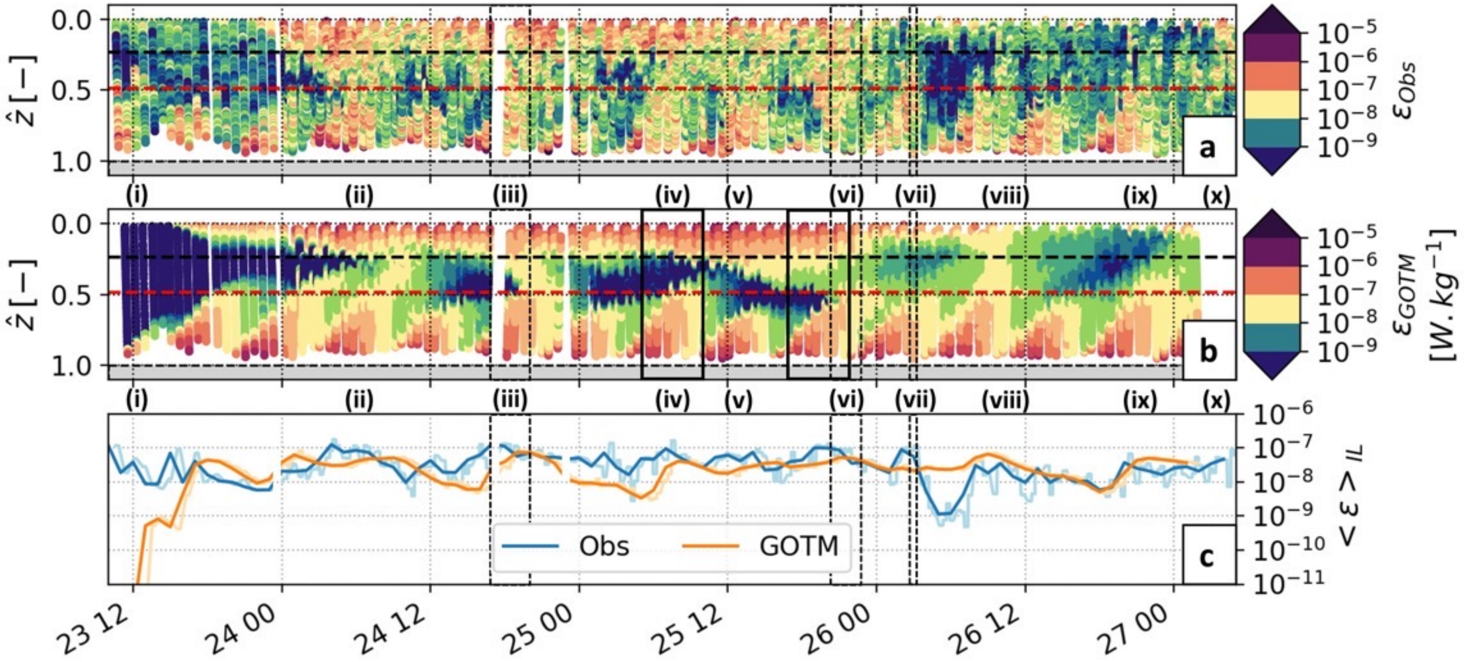


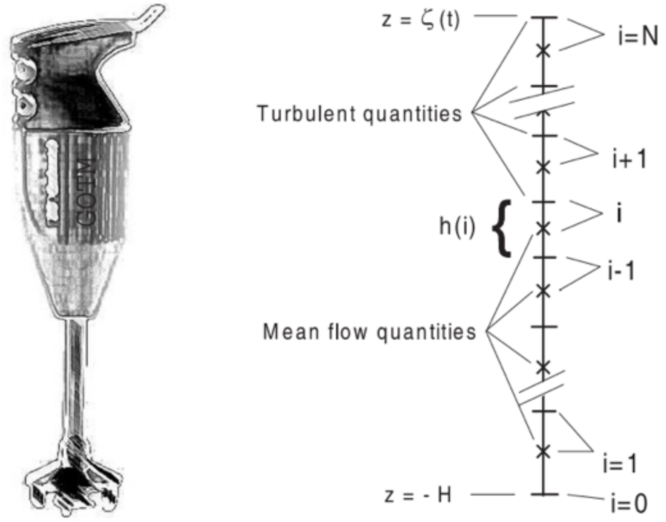
Turbulence interactions and mixed layer overlapping match periods of strong boundary forcing and weak stratification, consistent with DNS work Yan (2022)

1D turbulence model Umlauf (2012)
Shown success of observation coupling e.g. Liverpool Bay Rippeth (2001)

Moderately-forced here with obs of:
Mean flow (T-N-tides)
Wind variability (τ_w)

Discussion – Turbulence interactions, overlapping and restratification





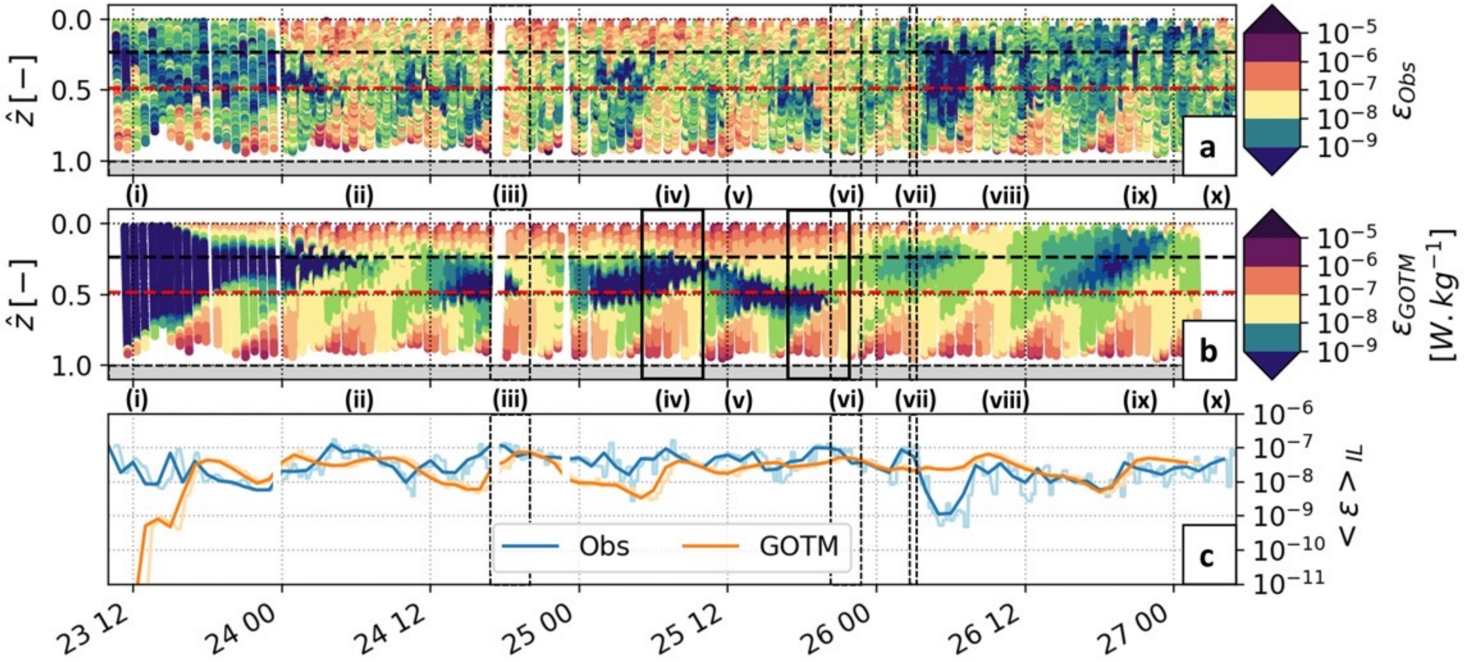
Turbulence interactions and mixed layer overlapping match periods of strong boundary forcing and weak stratification, consistent with DNS work Yan (2022)

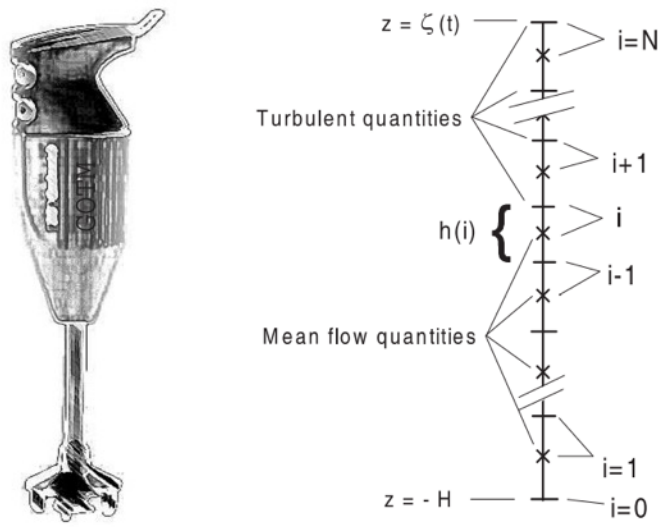
Enhanced transport of boundary-generated turbulence erodes interior stratification to allow overlapping, surface buoyancy fluxes help restratify

1D turbulence model Umlauf (2012)
Shown success of observation coupling e.g. Liverpool Bay Rippeth (2001)

Moderately-forced here with obs of:
Mean flow (T-N-tides)
Wind variability (τ_w)

Discussion – Turbulence interactions, overlapping and restratification





Turbulence interactions and mixed layer overlapping match periods of strong boundary forcing and weak stratification, consistent with DNS work Yan (2022)

Enhanced transport of boundary-generated turbulence erodes interior stratification to allow overlapping, surface buoyancy fluxes help restratify

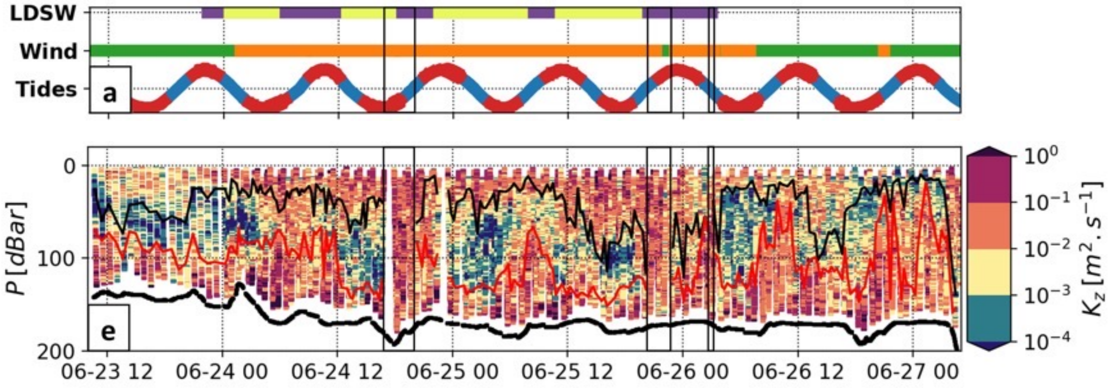
Occasional bottom turbulence burst ejections, similar to Thorpe (2008)

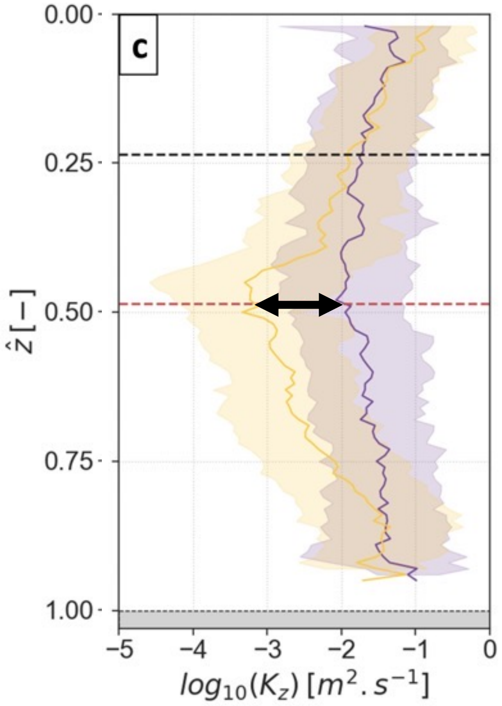
1D turbulence model Umlauf (2012)
Shown success of observation coupling
e.g. Liverpool Bay Rippeth (2001)

Moderately-forced here with obs of:
Mean flow (T-N-tides)
Wind variability (τ_w)

Discussion – Mixing efficiency coefficient

-- Stratified (LDSW) conditions -- Turbulence interactions and overlapping





Diapycnal diffusivity of density Osborn (1980)

$$K_\rho = \Gamma \frac{\epsilon}{N^2}$$

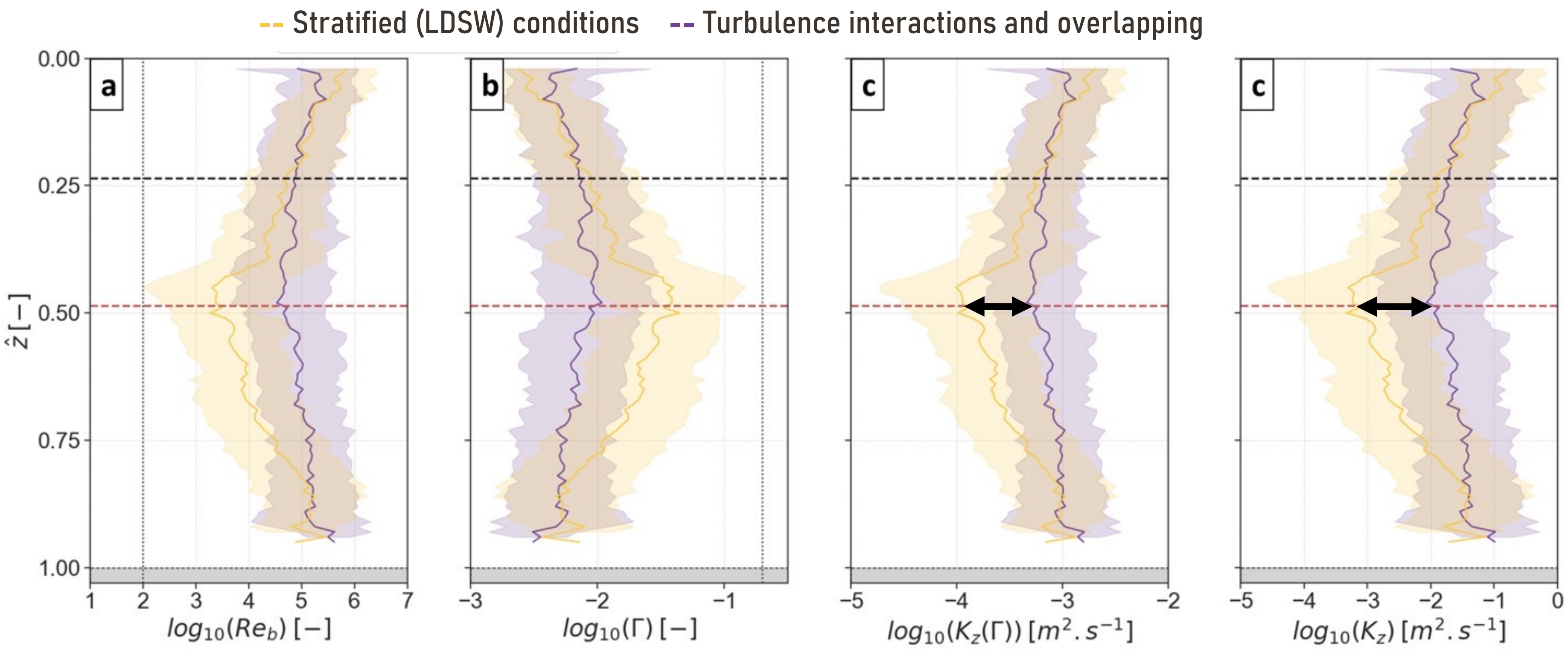
Passive

$\Gamma = 0.2$

Gregg (2017)

$\overline{K_\rho}$ increased 30 fold

Discussion – Mixing efficiency coefficient



Diapycnal diffusivity of density Osborn (1980)

$$K_\rho = \Gamma \frac{\epsilon}{N^2}$$

Active

$\Gamma = f(Re_b)$

Bouffard (2013)

$\overline{K_\rho}$ increased 5 fold

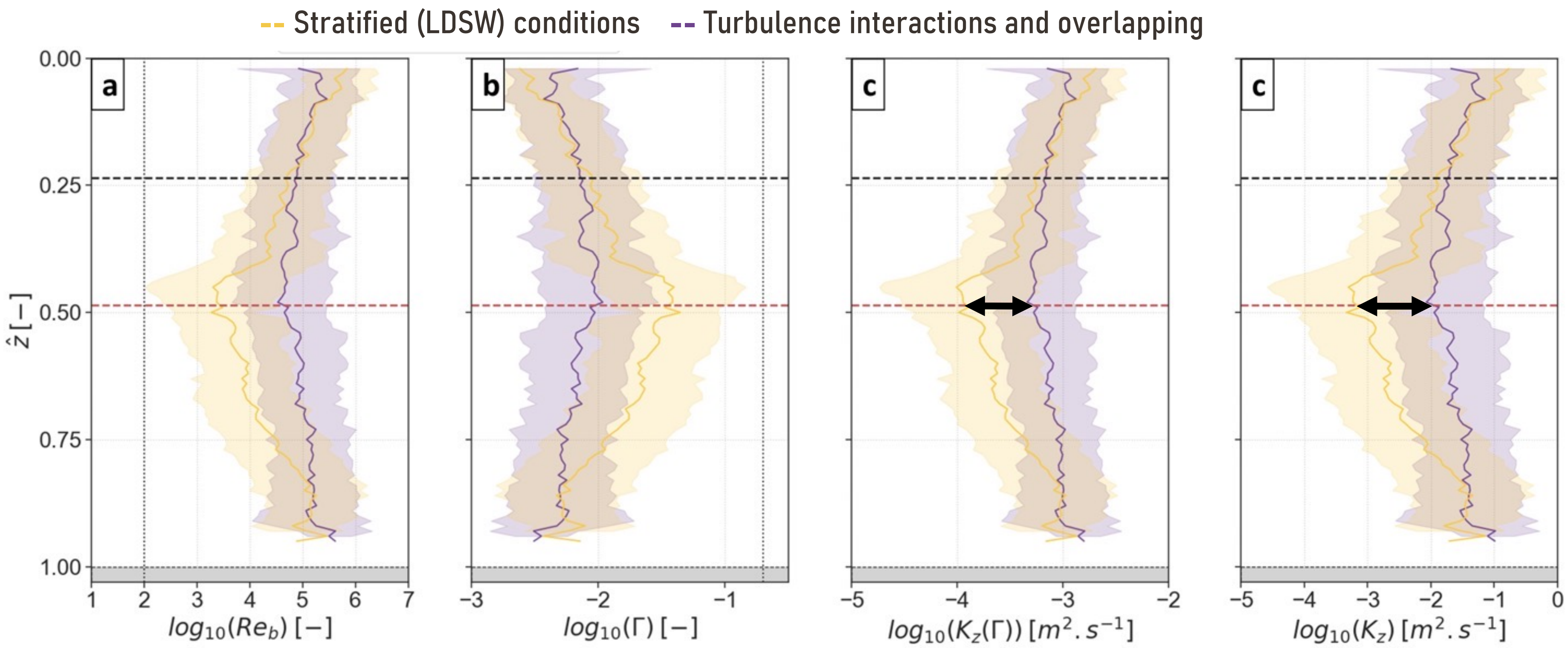
Passive

$\Gamma = 0.2$

Gregg (2017)

$\overline{K_\rho}$ increased 30 fold

Discussion – Mixing efficiency coefficient



Diapycnal diffusivity of density Osborn (1980)

$$\mathrm{K}_\rho = \Gamma \frac{\epsilon}{N^2}$$

Overlapping pattern persists but could be overestimated
→ See the "Extreme ocean mixing in coastal seas" poster

Active

$\Gamma = f(Re_b)$

Bouffard (2013)

$\overline{\mathrm{K}_\rho}$ increased 5 fold

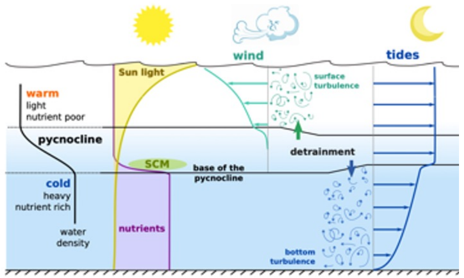
Passive

$\Gamma = 0.2$

Gregg (2017)

$\overline{\mathrm{K}_\rho}$ increased 30 fold

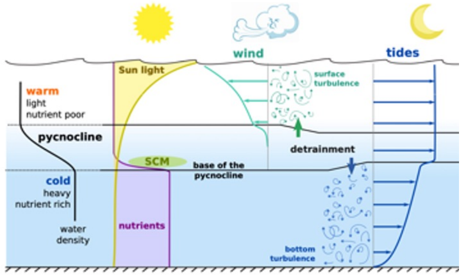
Main takeaways



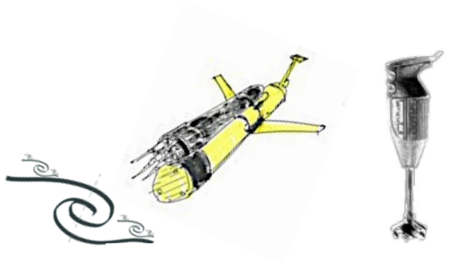
What was the motivation ? Understand boundary layer interactions in coastal seas

Main takeaways

What was the motivation ? Understand boundary layer interactions in coastal seas

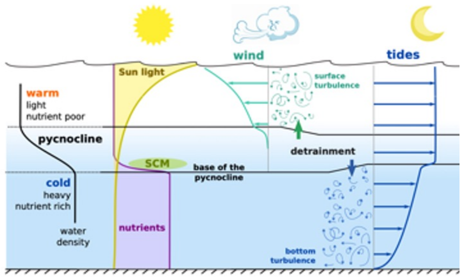


How did we approach the problem ? Ocean Microstructure Glider (OMG) mission
1D turbulent kinetic energy model

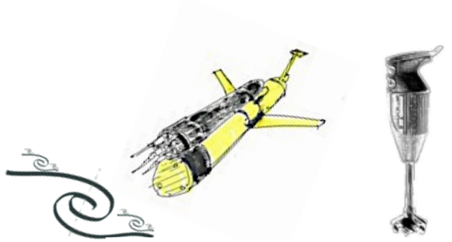


Main takeaways

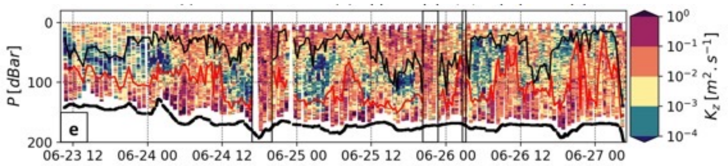
What was the motivation ? Understand boundary layer interactions in coastal seas



How did we approach the problem ? Ocean Microstructure Glider (OMG) mission
1D turbulent kinetic energy model

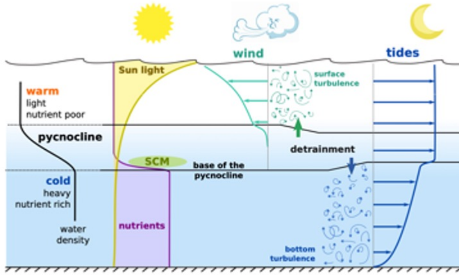


What did we find ? Mixed layer overlapping in a system 3-4 fold deeper than usual
Diffusivity increased 5-30 fold, depending on mixing efficiency
Enhanced vertical transport of boundary generated turbulence

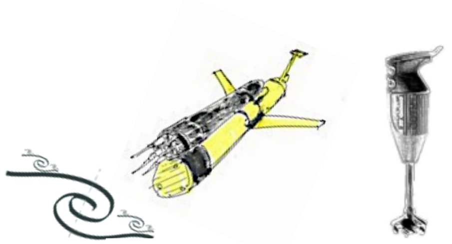


Main takeaways

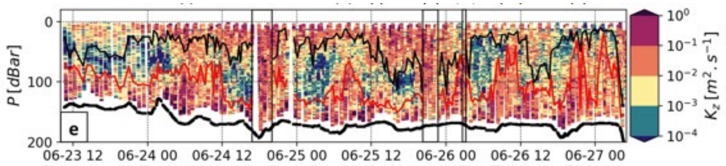
What was the motivation ? Understand boundary layer interactions in coastal seas



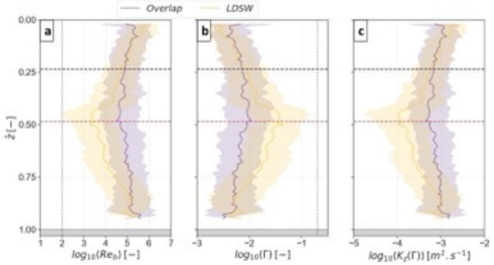
How did we approach the problem ? Ocean Microstructure Glider (OMG) mission
1D turbulent kinetic energy model

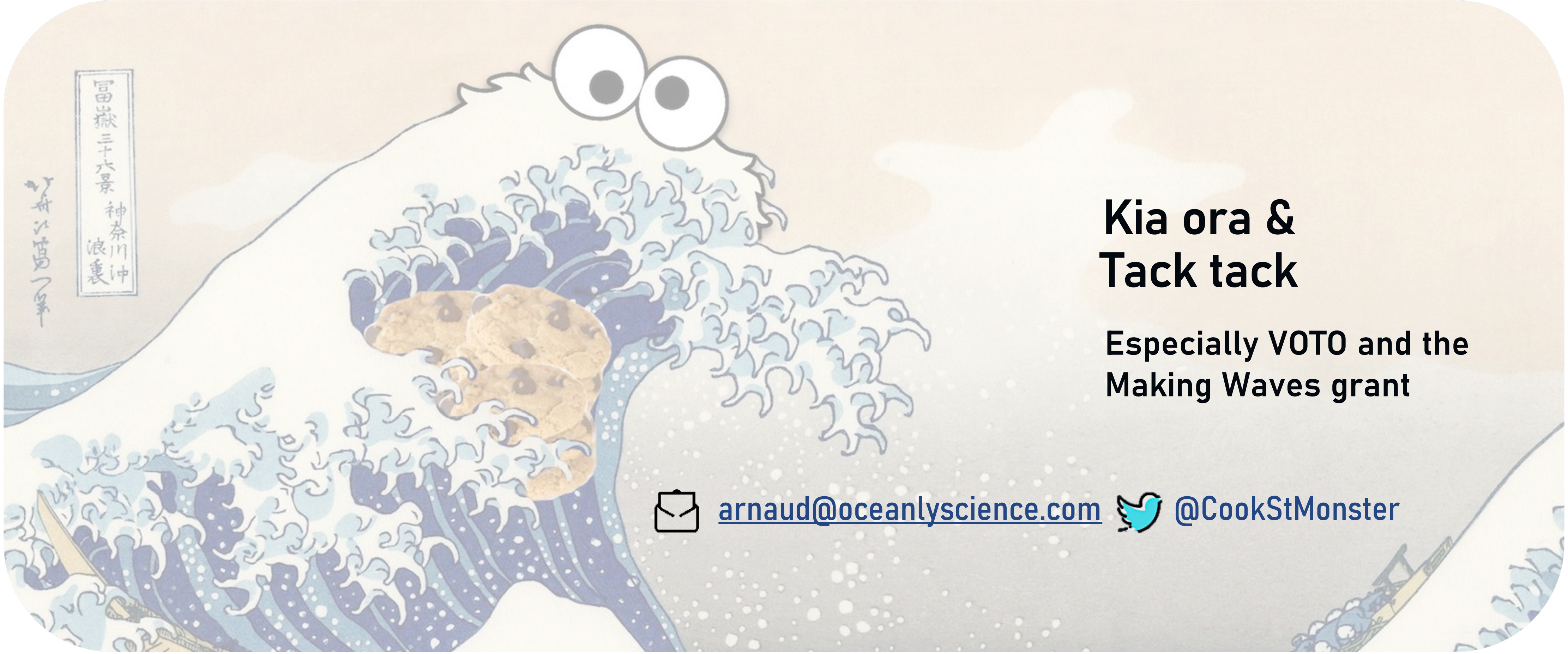


What did we find ? Mixed layer overlapping in a system 3-4 fold deeper than usual
Diffusivity increased 5-30 fold, depending on mixing efficiency
Enhanced vertical transport of boundary generated turbulence
→ Overlapping … Valcarcel et al. *(JGR Oceans, in review)*



What are we following up on ? Direct mixing efficiency estimates from OMG data (poster)
Direct Numerical Simulations of e.g. Langmuir processes
Connections to mean Nitrate, ChlA profiles





Kia ora & Tack tack

Especially VOTO and the Making Waves grant

arnaud@oceanlyscience.com @CookStMonster