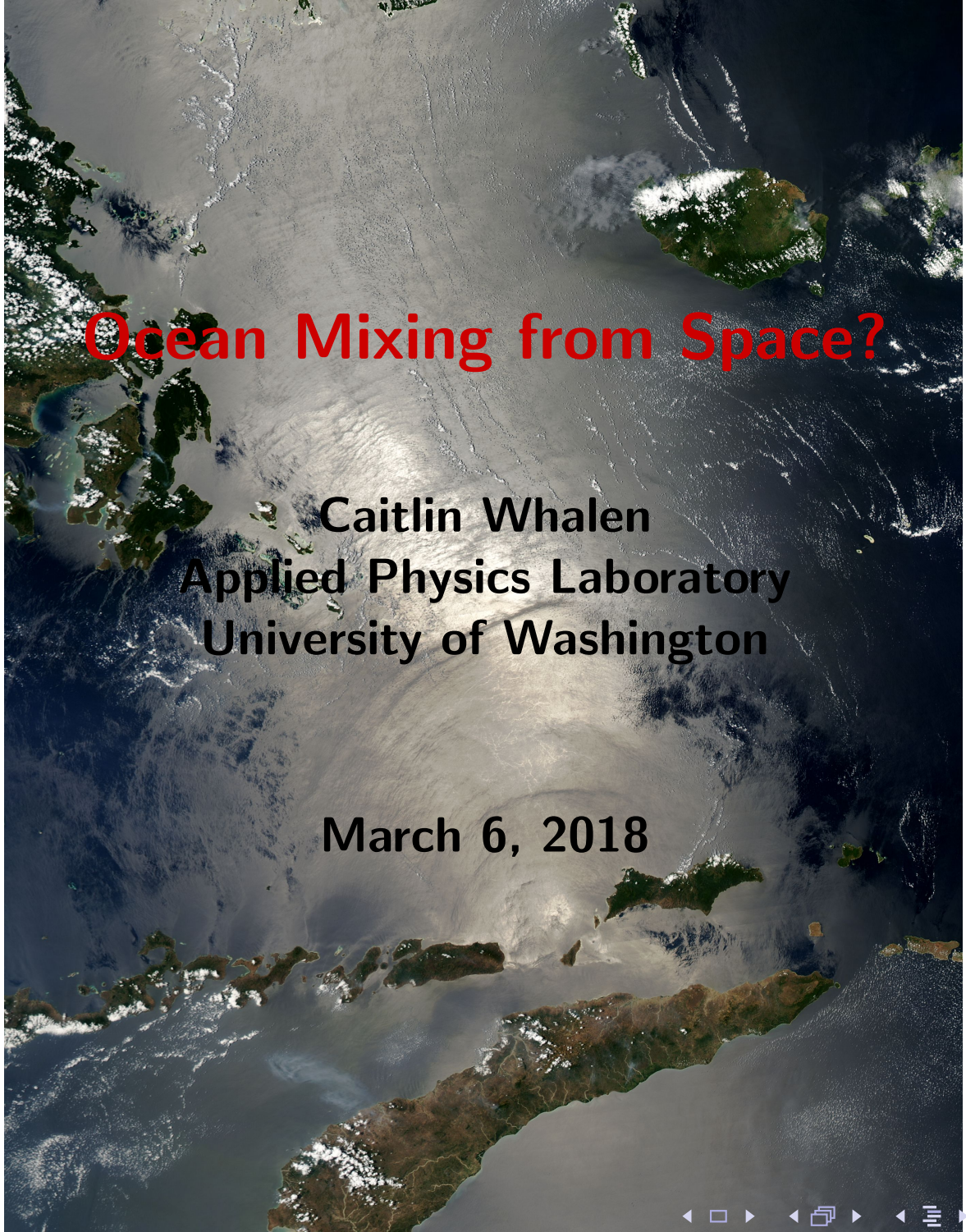


Ocean Mixing from Space?

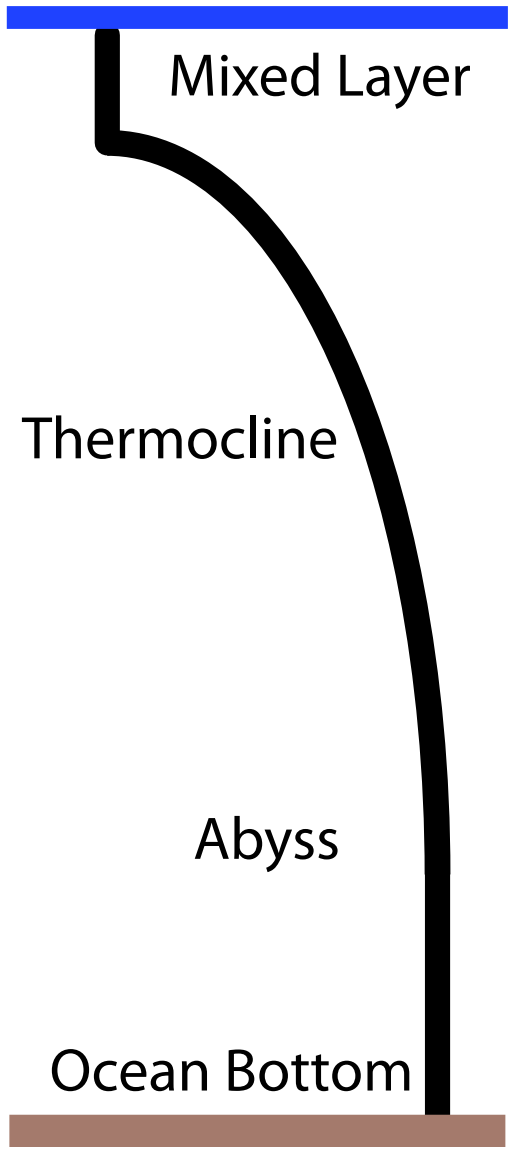
Caitlin Whalen
Applied Physics Laboratory
University of Washington

March 6, 2018

Many Types of Ocean Mixing

Mixing Occurs:

- Mixed layer
  (Convection, wind stress, mixed layer instabilities, etc)



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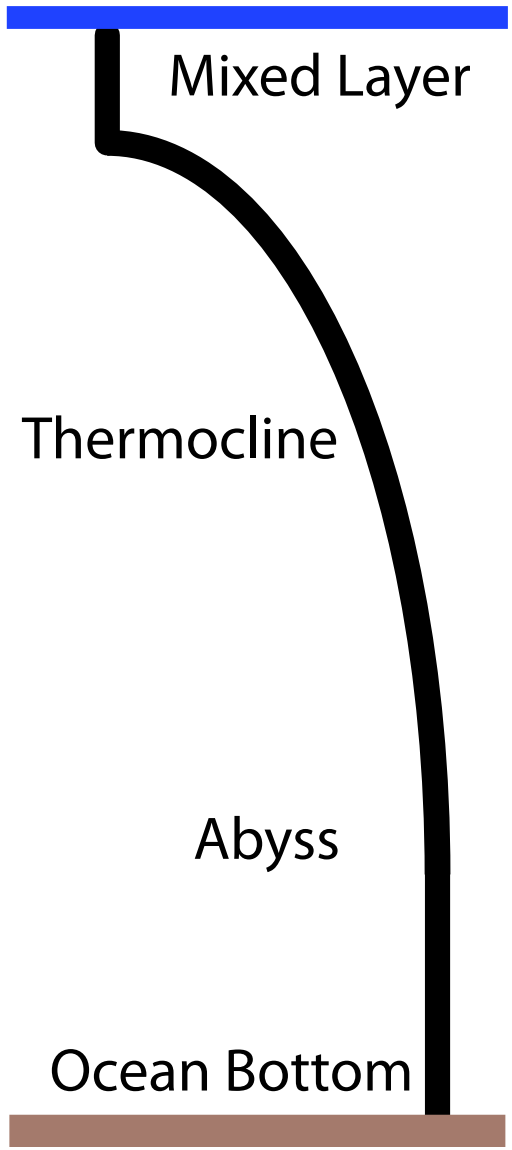

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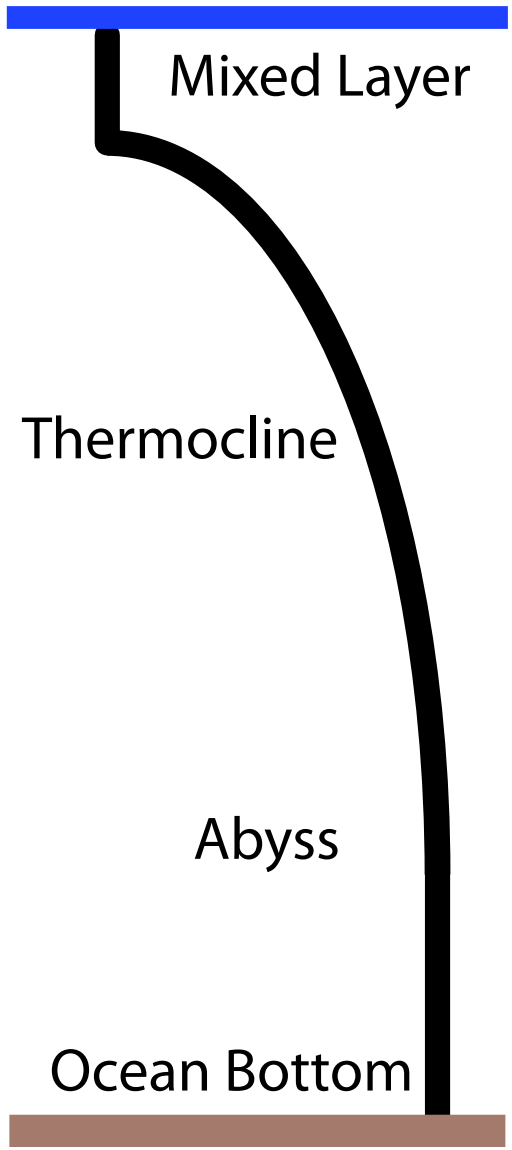

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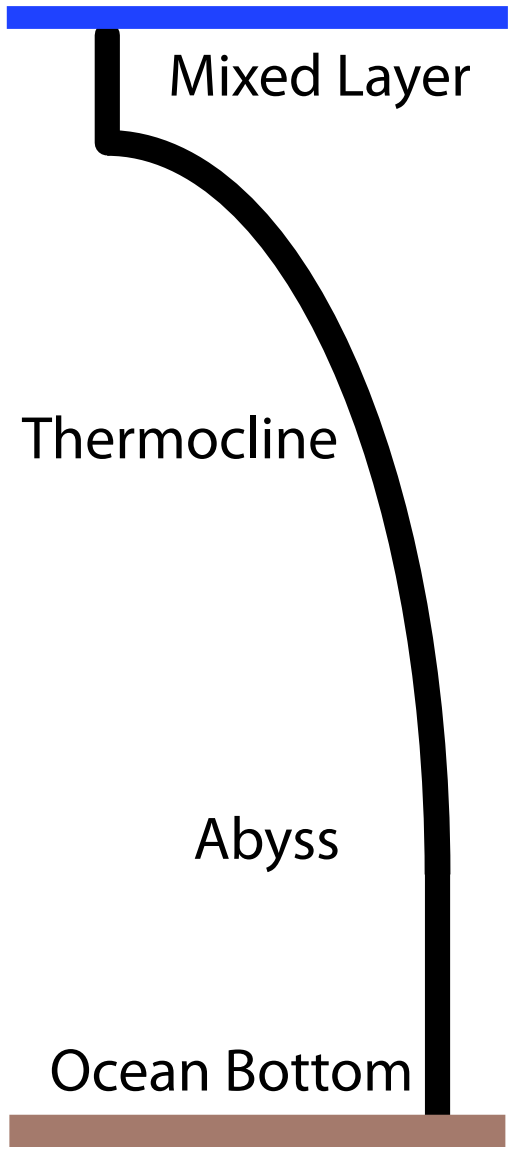

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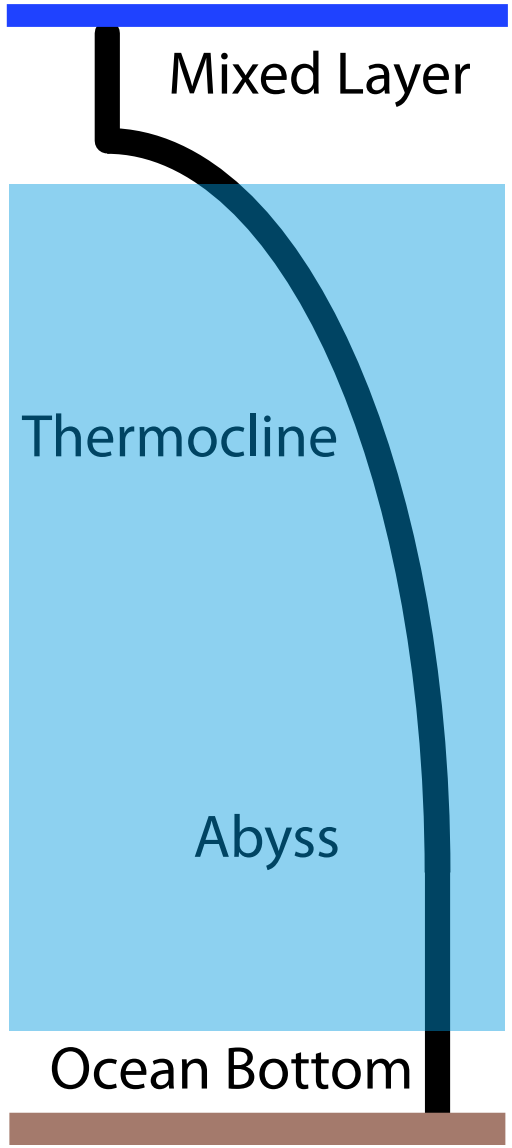

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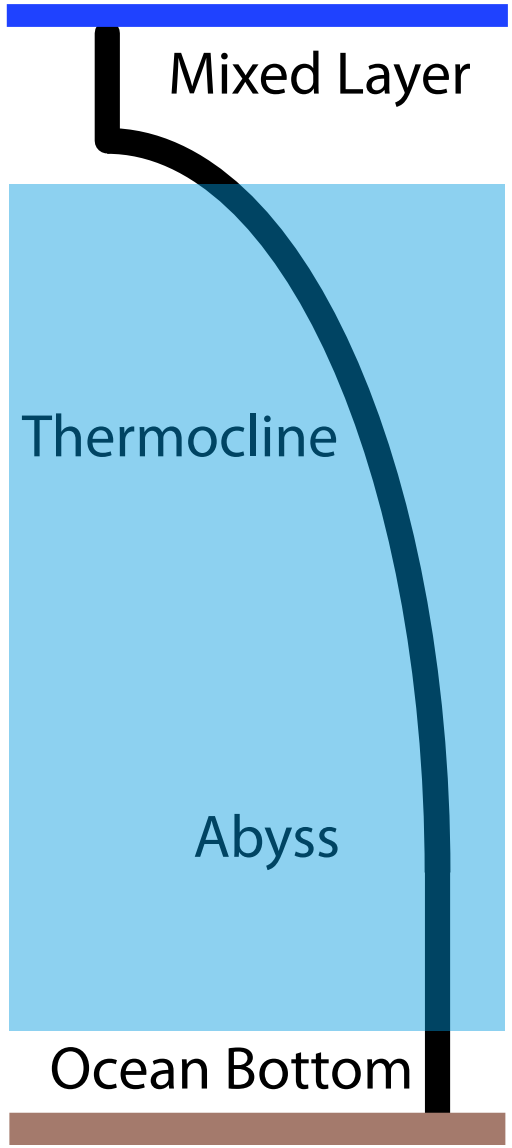
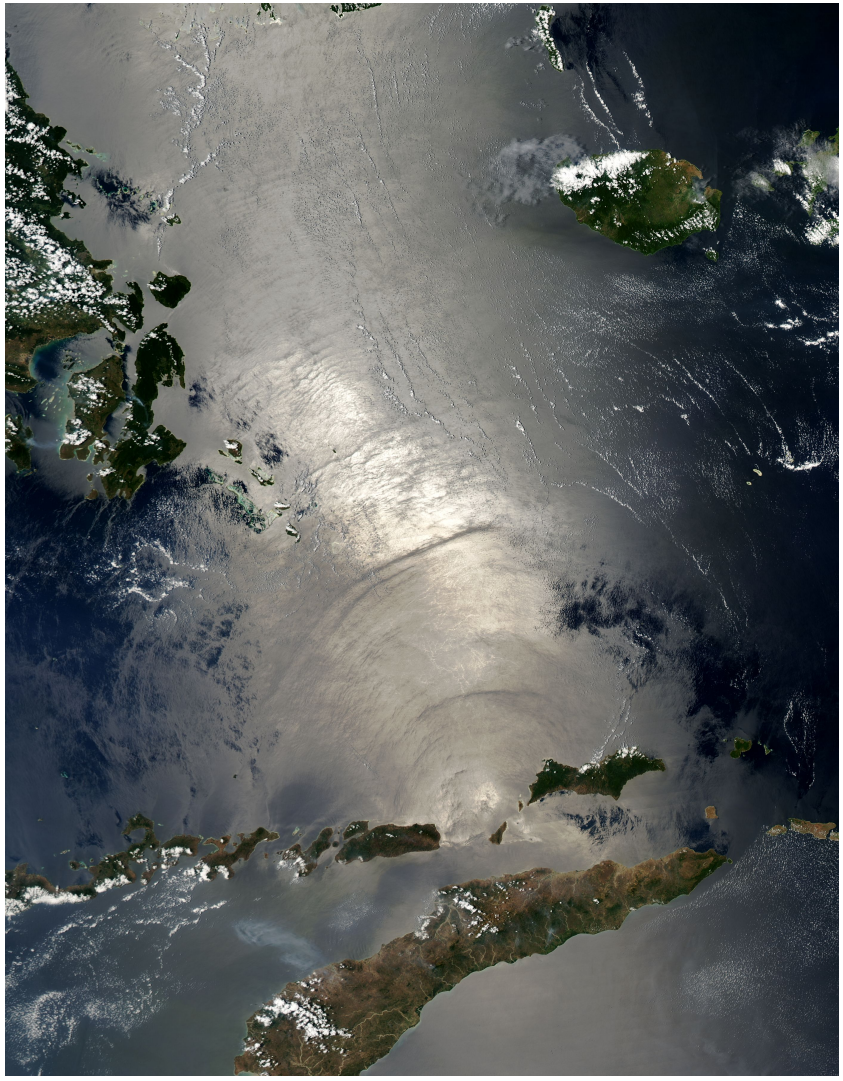
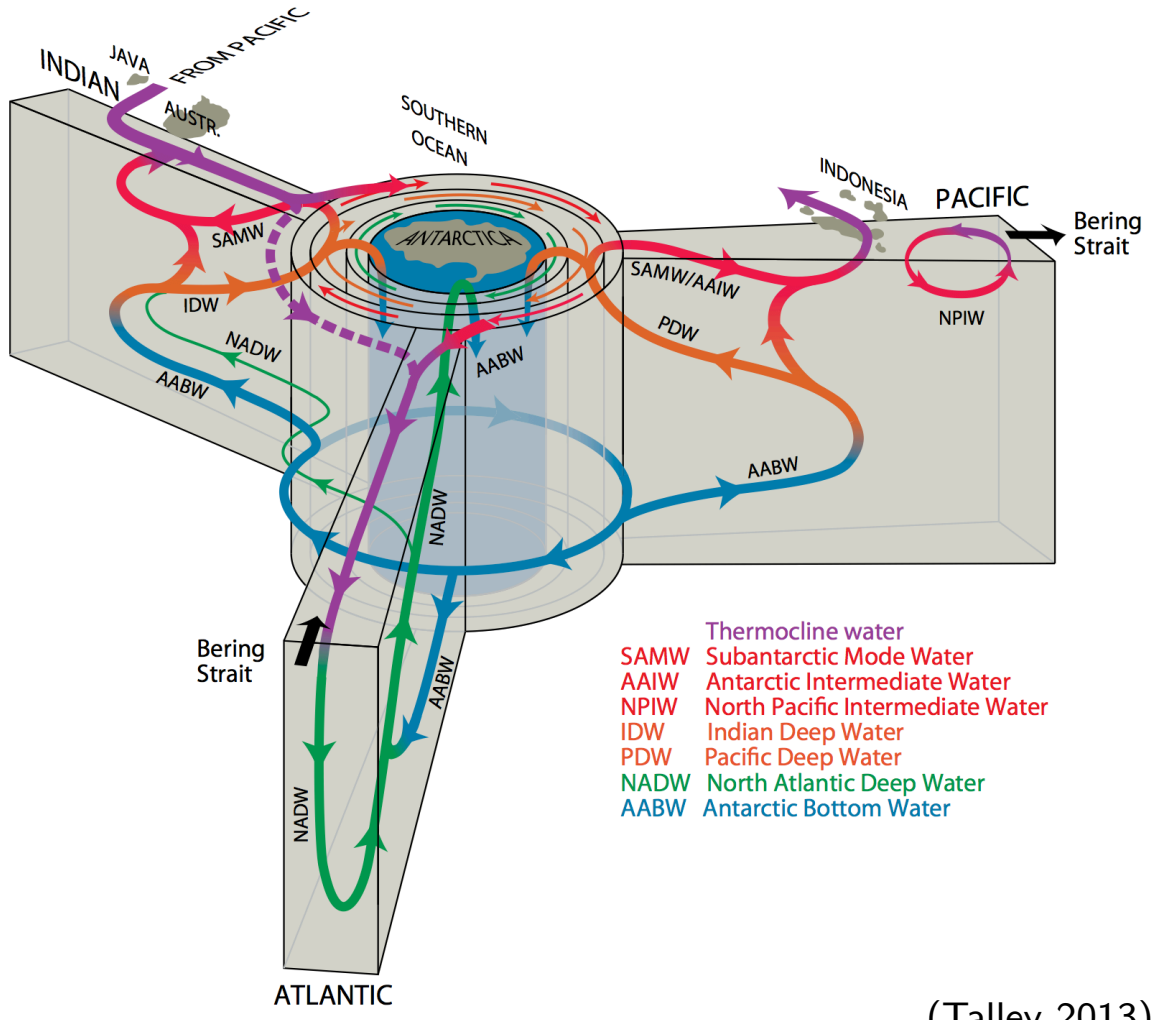


Internal Wave Driven Mixing and the Global Ocean

Internal Waves Near Indonesia

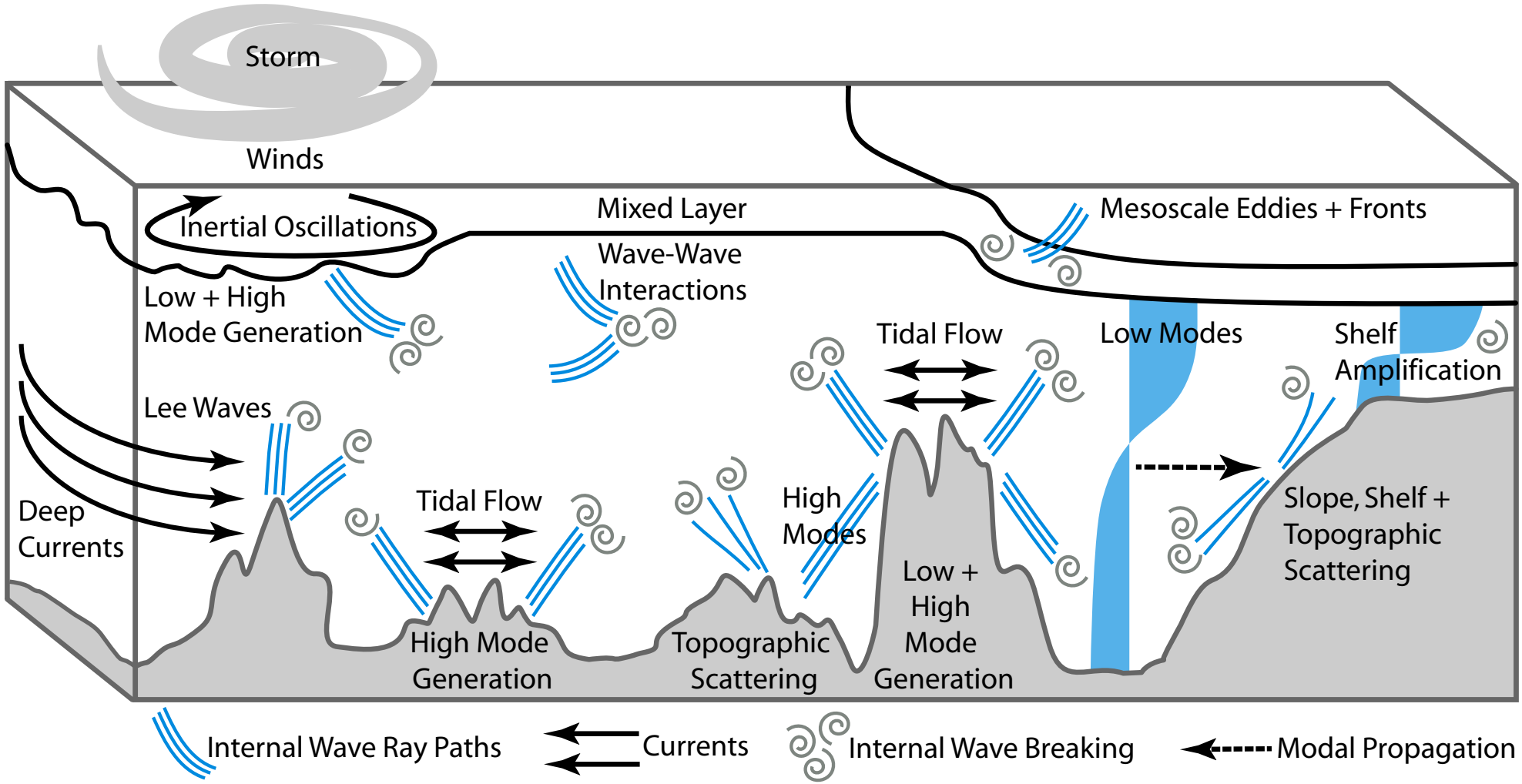


(http://earthdata.nasa.gov/lance/rapid-response)



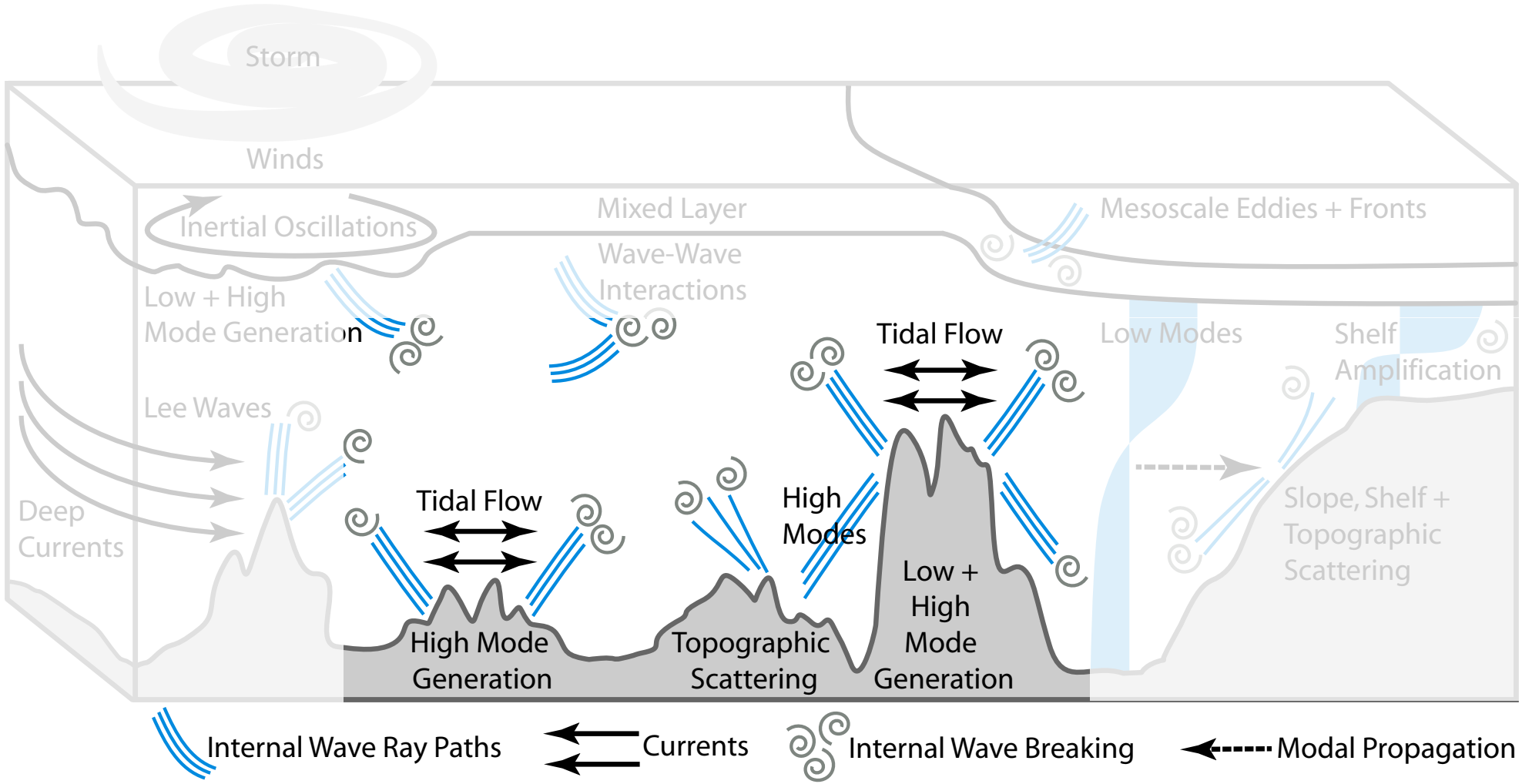
(Talley 2013)

Internal Wave Driven Mixing



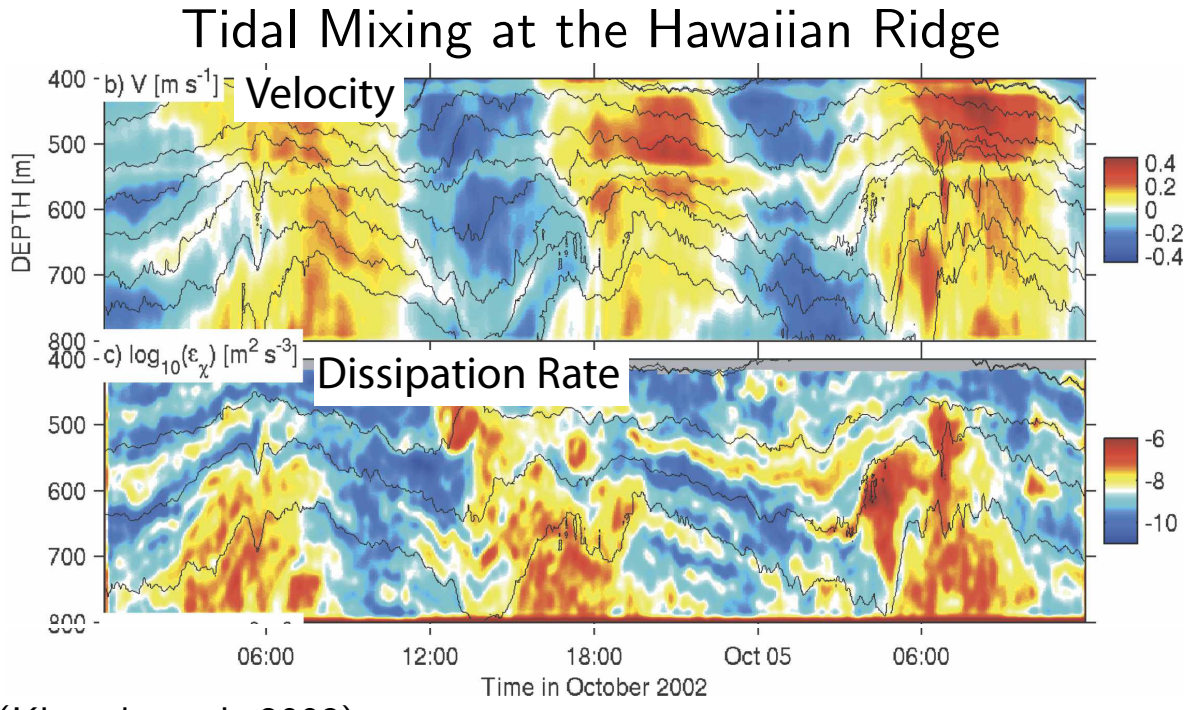
(MacKinnon et al. 2017)

Internal Wave Driven Mixing

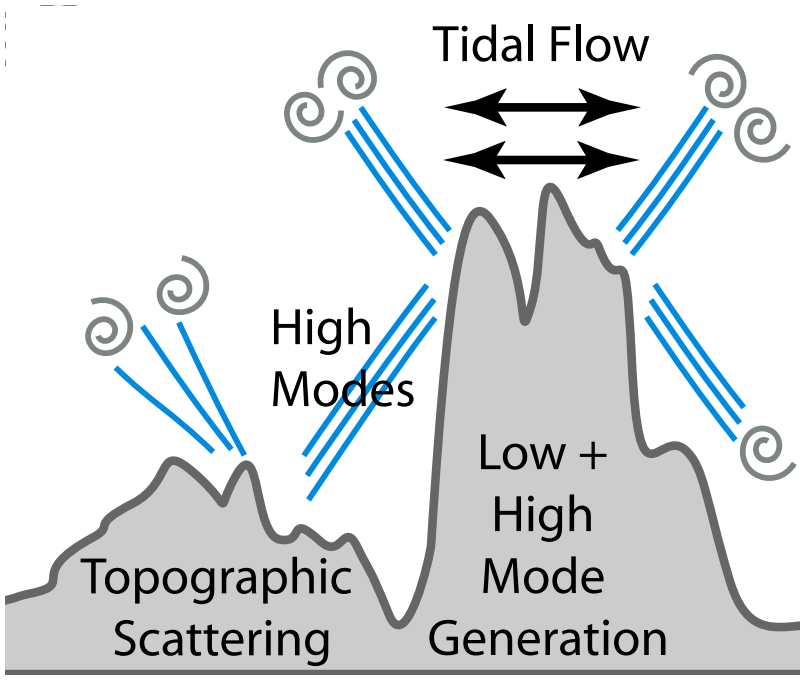


(MacKinnon et al. 2017)

Rough Seafloor and Tidal Energy → Elevated Mixing



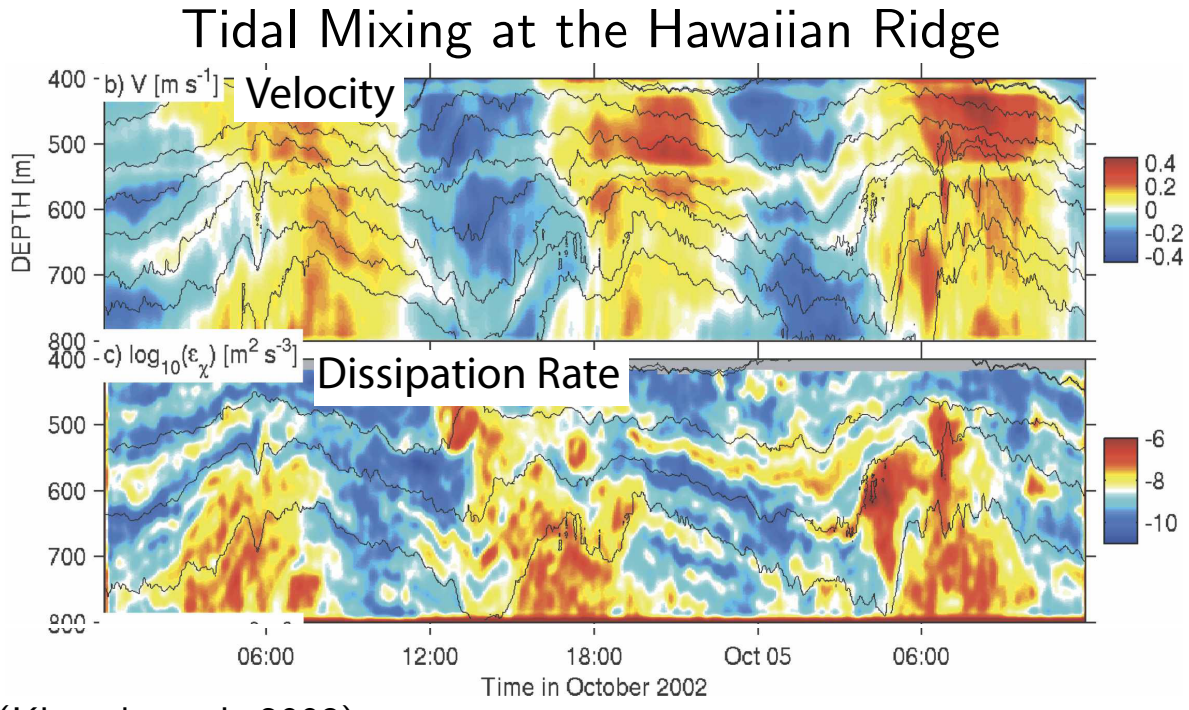
(Klymak et al. 2008)



Tides → Generate Internal Waves → Mixing

Internal Waves → Scattered by Rough Topography → Mixing

Rough Seafloor and Tidal Energy → Elevated Mixing



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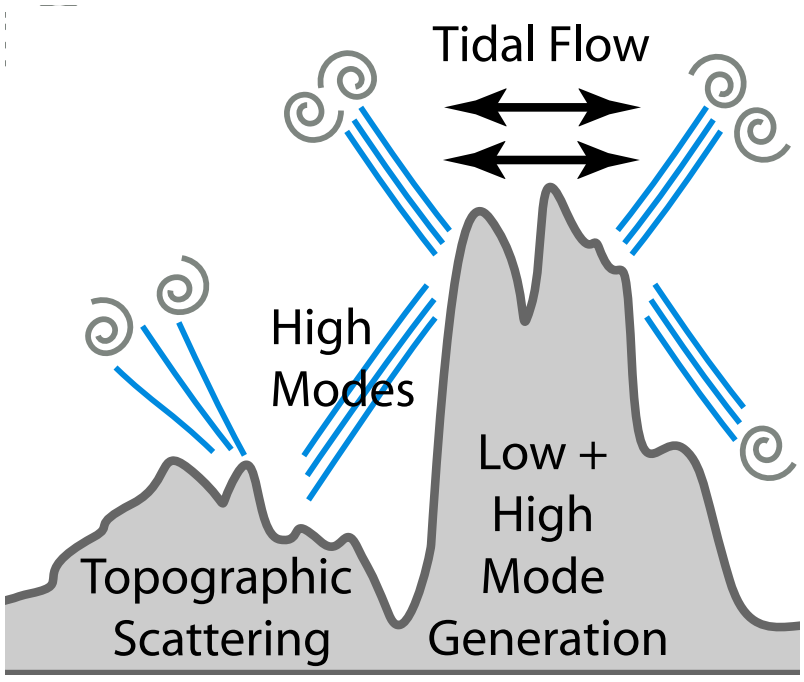
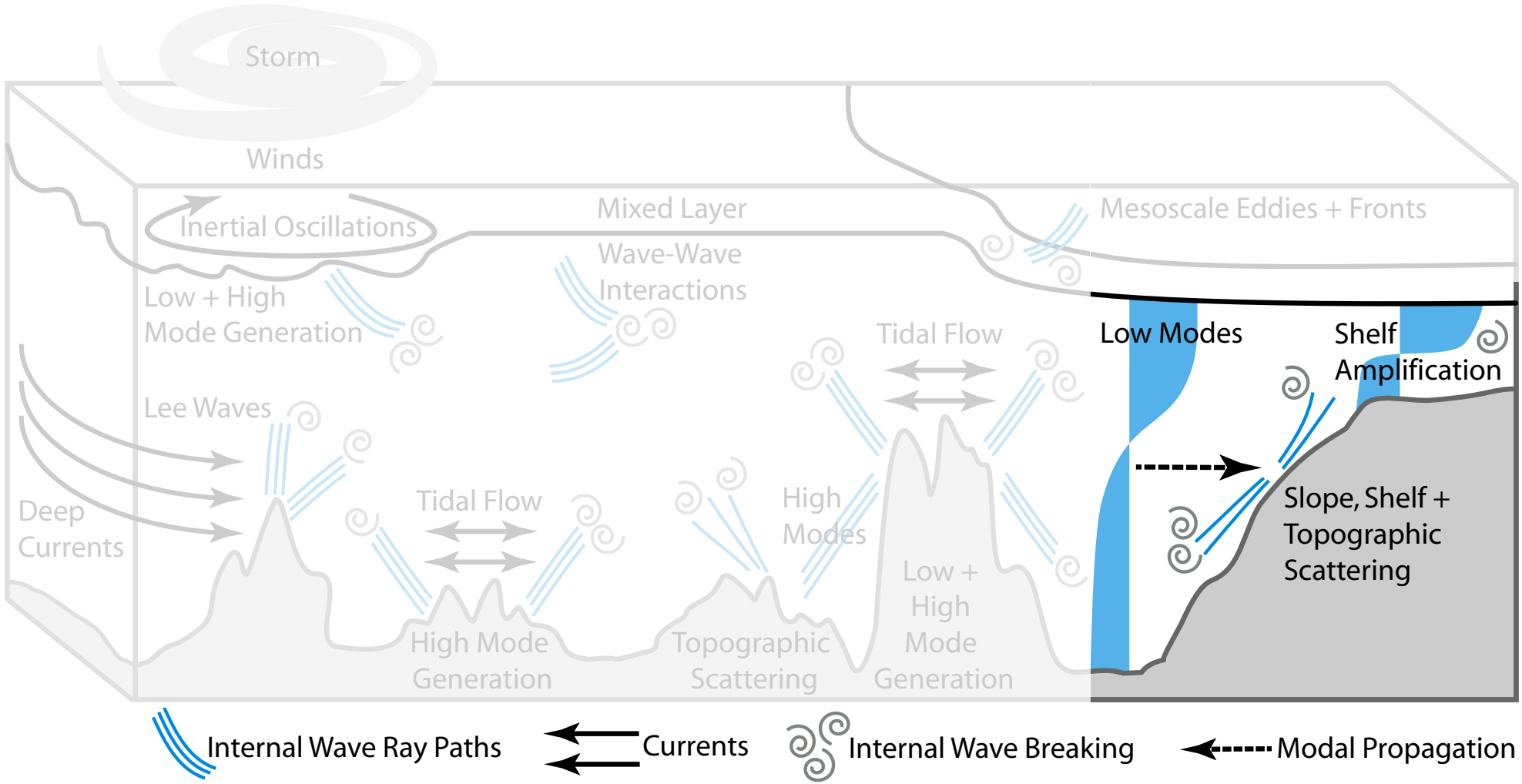


Tides → Generate Internal Waves → Mixing

Internal Waves → Scattered by Rough Topography → Mixing

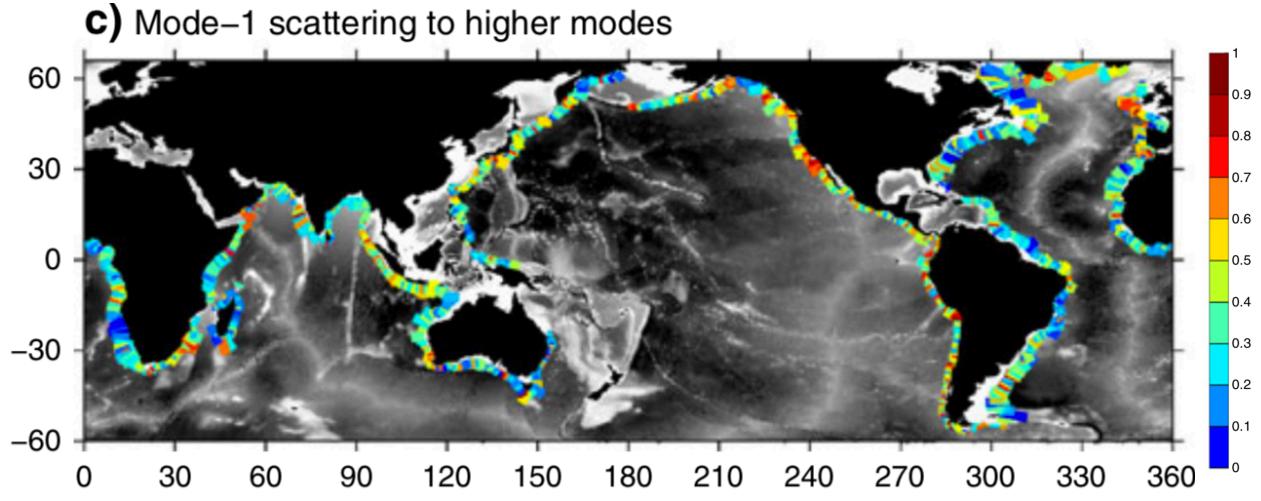
- Big Question: What are the internal wave energy pathways?
- Specific Question: What fraction of energy from internal waves dissipates close to generation sites? How much propagates away?

Internal Wave Driven Mixing at the Slopes and Shelves

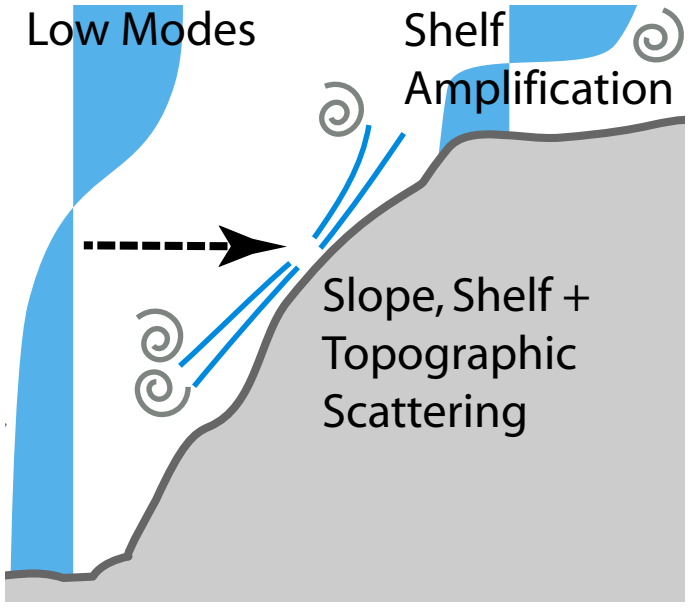


(MacKinnon et al. 2017)

Internal Wave Driven Mixing at the Slopes and Shelves



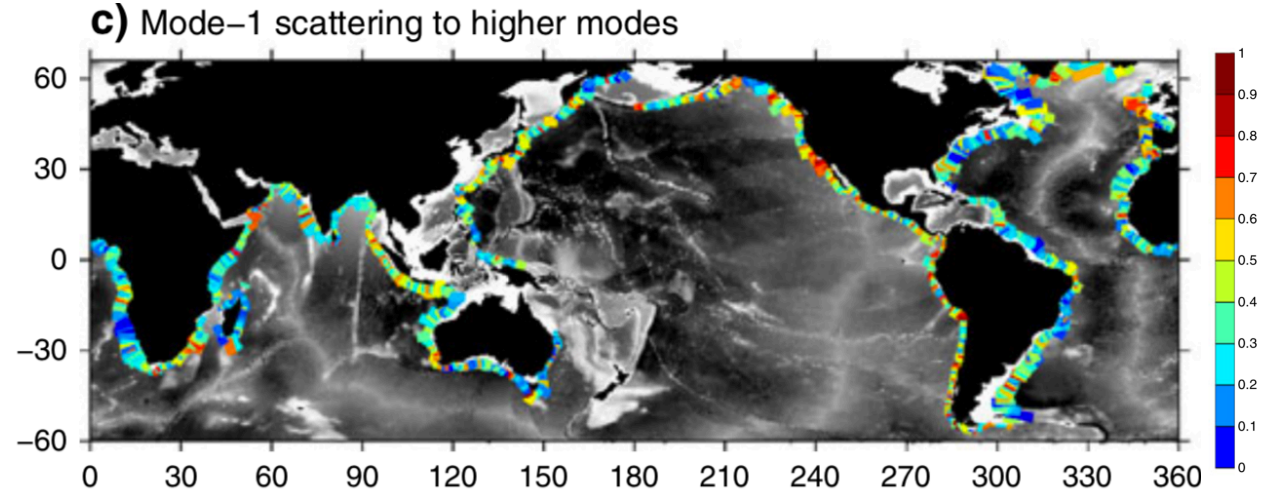
(Kelly et al. 2013)



Low-Mode Internal Waves $\rightarrow$ Scattering on Shelves/Slopes $\rightarrow$ Mixing

Low-Mode Internal Waves $\rightarrow$ Reflection $\rightarrow$ Mixing in Interior

Internal Wave Driven Mixing at the Slopes and Shelves



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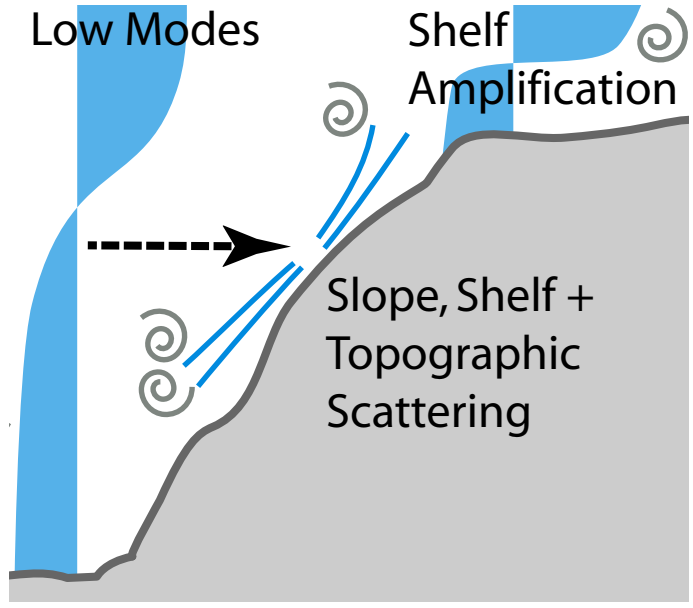


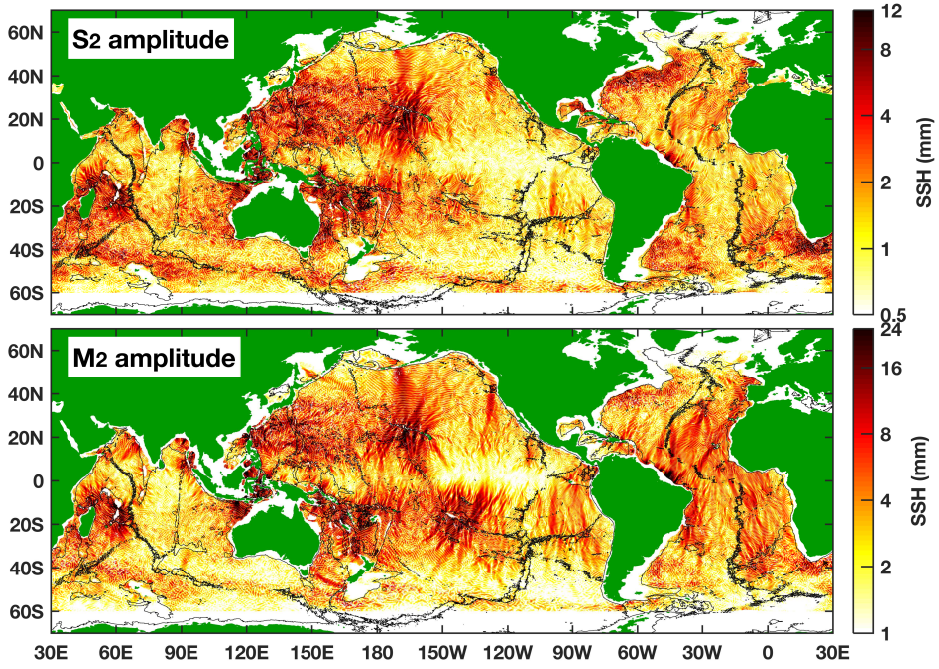
Low-Mode Internal Waves $\rightarrow$ Scattering on Shelves/Slopes $\rightarrow$ Mixing
Low-Mode Internal Waves $\rightarrow$ Reflection $\rightarrow$ Mixing in Interior

- How much of the energy is scattered, reflected, or transmitted for all low-mode waves under different shelf/slope geometries?

Project 1: Tides from Altimetry and HYCOM

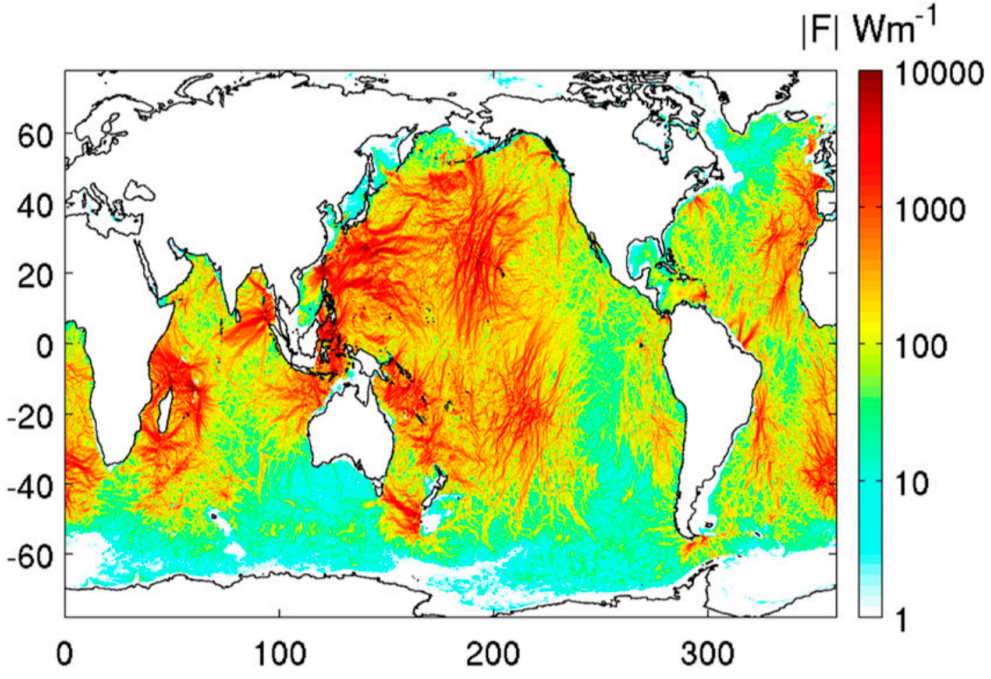
Zhongxiang Zhao and Maarten Buijsman

Internal Tide Amplitudes from Altimetry



(Z. Zhao)

Semidiurnal Baroclinic Pressure Flux



(Buijsman et al. 2016)

Altimetry + HYCOM $\rightarrow$ more complete understanding of internal tides

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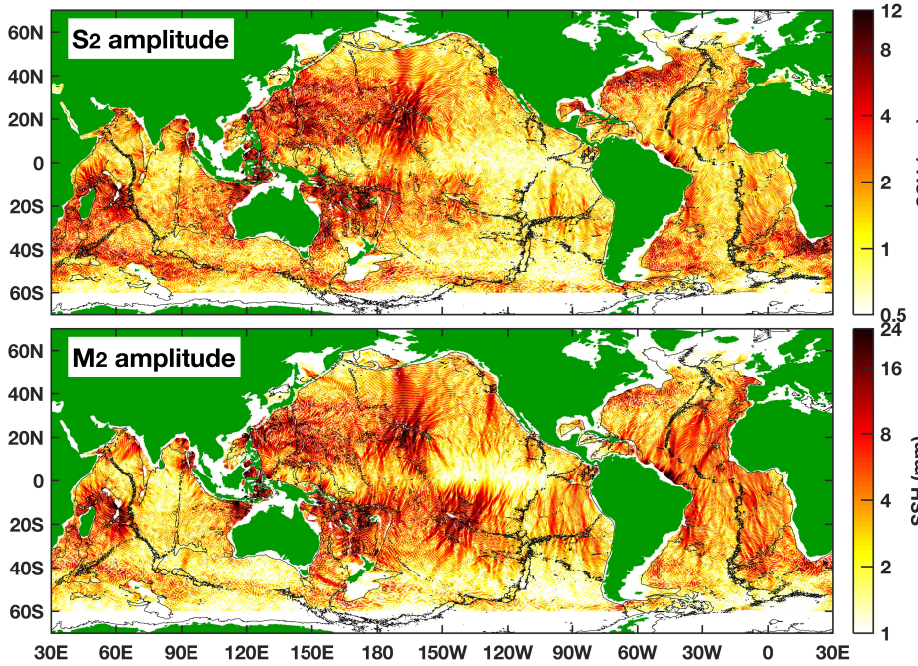

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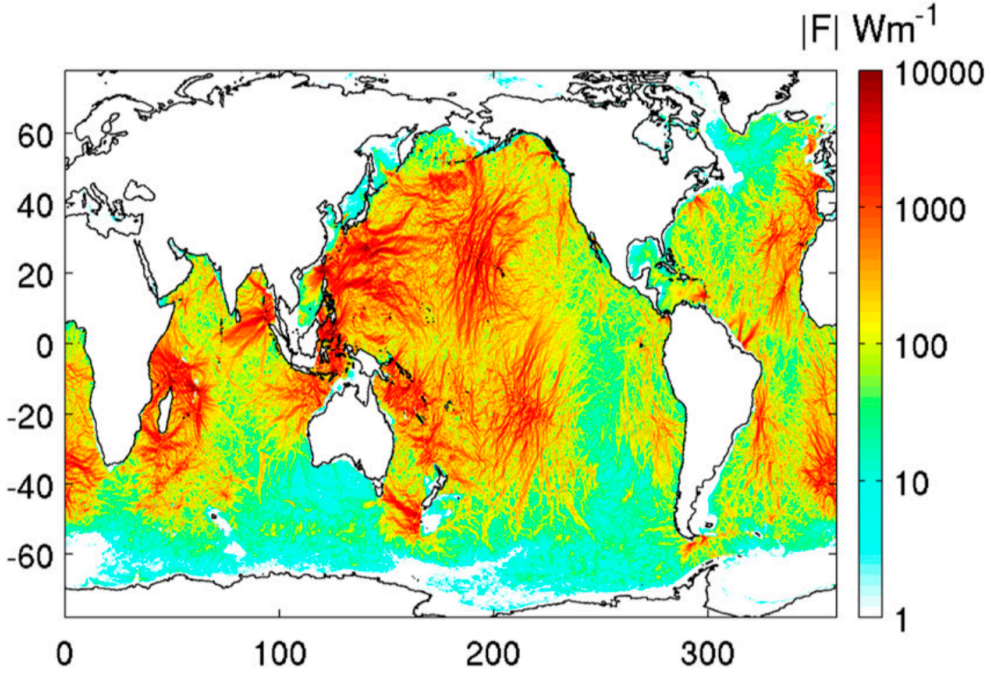


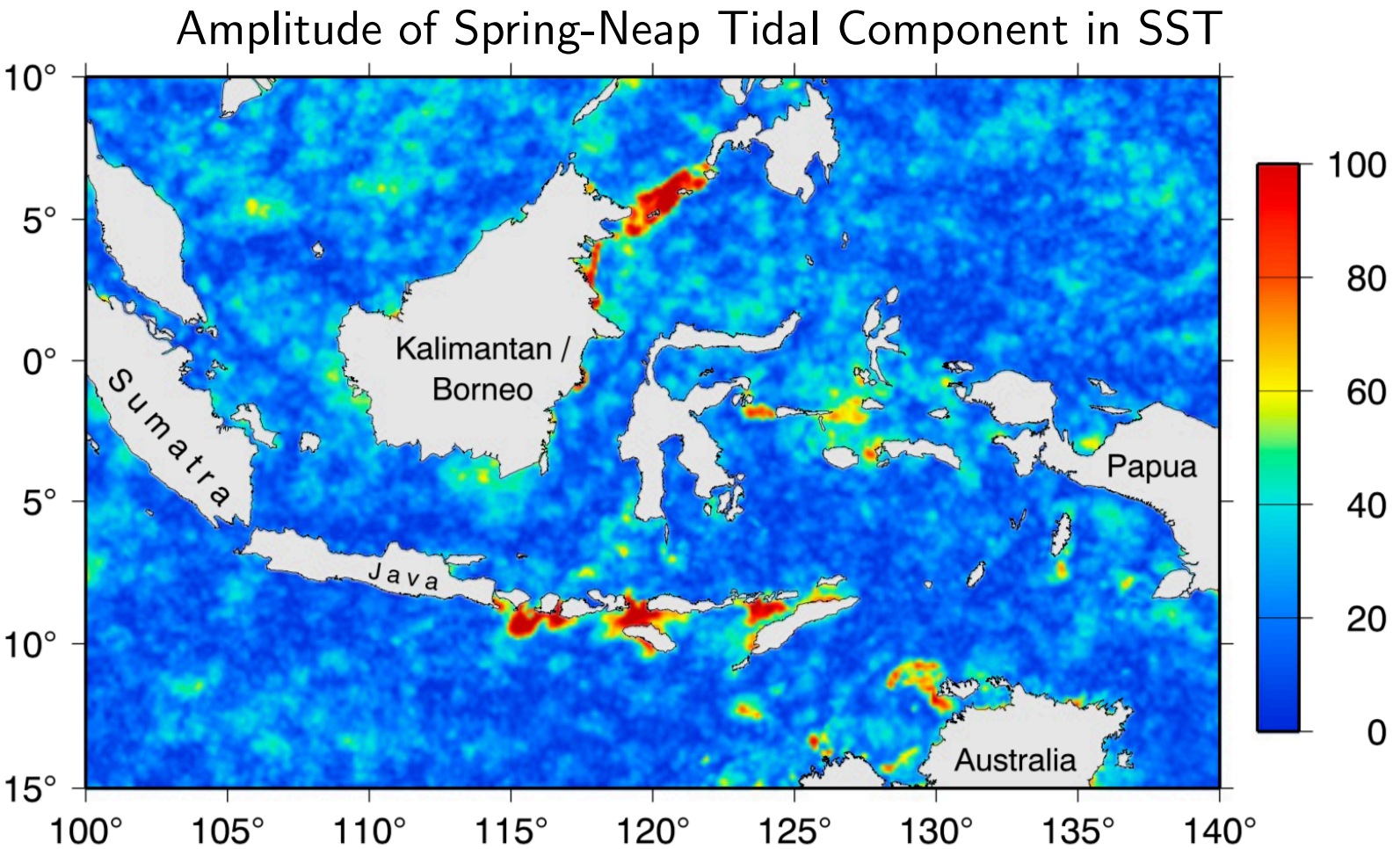
(Buijsman et al. 2016)

Altimetry + HYCOM → more complete understanding of internal tides

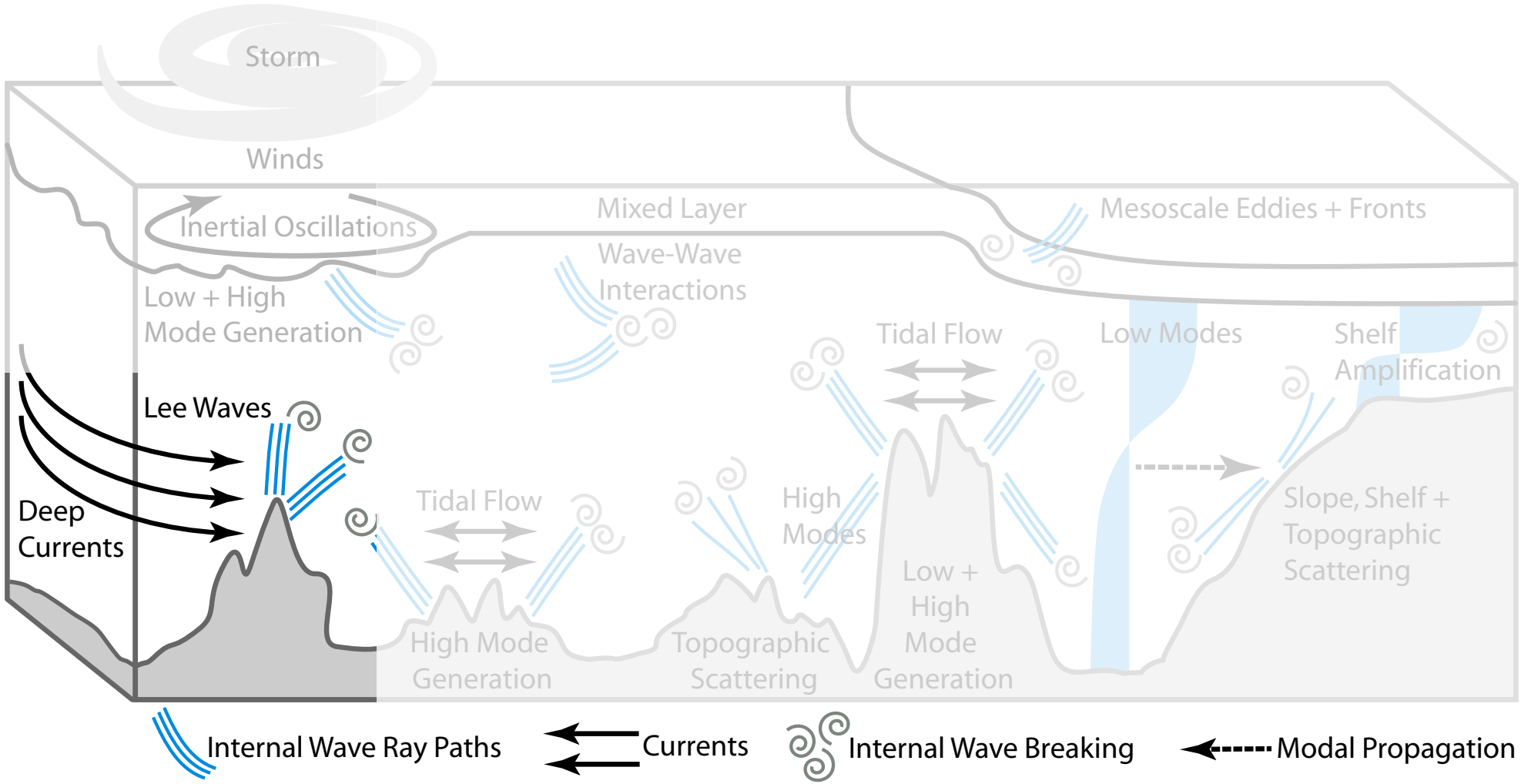
- What is the spatial distribution of the mixing due to internal tides?

Project 2: Changes in SST at the Tidal Frequency

Dwi Susanto et al



Internal Wave Driven Mixing from Lee Waves



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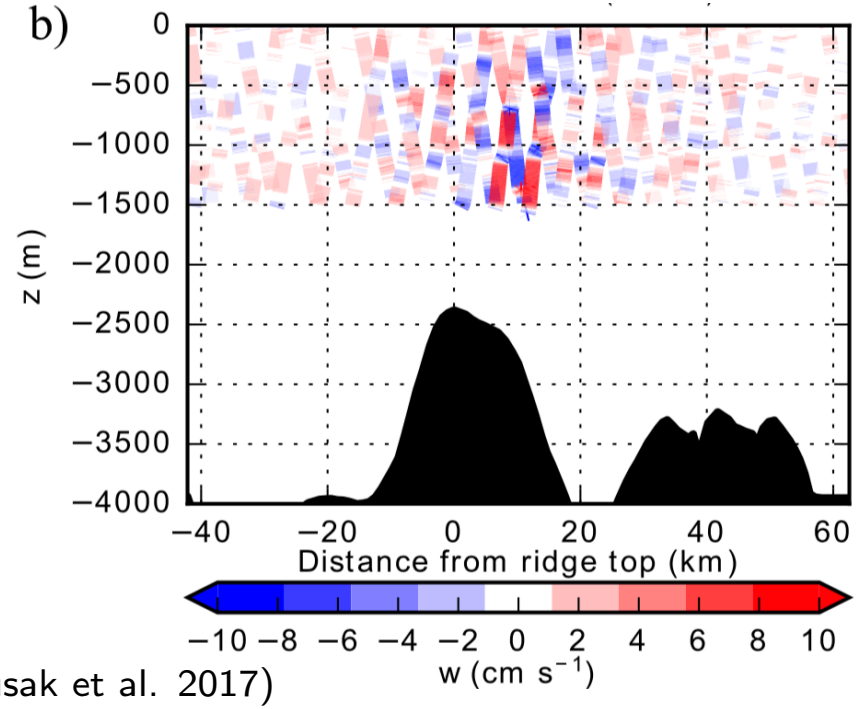
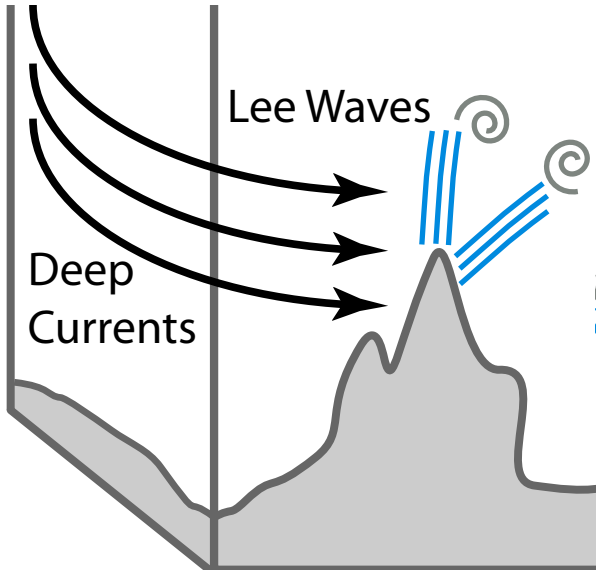
Internal Wave Driven Mixing from Lee Waves

Observed lee wave vertical velocities



(Cusak et al. 2017)



Flow over Topography$\rightarrow$ Lee Wave Generation $\rightarrow$ Mixing

Internal Wave Driven Mixing from Lee Waves

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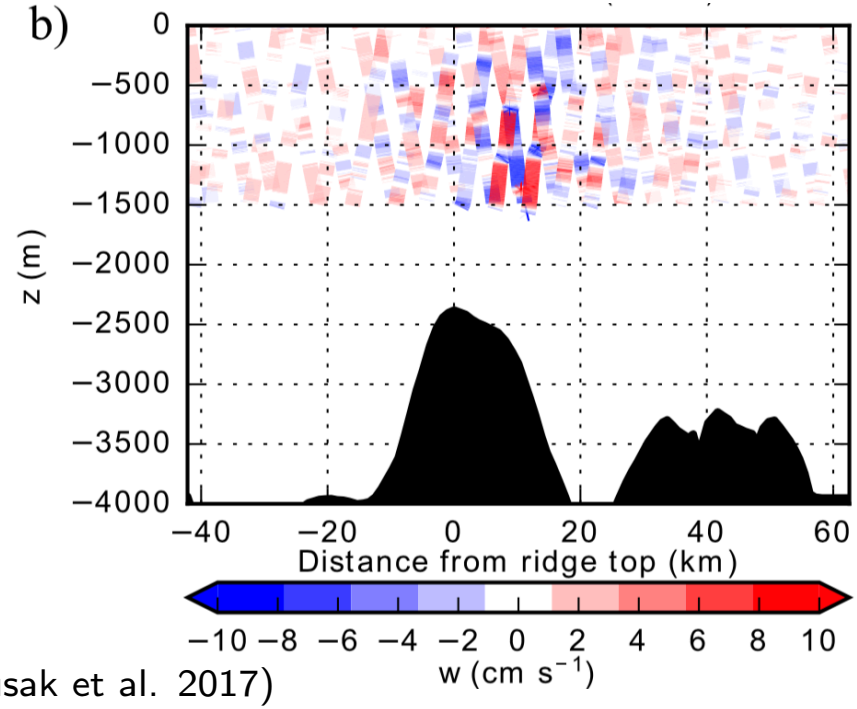

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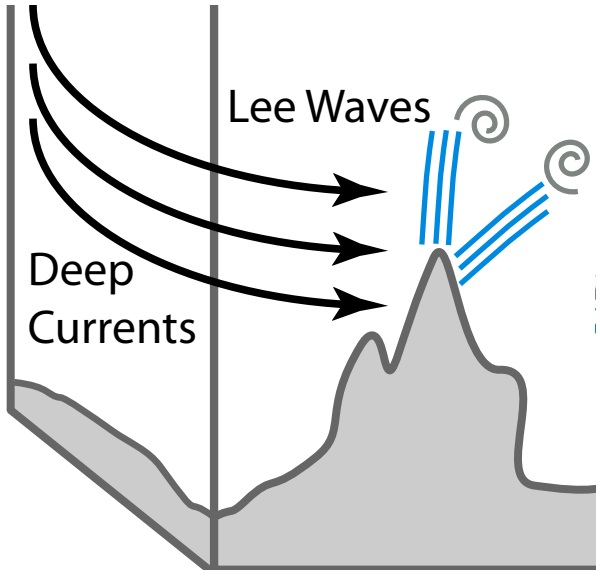

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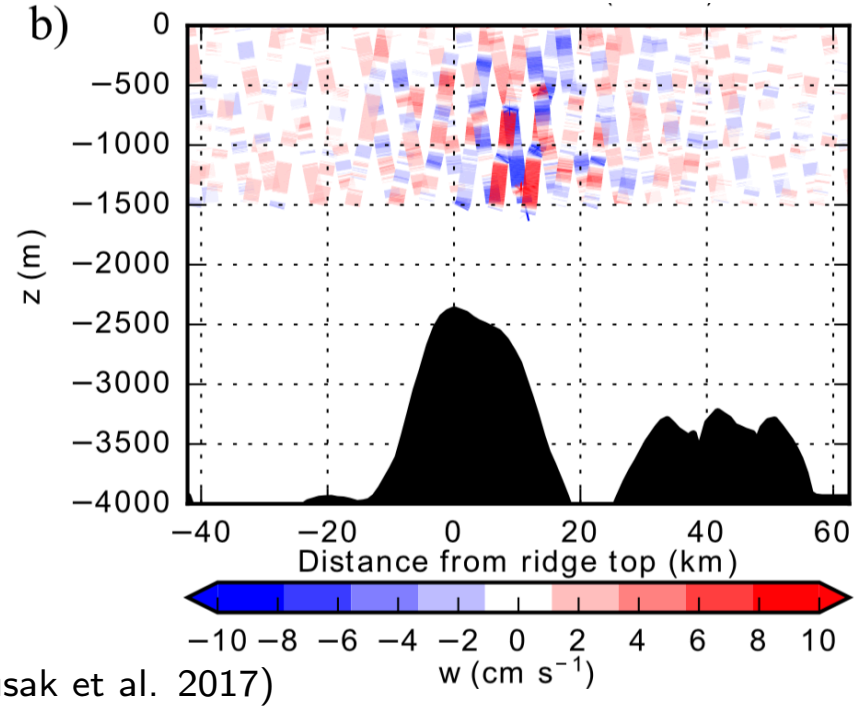

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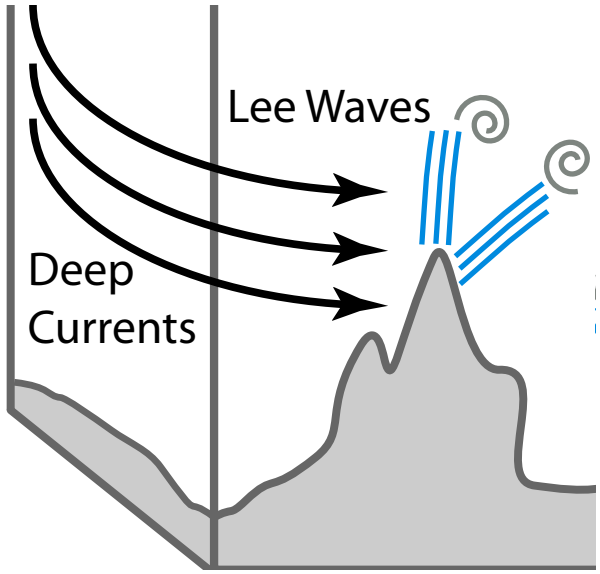
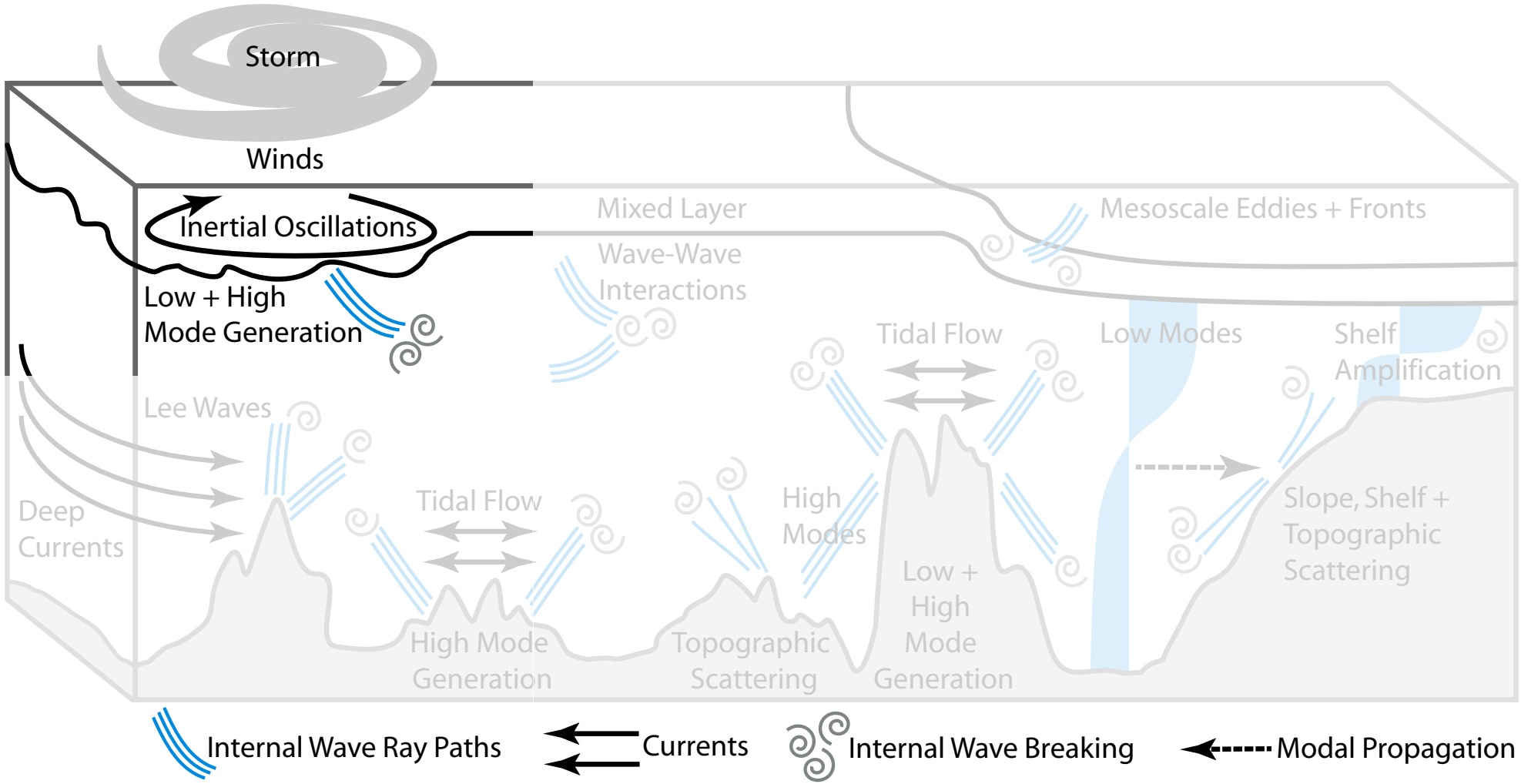


Flow over Topography$\rightarrow$ Lee Wave Generation $\rightarrow$ Mixing

- Big Question: Where and why do lee waves dissipate their energy, and is this large enough to be important globally?
- Specific Question: How much energy dissipates close to the sources of lee waves vs how much propagates away?

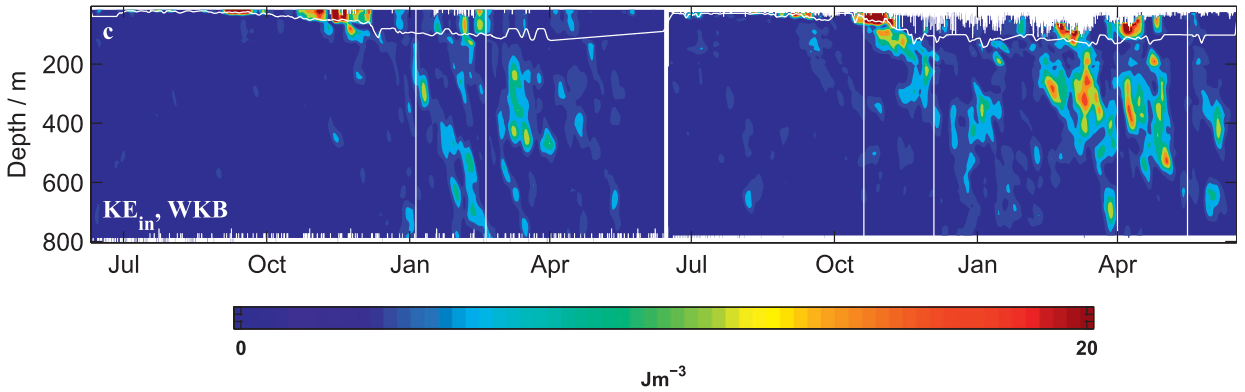
Mixing from Wind-Driven Internal Waves



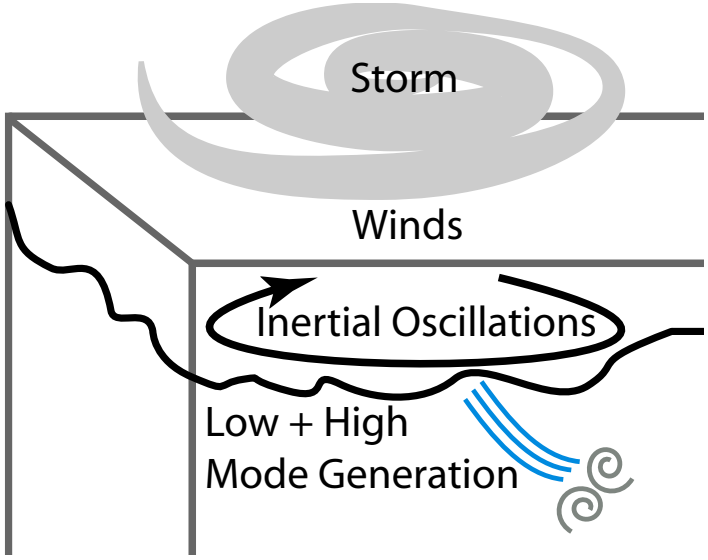
(MacKinnon et al. 2017)

Near-Inertial Energy From Wind → Elevated Mixing

Seasonal Cycle in Near-Inertial Kinetic Energy

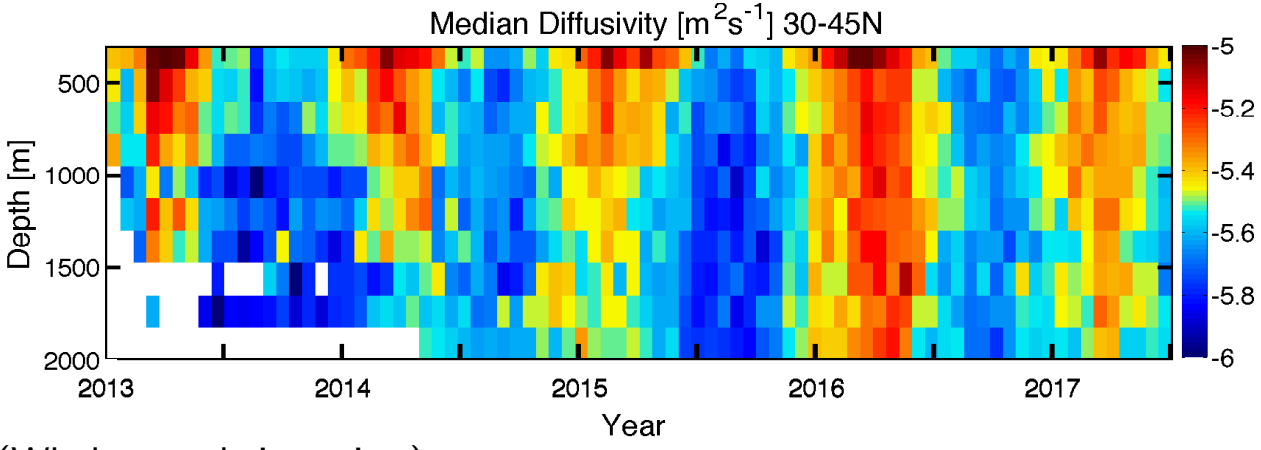


(Alford et al. (2012))

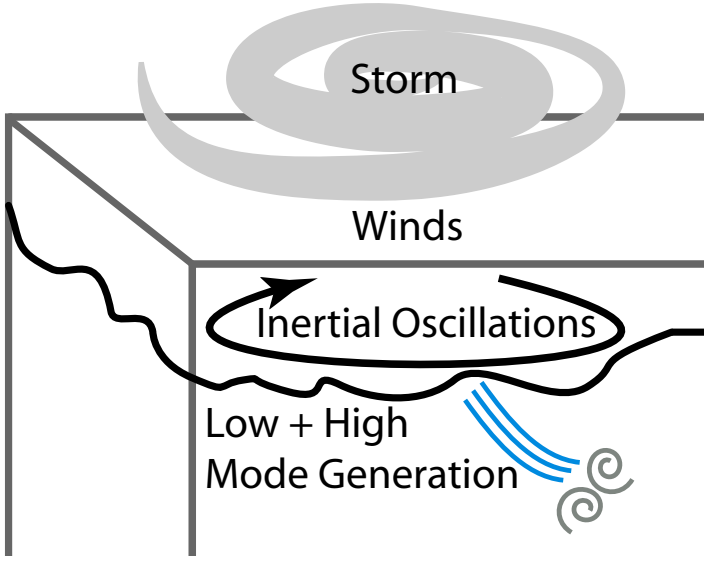


Wind → Inertial Oscillations in Mixed Layer → Near-Inertial Internal Waves → Mixing

Near-Inertial Energy From Wind → Elevated Mixing



(Whalen et al. in review)



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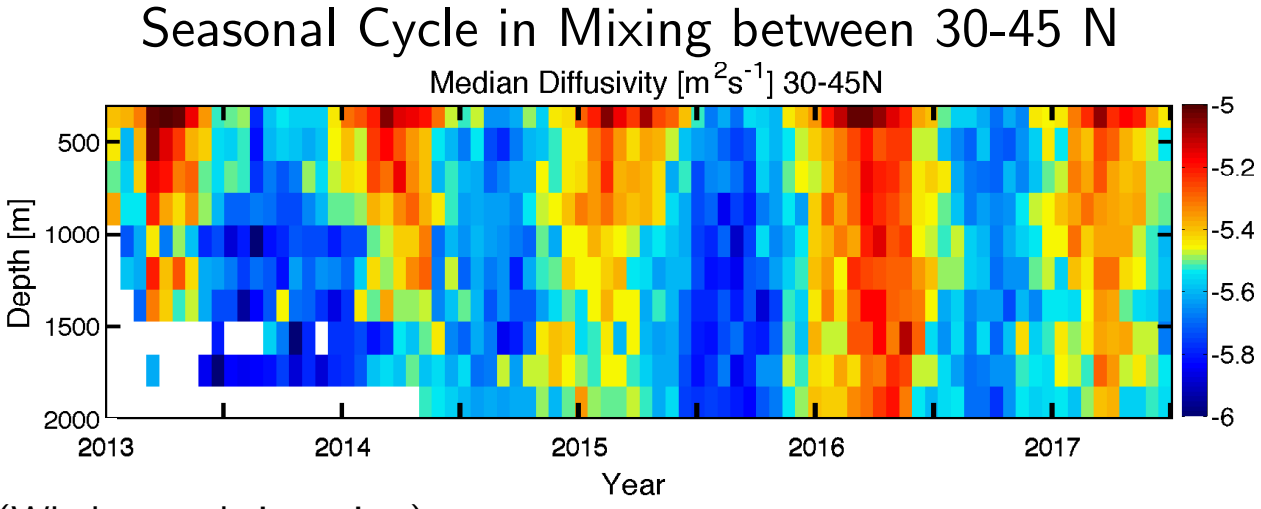

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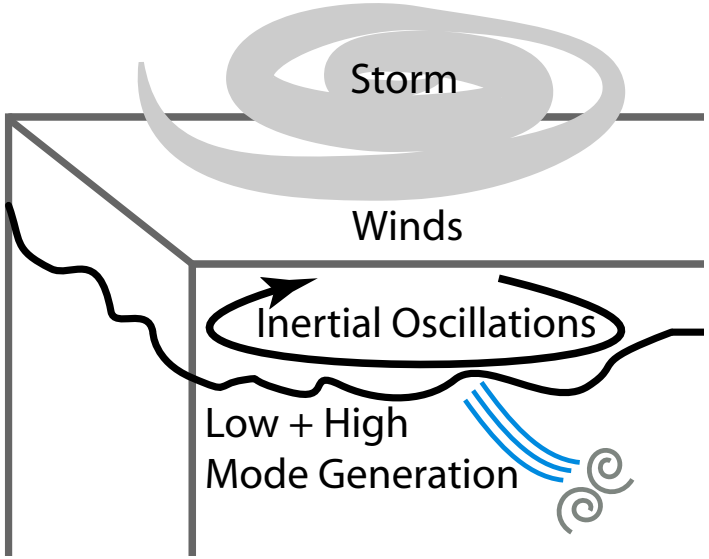
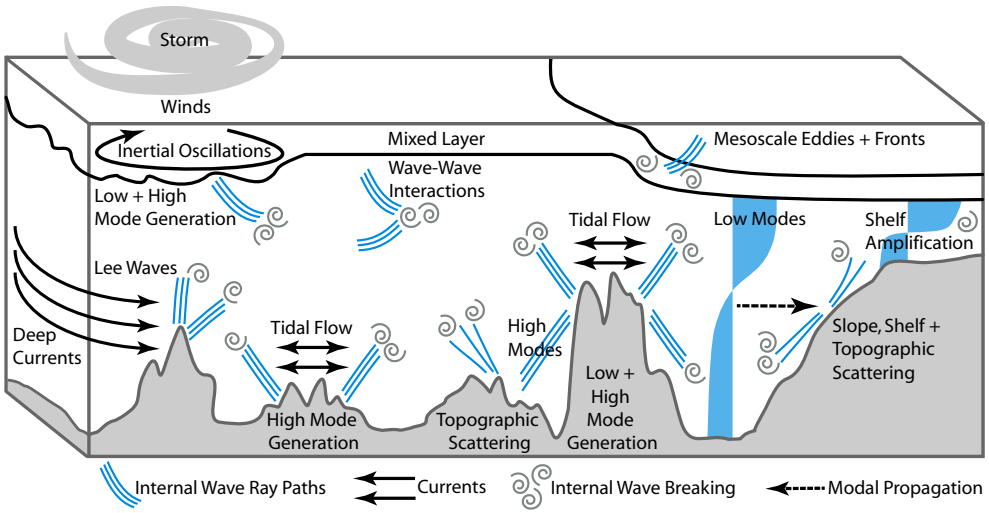
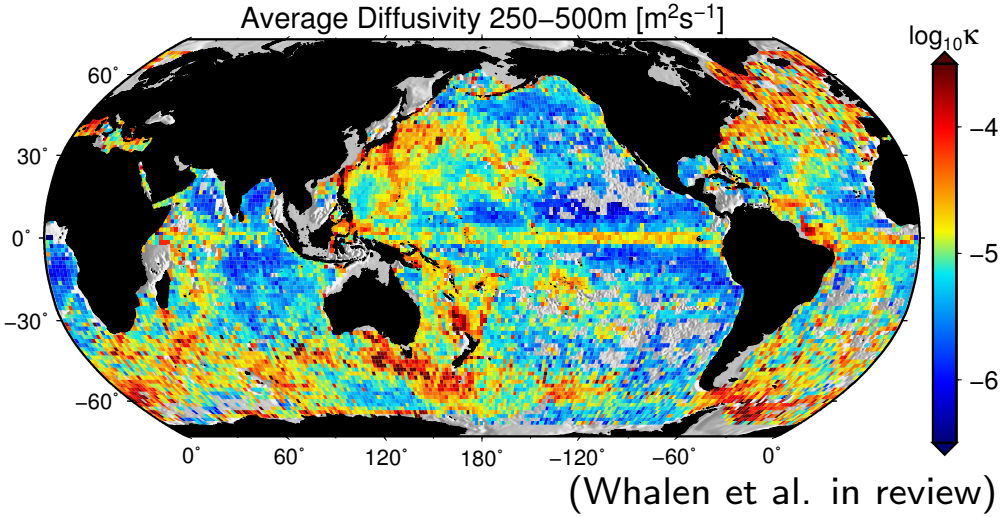


Wind → Inertial Oscillations in Mixed Layer → Near-Inertial Internal Waves → Mixing

- Big Question: What are the near-inertial internal wave energy pathways?
- Specific Question: Where and why do wind-driven near-inertial waves dissipate and cause mixing?

Implications of Spatially Variable Mixing for the MOC?





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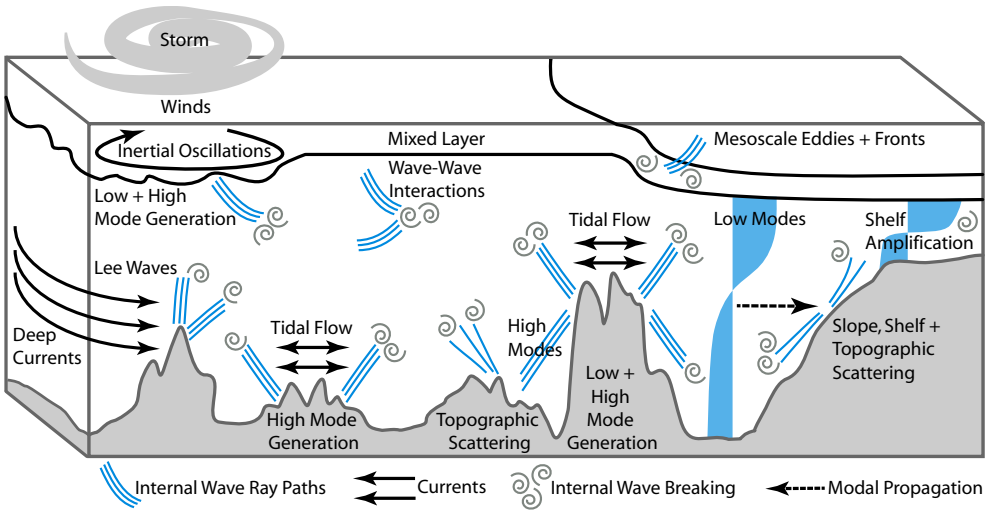
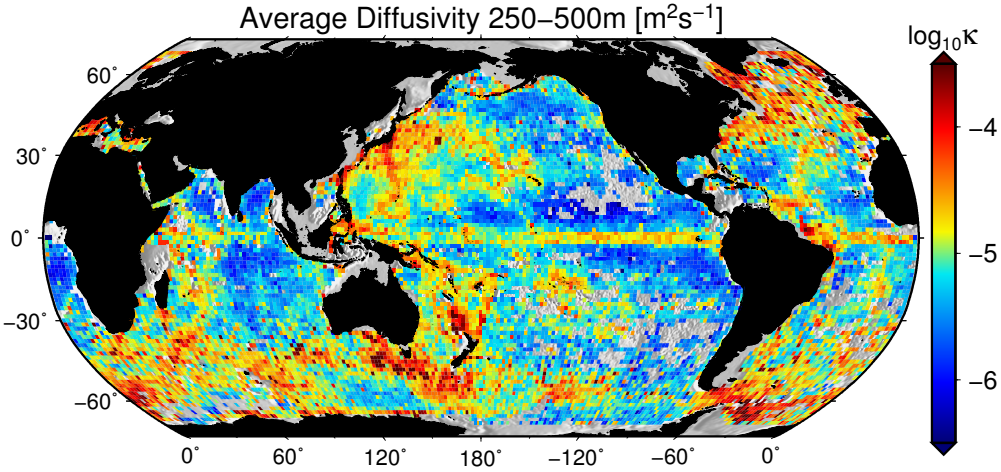
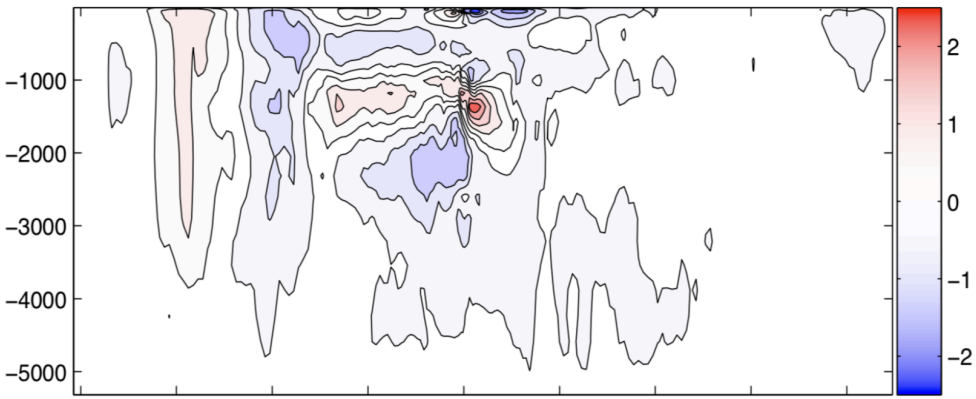




(Whalen et al. in review)

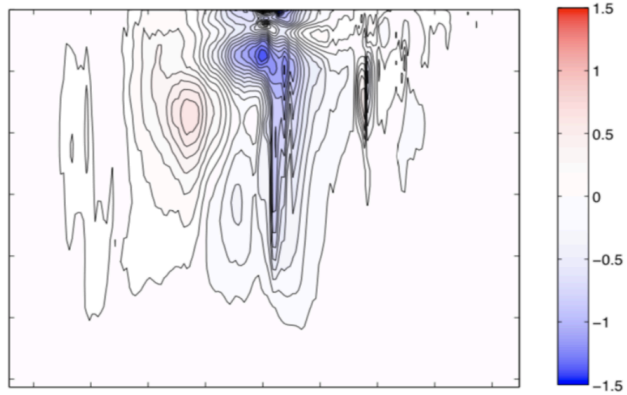
When observationally-based diffusivities are incorporated:

Changes in the MOC in GEOS5/MOM5



(Trossman et al. 2018b in prep)

Changes in the MOC in ECCO



(Trossman et al. 2018a in prep)

How does the spatial/temporal variability of mixing affect the MOC?

Mixing from Internal Waves: Lingering Questions

Internal Wave Energy Pathways

- e.g. What fraction of energy from internal waves dissipates close to generation sites? How much propagates away? (From Tides, Winds, Lee waves)

Where, When and Why Internal Waves do Dissipate and Cause Mixing

- e.g. What fraction of internal wave energy encountering boundaries (rough topography, slopes, and shelves) locally dissipates, and how much staying in the internal wave field?
- e.g. Where in the ocean does the majority of wind-driven internal wave energy dissipate?

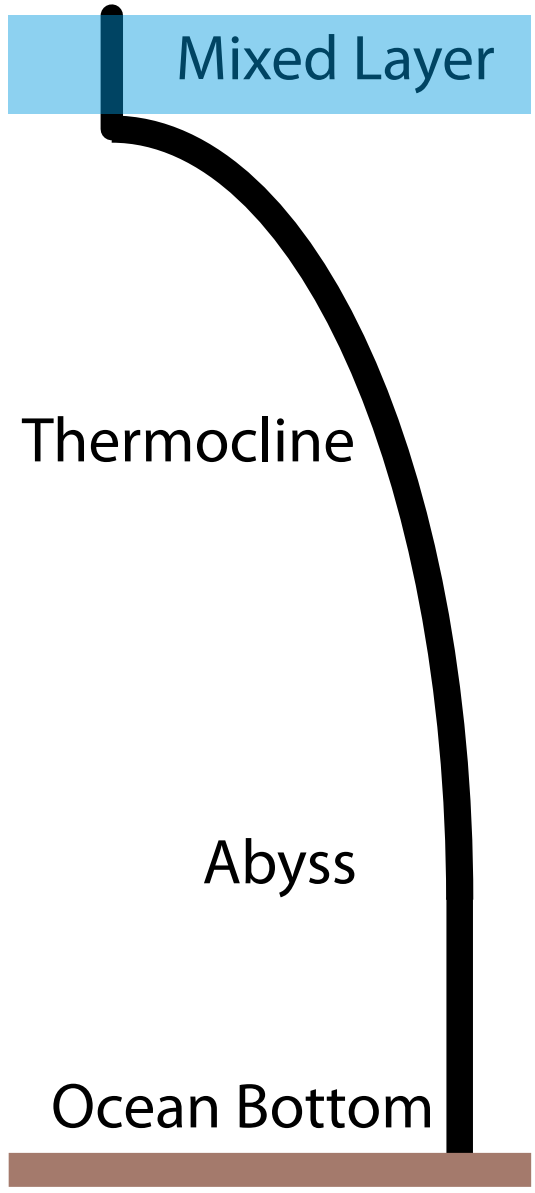
The Impacts of this Mixing

- e.g. How does the spatial/temporal variability of mixing affect the MOC?

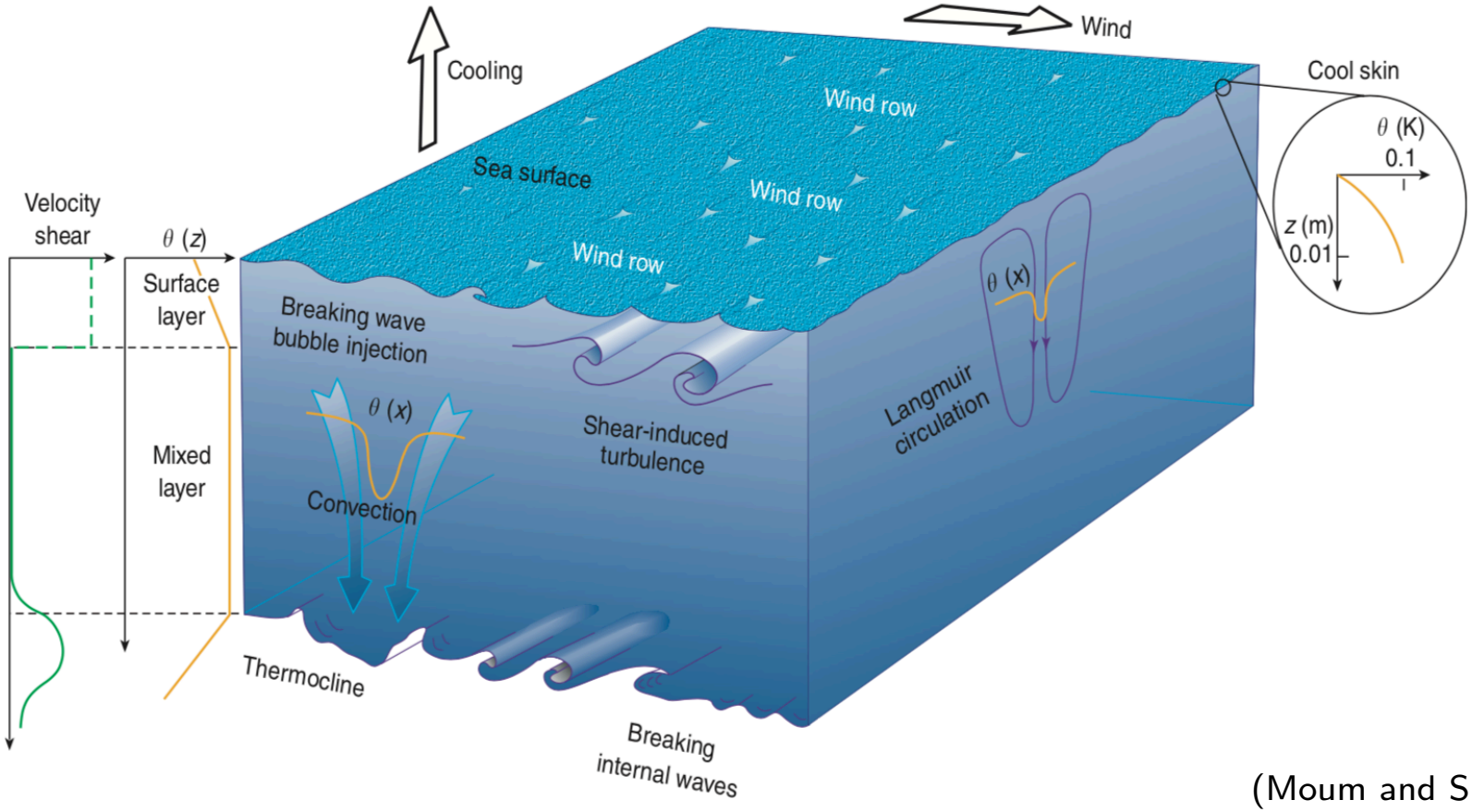
Many Types of Ocean Mixing

Mixing Occurs:

- **Mixed layer**
  (Convection, wind stress, mixed layer instabilities, etc)
- Mixed layer base
  (Shear, etc)
- Thermocline and abyss
  (Internal wave driven mixing, double diffusion, etc)
- Close to the seafloor
  (Dense overflows, turbulent boundary layers, etc)

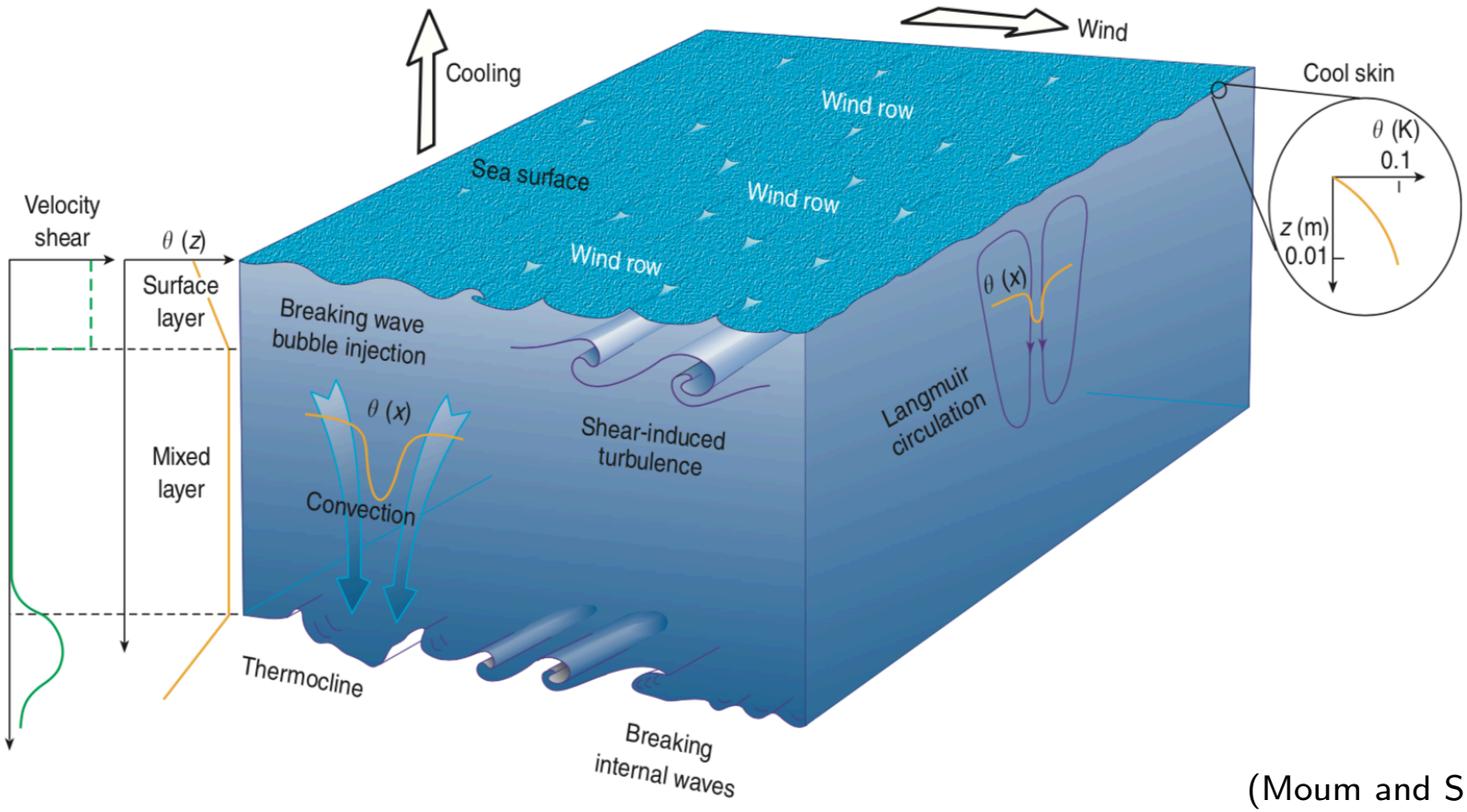


Mixing Processes in the Mixed Layer



(Moum and Smyth 2001)

Mixing Processes in the Mixed Layer



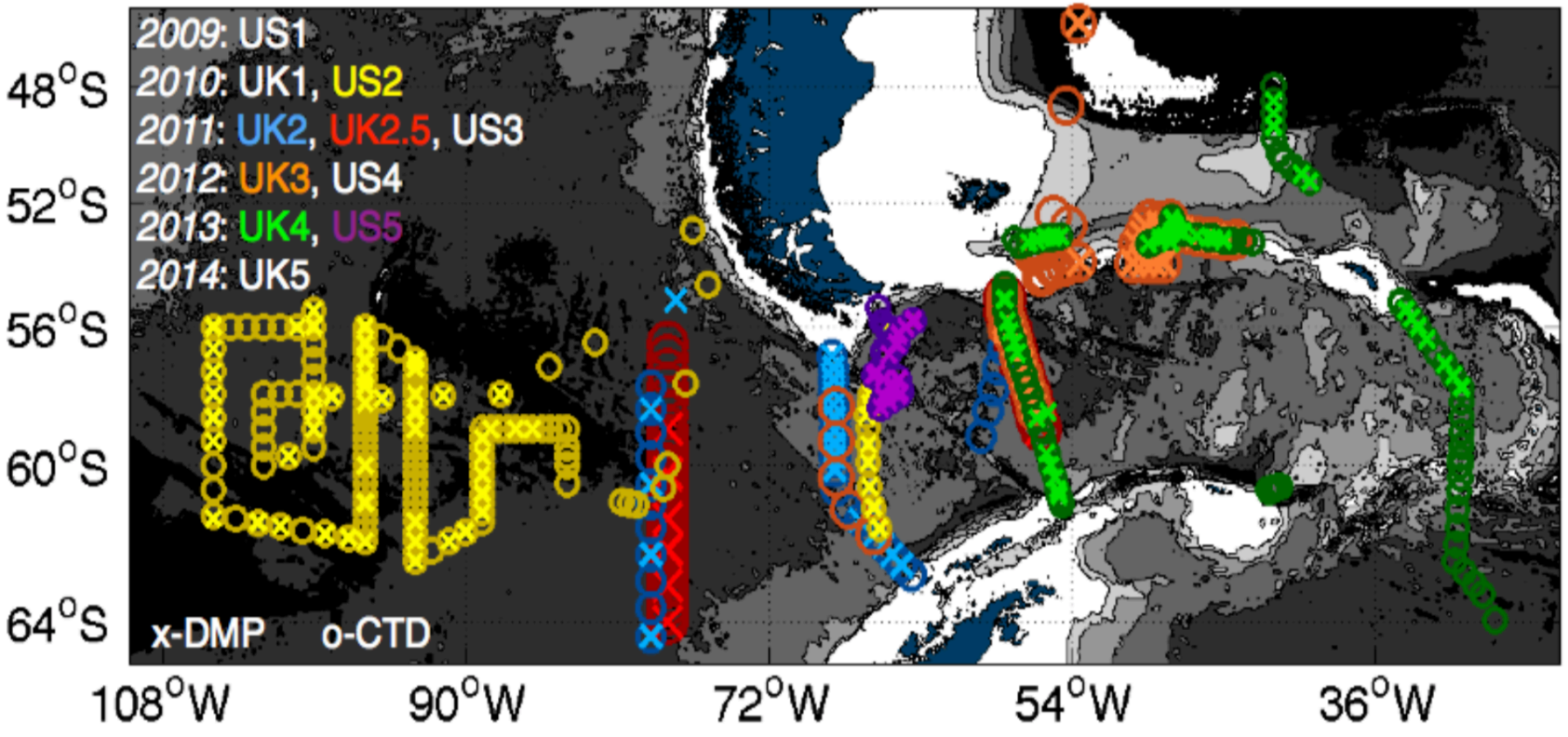
(Moum and Smyth 2001)

- What is the spatial and temporal variability of surface boundary layer mixing on large spatial and long temporal scales?
- How do processes beyond buoyancy fluxes and winds affect mixing? (e.g. Langmuir circulation, waves, storms)

Project 3: Surface Boundary Layer Mixing from Satellites

Clayson, Jayne, and St. Laurent

Locations of Microstructure and CTD in the Drake Passage Region

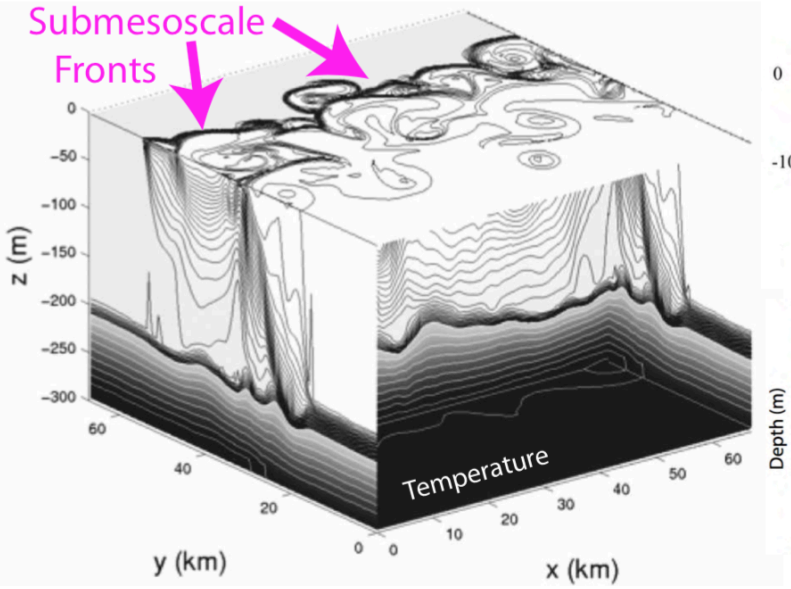


(Merrifield et al 2016)

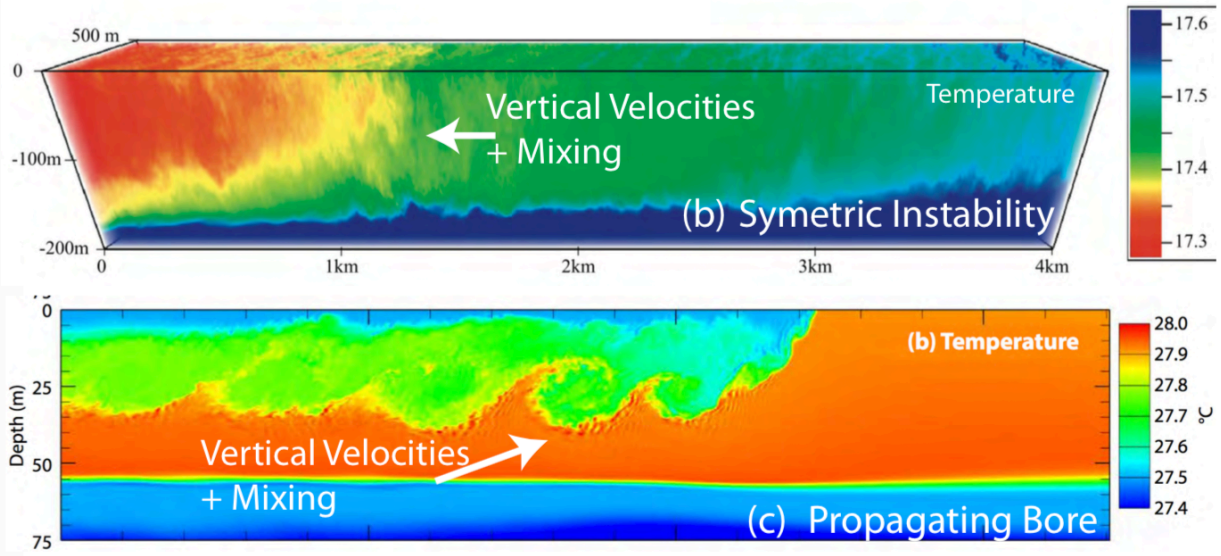
- Can satellite observations of surface buoyancy and moment fluxes be used to estimate surface boundary layer mixing?

Mixing from Submesoscale Instabilities

(a) Mixed Layer Baroclinic Instability



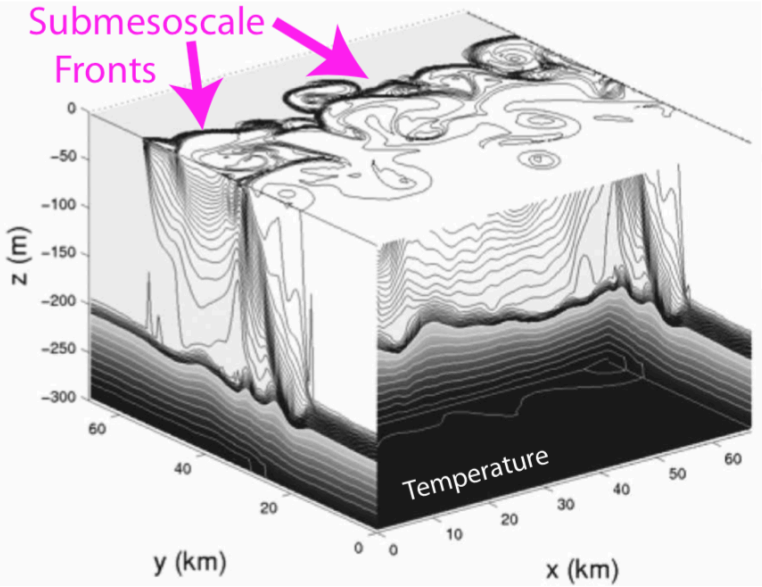
Instabilities at Submesoscale Fronts with Strong Vertical Velocities



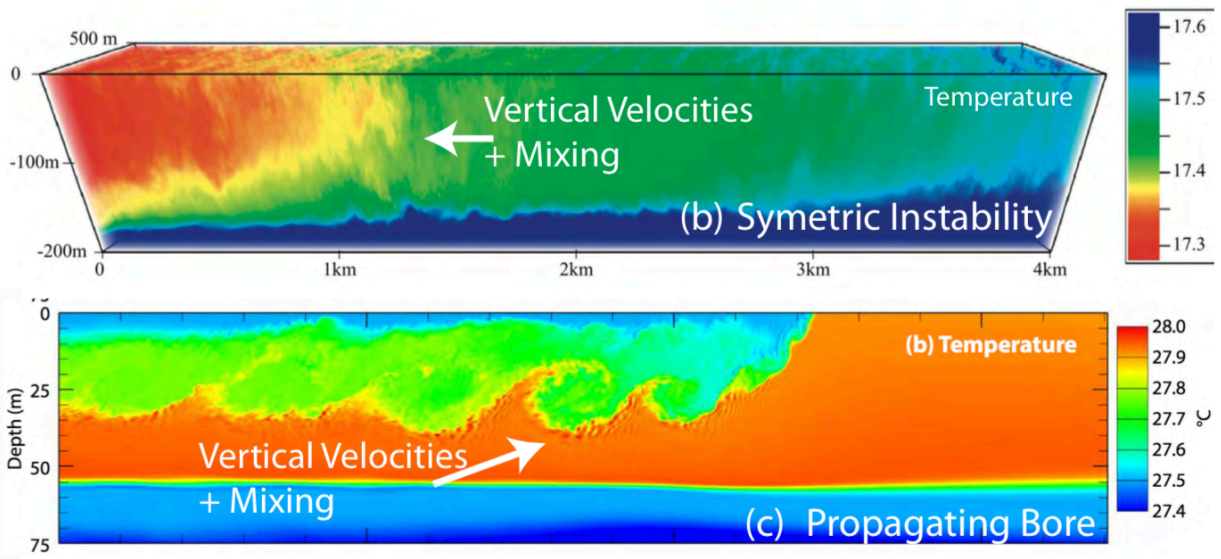
(a) Fox-Kemper et al (2008), (b) Thomas et al (2013), and (c) Sarkar et al (2016)

Mixing from Submesoscale Instabilities

(a) Mixed Layer Baroclinic Instability



Instabilities at Submesoscale Fronts with Strong Vertical Velocities



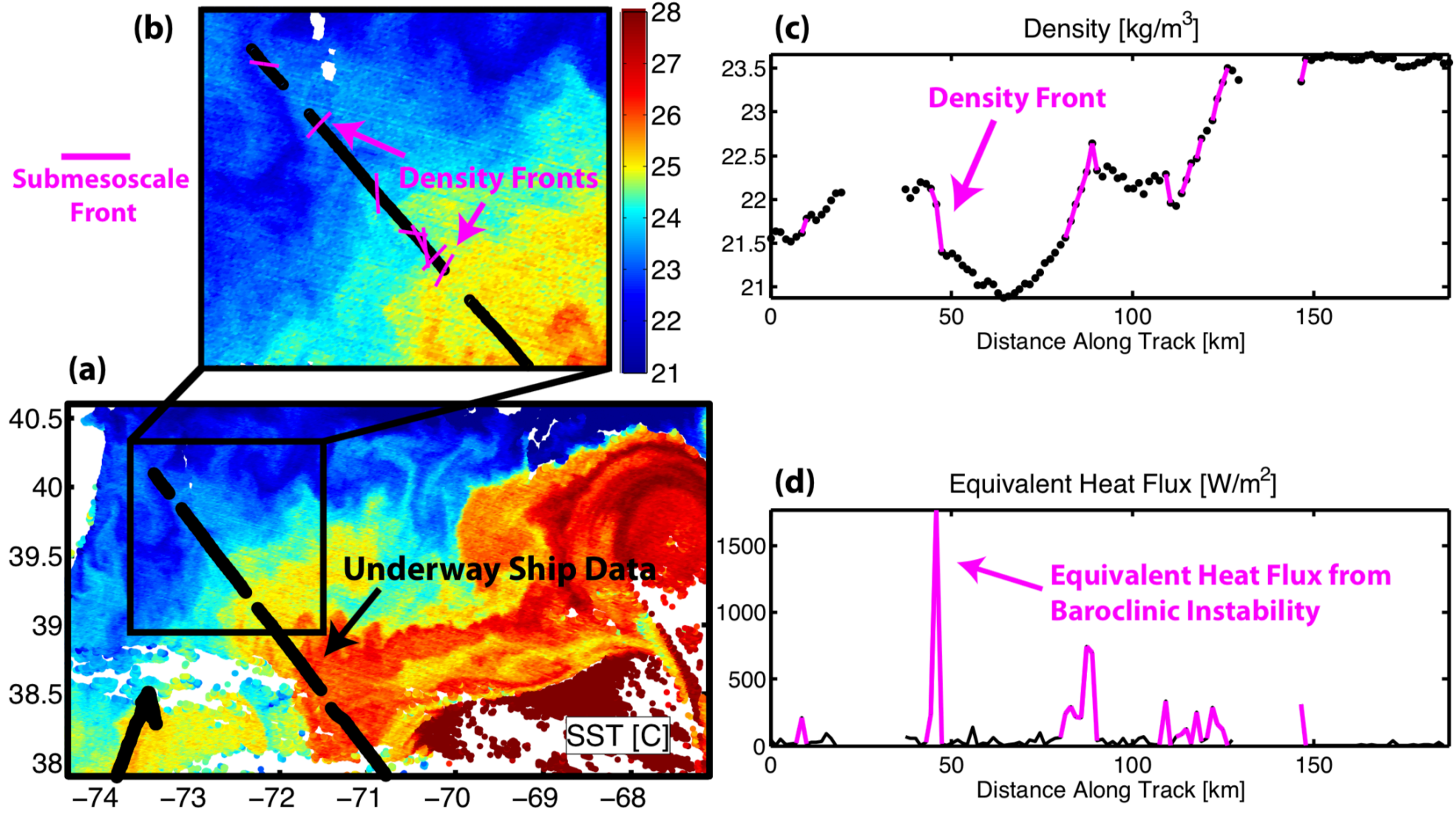
(a) Fox-Kemper et al (2008), (b) Thomas et al (2013), and (c) Sarkar et al (2016)

- What are the regional and global impacts of mixing due to submesoscale processes on mixed layer depth, heat fluxes, and energy budgets?

Project 4: Heat Flux from Submesoscale Instabilities

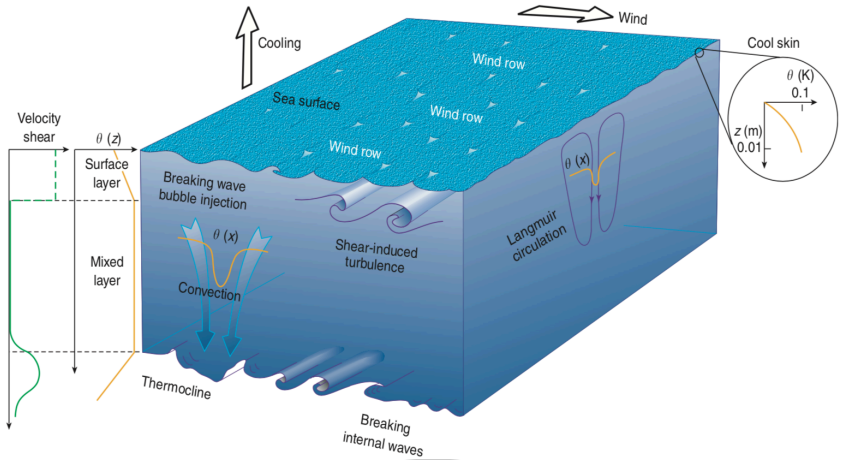
Whalen, Druska, and Gaube

Equivalent Heat Flux Estimates from Ship Tracks and Satellite SST

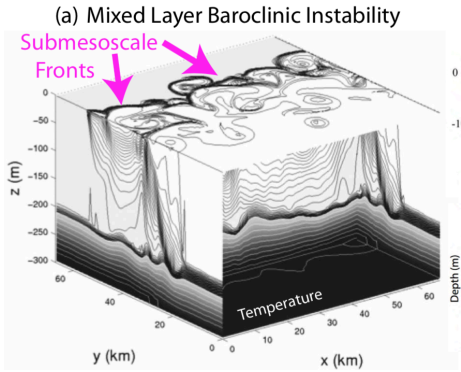


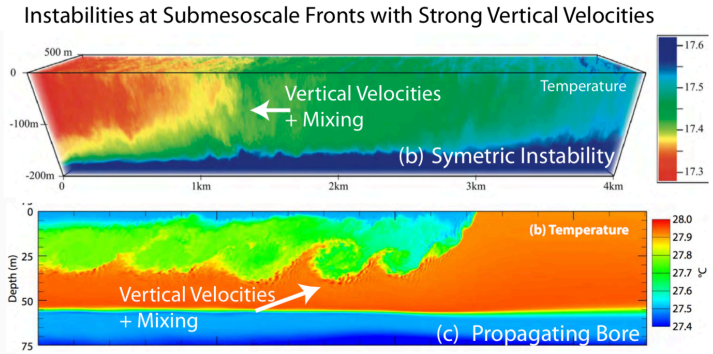
Summary

Surface Boundary Layer Mixing

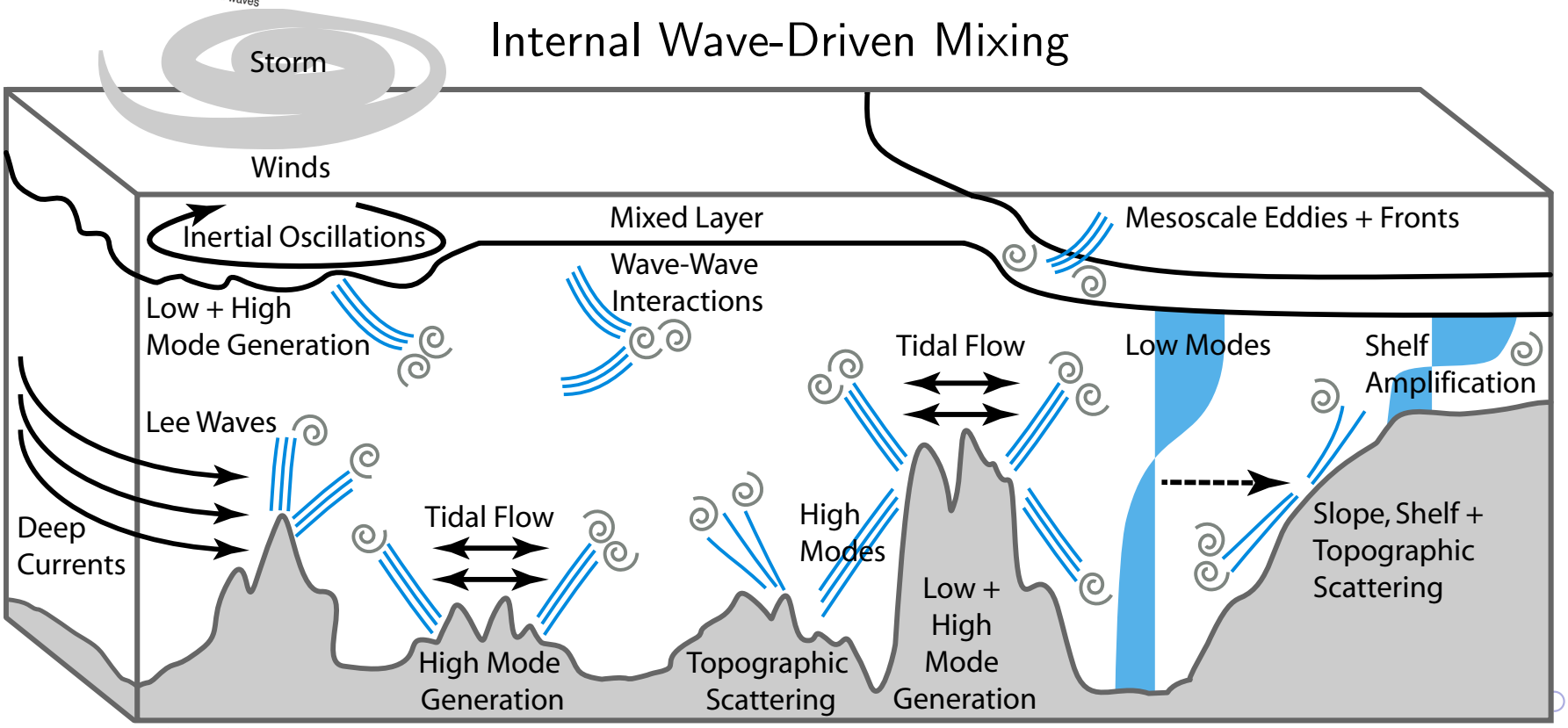


Mixing from Submesoscale Instabilities





Internal Wave-Driven Mixing



Mixing Questions

Mixing from Internal Waves

- Where, when and why internal waves do dissipate and cause mixing? What are the pathways from generation to dissipation? (Tides, Winds, Lee waves)
- What are the implications of spatially and temporally varying mixing on the circulation? (e.g. MOC)

Mixing in the Mixed Layer

- What is the spatial and temporal variability of surface boundary layer mixing on large spatial and long temporal scales?
- How do processes beyond buoyancy fluxes and winds affect mixing? (e.g. Langmuir circulation, waves, storms)

Mixing in the Submesoscale

- What are the regional and global impacts of mixing due to submesoscale processes on mixed layer depth, heat fluxes, and energy budgets?