Examining shoreface disequilibrium morphodynamics and their influence on shoreline change

Megan Gillen[1], Andrew Ashton[2], Jennifer Miselis[3], Emily Wei[3], Daniel Ciarletta[3], and Christopher Sherwood[4]

[1]MIT-WHOI Joint Program in Oceanography/Applied Ocean Science & Engineering
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[4]USGS Coastal and Marine Science Center Woods Hole

November 23, 2022

Abstract

The lower shoreface, a transitional subaqueous region extending from the seaward limit of the surf zone to beyond the closure depth, often serves as a sediment sink or source in sandy beach environments over annual to millennial time scales. Despite its important role in shoreline dynamics, however, the morphodynamics of the lower shoreface remain poorly understood. This knowledge deficit is partly due to the absence of sediment compositional data across the seabed and to the challenges inherent in measuring subtle bed changes (mm-cm/yr) over historical time scales. It is also unclear how diverse lithologies and long-term changes in wave climate influence shoreface morphodynamics as previous work often considers these steady-state systems in equilibrium. To better understand the controls on shoreface dynamics, we extend an existing energetics-based framework to model sediment transport across theoretical shoreface equilibrium profiles under various physical and geologic disequilibrium conditions. We further incorporate varying shoreline input flux scenarios (i.e., accretion, erosion) to investigate potential coastline inheritance controls on shoreface evolution. Equilibrium profile shapes and disequilibrium sediment transport rates are more sensitive to changes in sediment settling velocity than wave period, indicating that grain size provides a strong geologic control on shoreface morphodynamics. We find that at depths greater than 20 meters, shallow water wave assumptions predict larger sediment transport rates (˜1-8 orders of magnitude) than linearly shoaled waves. Furthermore, for linear wave theory, we find an abrupt, discontinuous offshore transition where the bed response to changing wave climates becomes exceptionally slow. Our results provide insight into the sediment dynamics that drive the spatiotemporal evolution of the shoreface, improving our understanding of the interactions between onshore and nearshore processes and geological inheritance.

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AGU Fall Meeting 2021
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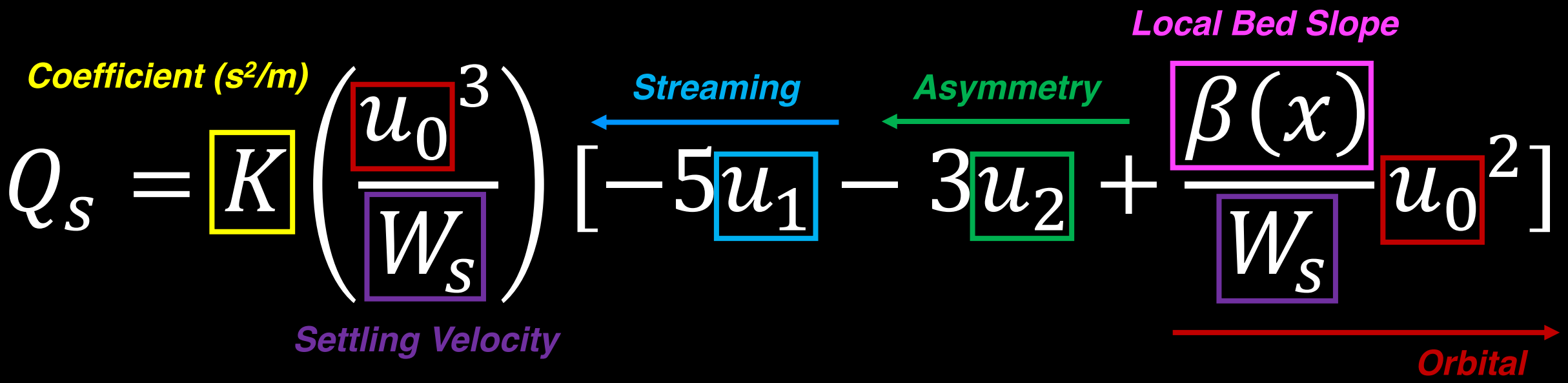
Background

- Transitional zone on passive margins
- Morphodynamic evolution not well understood
  - Lack of sediment data
  - Long timescales (10^1-10^3 yrs)
- Steady-state assumptions

(Ortiz & Ashton 2016; Derived from Bagnold 1963, Bowen 1980, Stive & deVriend 1995)

Energetics Transport Equation



(Ortiz & Ashton 2016; Derived from Bagnold 1963, Bowen 1980, Stive & deVriend 1995)

Energetics Transport Equation

Coefficient (s^2/m)

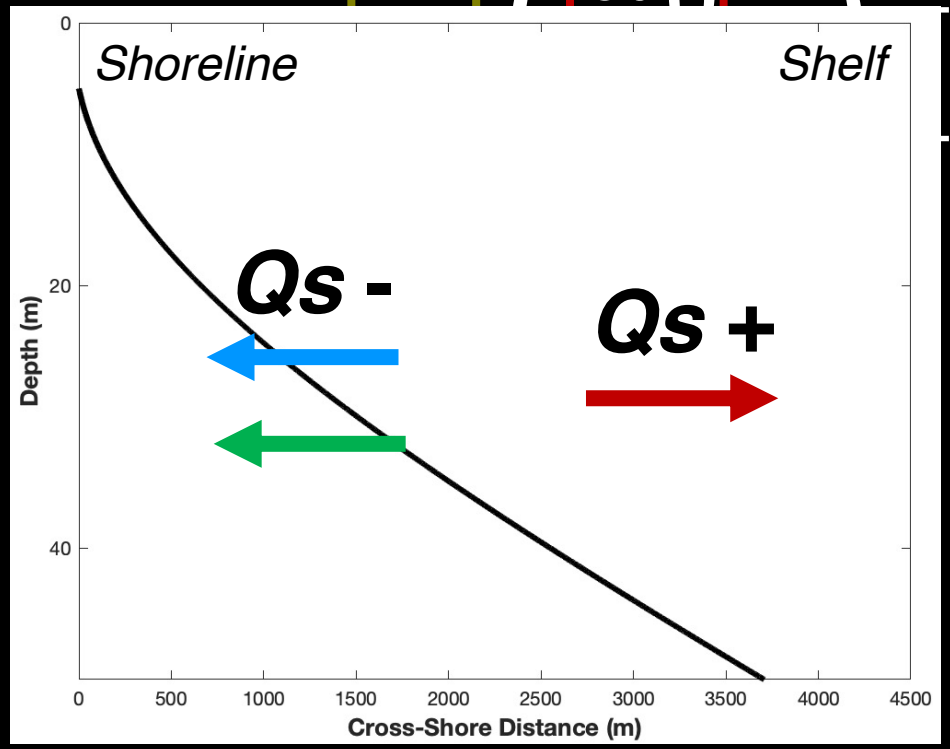
$$\left(u_0^3\right)\left[-5u_1 - 3u_2 + \frac{\beta(x)}{W_s}u_0^2\right]$$

Streaming ← $-5u_1$

Asymmetry ← $-3u_2$

Local Bed Slope → $\frac{\beta(x)}{W_s}u_0^2$

Orbital →



(Ortiz & Ashton 2016; Derived from Bagnold 1963, Bowen 1980, Stive & deVriend 1995)

Energetics Transport Equation

Coefficient (s^2/m)

Settling Velocity

Streaming

Asymmetry

Local Bed Slope

Orbital

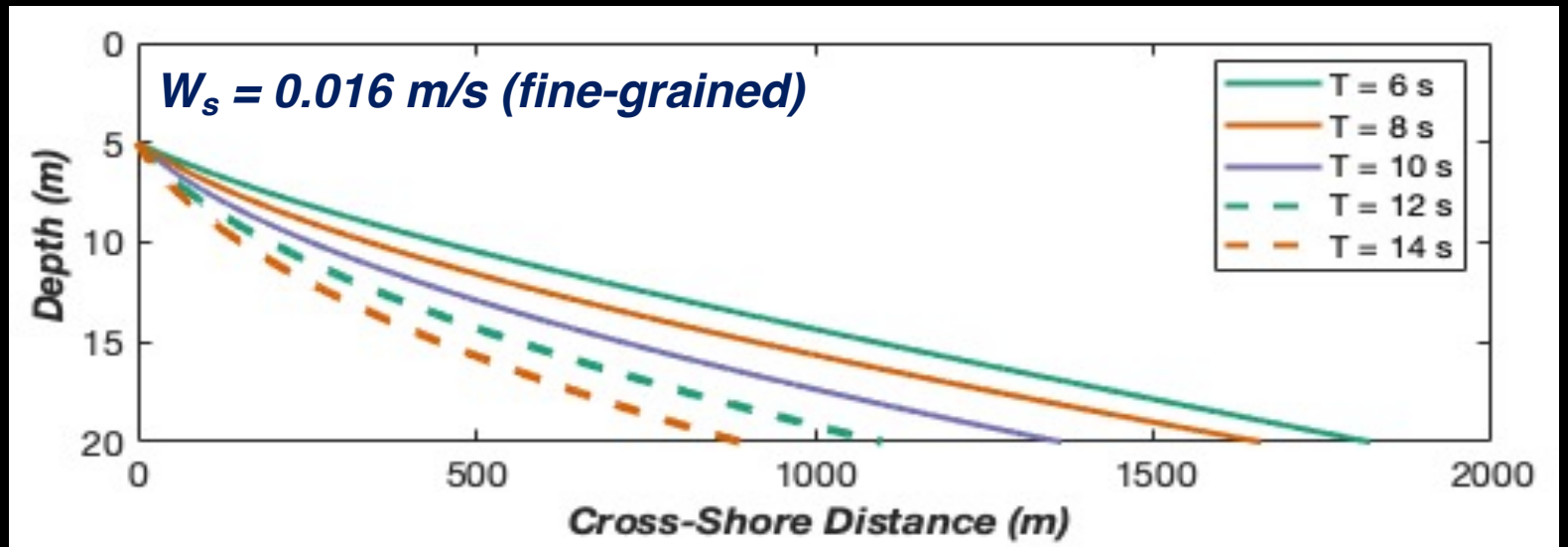
$$Q_s = K\left(\frac{u_0^{\,3}}{W_s}\right)\left[-5u_1 - 3u_2 + \frac{\beta(x)}{W_s}u_0^{\,2}\right]$$

Equilibrium Slope

$$\beta_e(z(x)) = \frac{W_{s_e}}{u_0^{\,2}}\left[5u_1 + 3u_2\right]$$

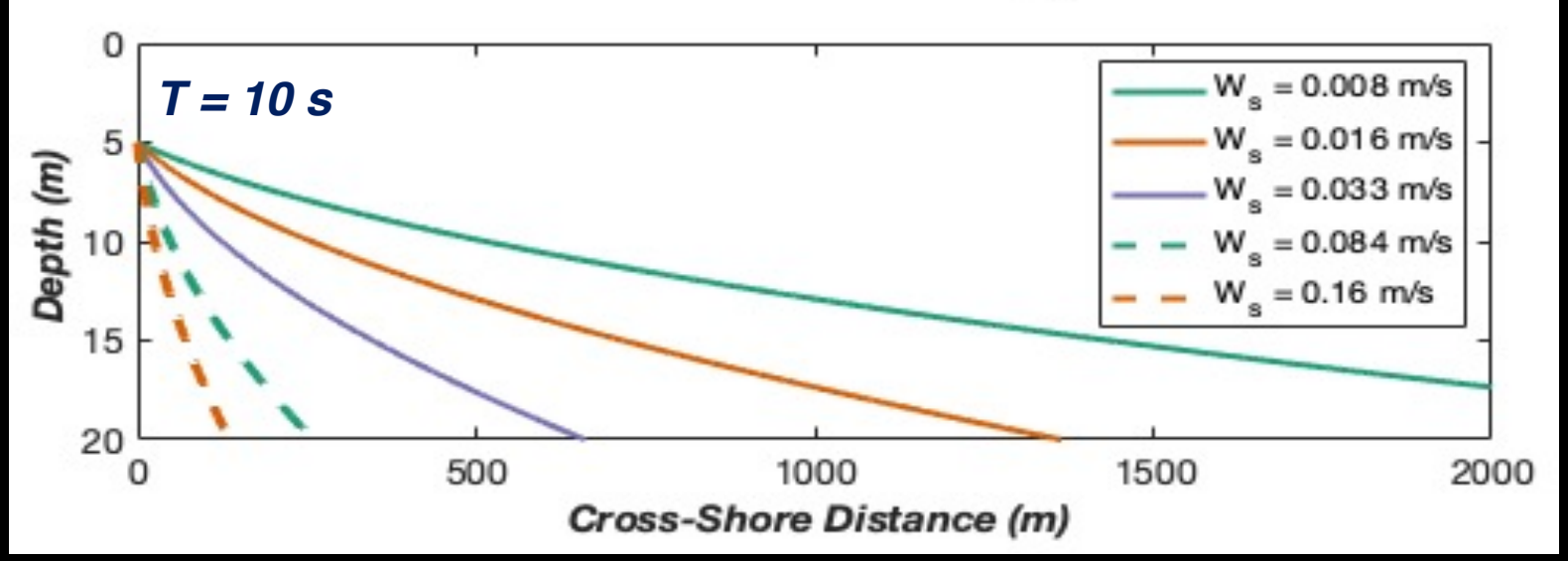
Modified from Ortiz & Ashton 2016

Wave Period



As T ↑, profile steepens

Settling Velocity



As W_s ↑, profile steepens

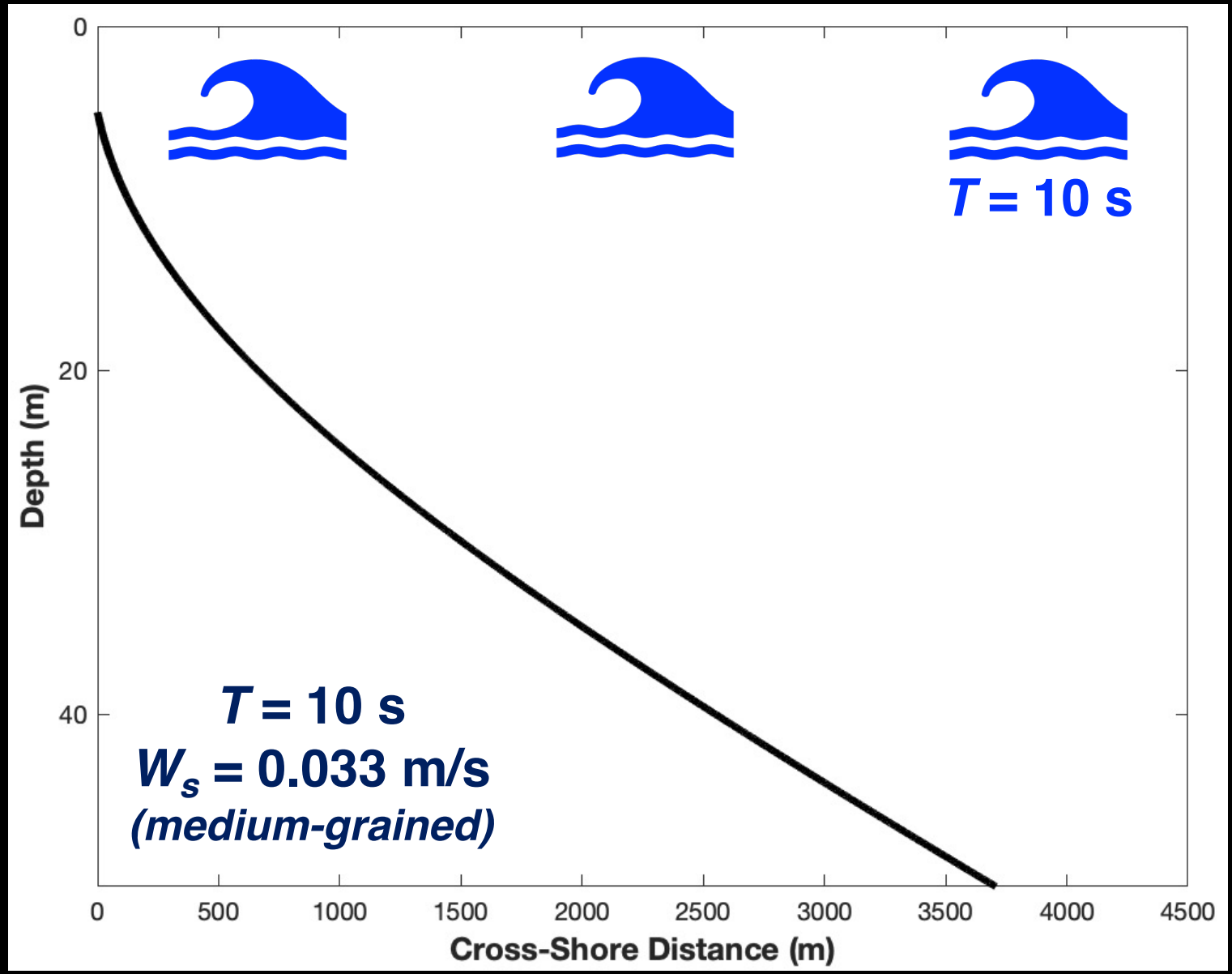
Equilibrium Profiles

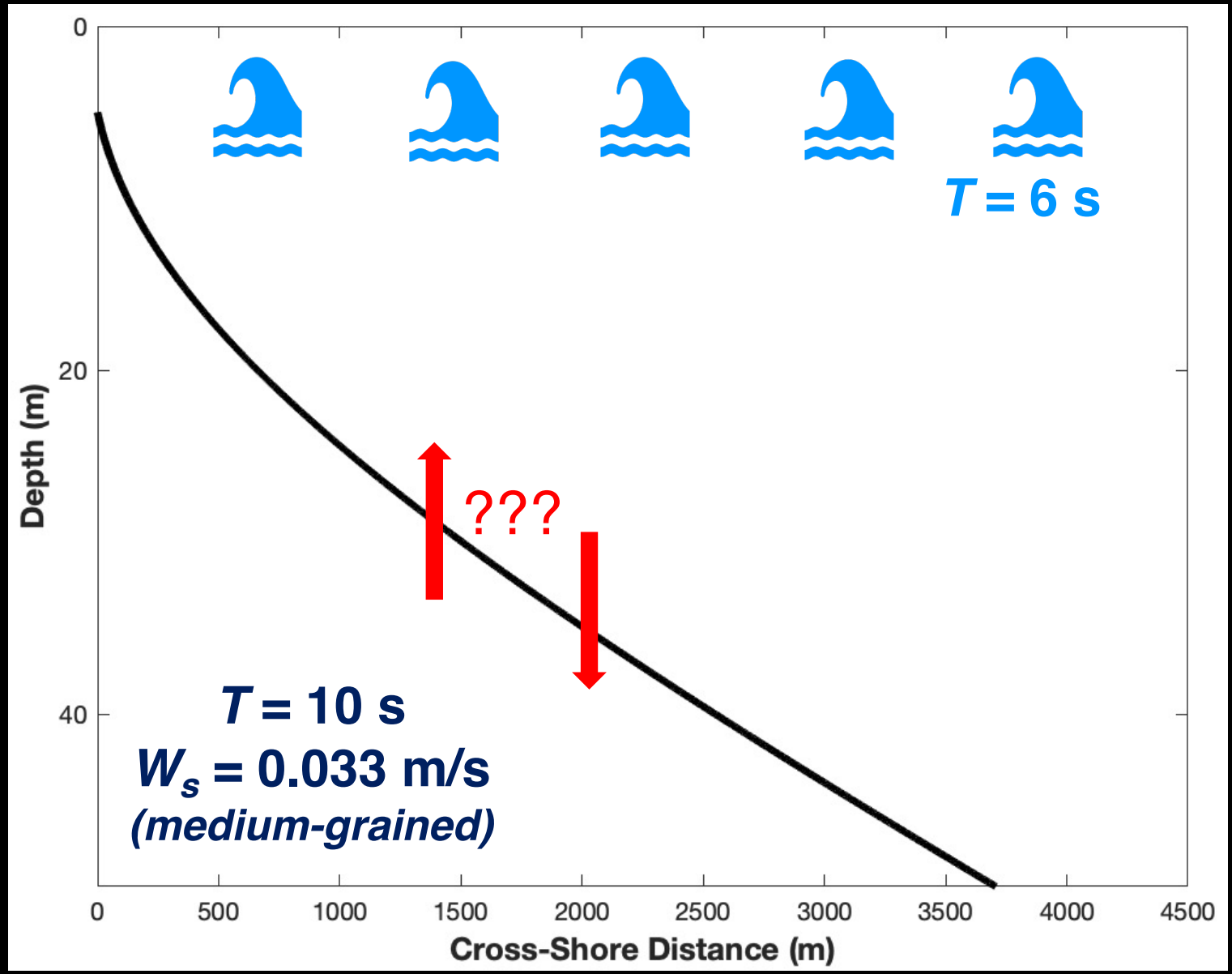
Outline

I. Shoreface Disequilibrium Modeling

II. Disequilibrium Conditions

III. Time Series & Profile Change


0
20
40
Depth (m)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Cross-Shore Distance (m)
T = 10 s
T = 10 s
W_s = 0.033 m/s
(medium-grained)


0
20
40
Depth (m)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Cross-Shore Distance (m)
T = 6 s
???
T = 10 s
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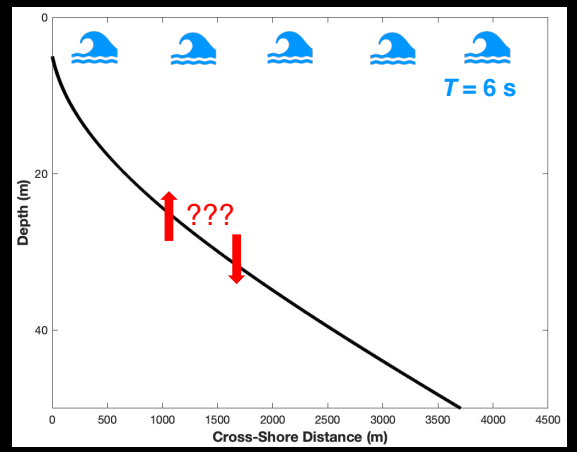
(medium-grained)

(Ortiz & Ashton 2016; Derived from Bagnold 1963, Bowen 1980, Stive & deVriend 1995)

Disequilibrium Sediment Transport

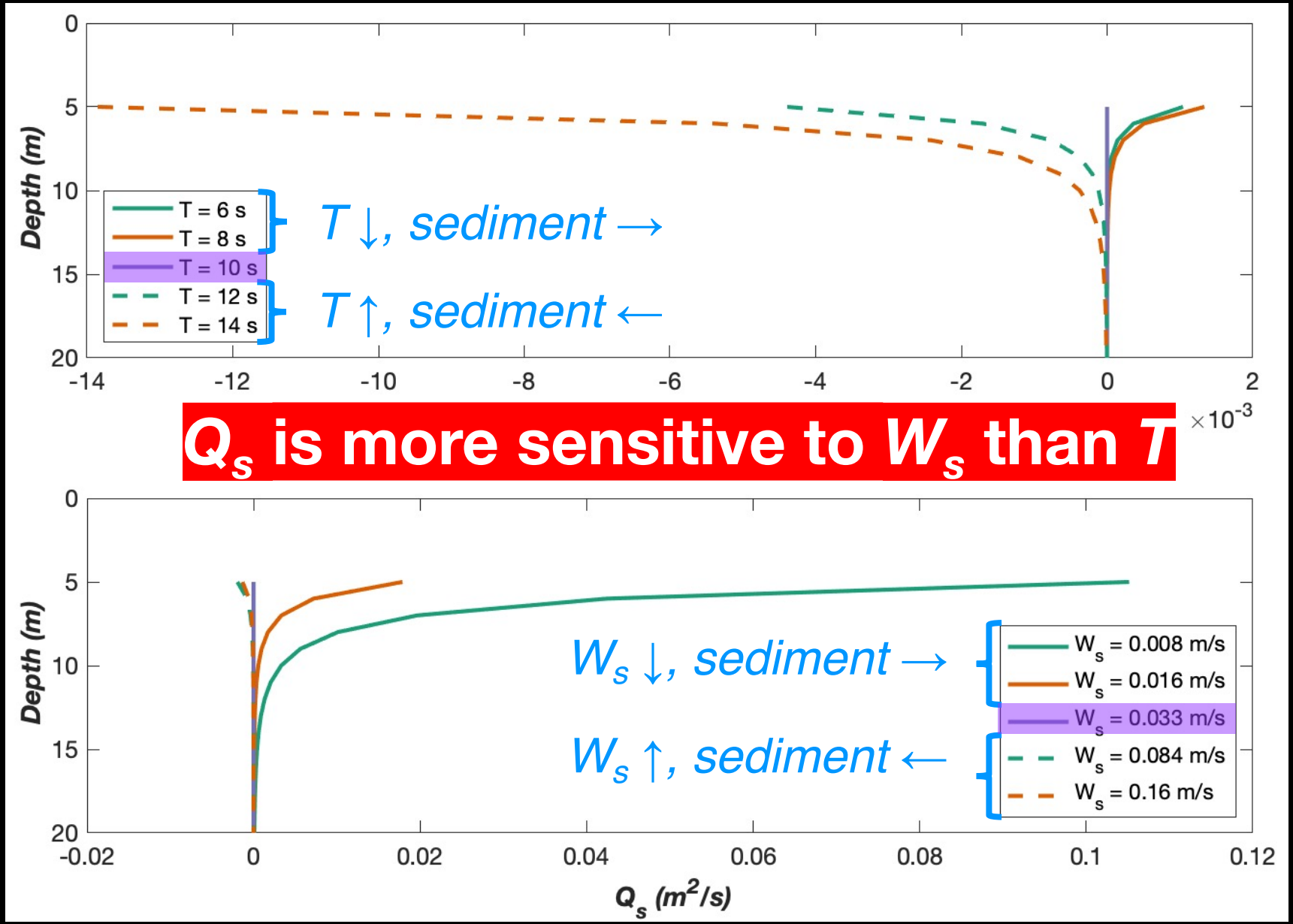


$T_e = 10\ s$
$W_{s_e} = 0.033\ m/s$
(medium-grained)

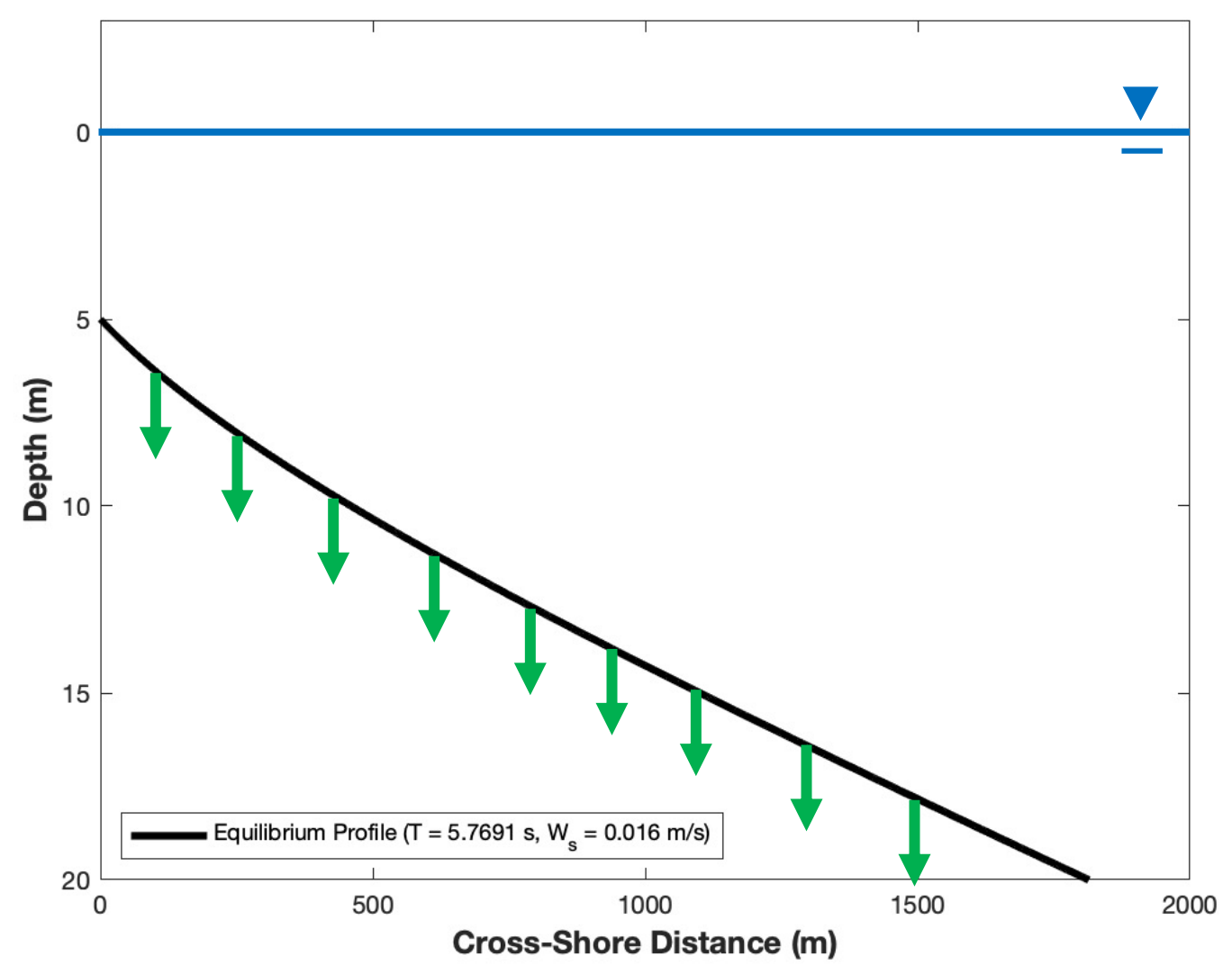
$$\beta_e(z(x)) = \frac{W_{s_e}}{{u_0}^2}\left[5u_1 + 3u_2\right]$$

$$Q_s = K\left(\frac{{u_0}^3}{W_s}\right)\left[-5u_1 - 3u_2 + \frac{\beta_e(x)}{W_s}{u_0}^2\right]$$

$T = 6\ s$
$W_s = 0.016\ m/s$ *(fine-grained)*


Depth (m)
T = 6 s
T = 8 s
T = 10 s
T = 12 s
T = 14 s
T ↓, sediment →
T ↑, sediment ←
×10^-3
Q_s is more sensitive to W_s than T
W_s ↓, sediment →
W_s ↑, sediment ←
W_s = 0.008 m/s
W_s = 0.016 m/s
W_s = 0.033 m/s
W_s = 0.084 m/s
W_s = 0.16 m/s
Q_s (m^2/s)

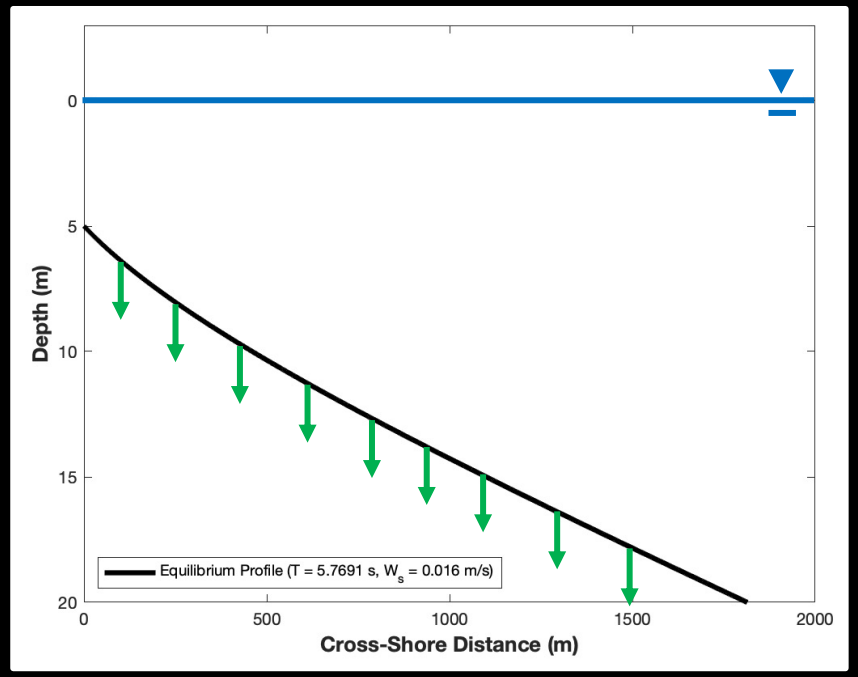
Sea-level Rise (SLR)

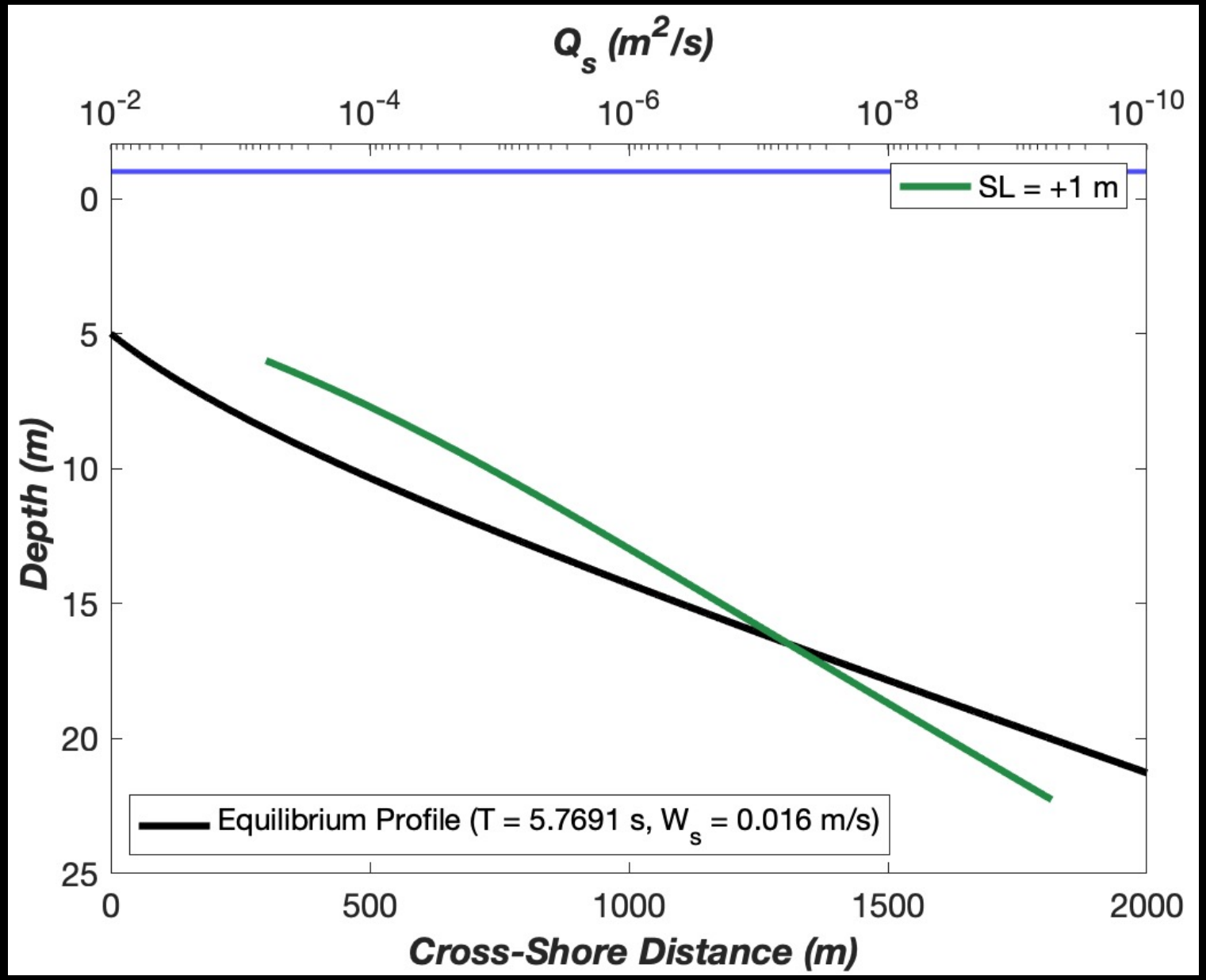


(Ortiz & Ashton 2016; Derived from Bagnold 1963 & Bowen 1980)

SLR Transport & Timescales

$$Q_s(z+1) = K\left(\frac{{u_0}^3}{W_s}\right)\left[-5u_1 - 3u_2 + \frac{\beta_e(x(z_o))}{W_s}{u_0}^2\right]$$



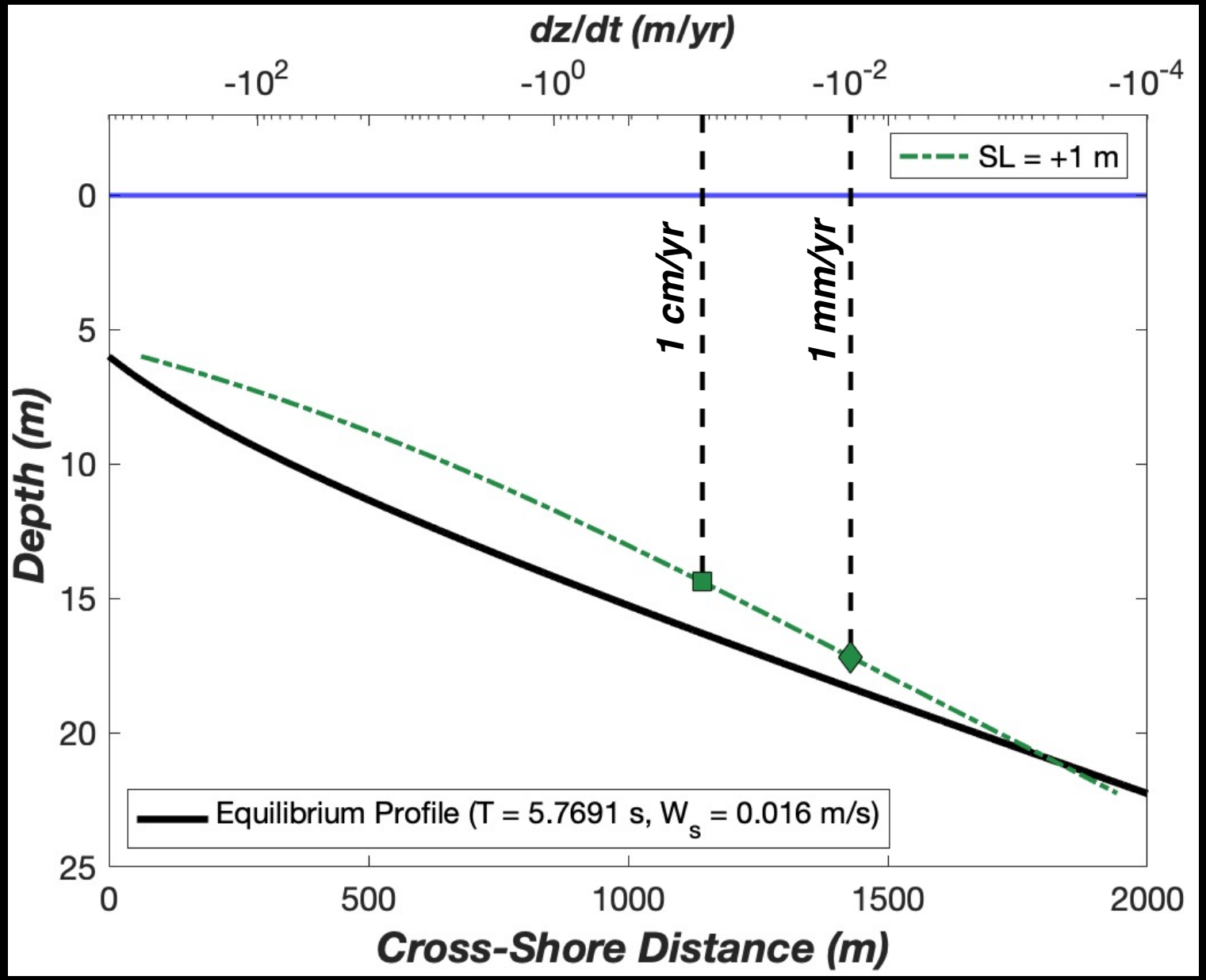


SLR Timescale

$$\frac{\partial z}{\partial t} = \frac{1}{\varepsilon}\frac{\partial Q_s}{\partial x}$$

H_{eff}: 4.1 m

(Fire Island, NY est.; Ortiz & Ashton 2016)



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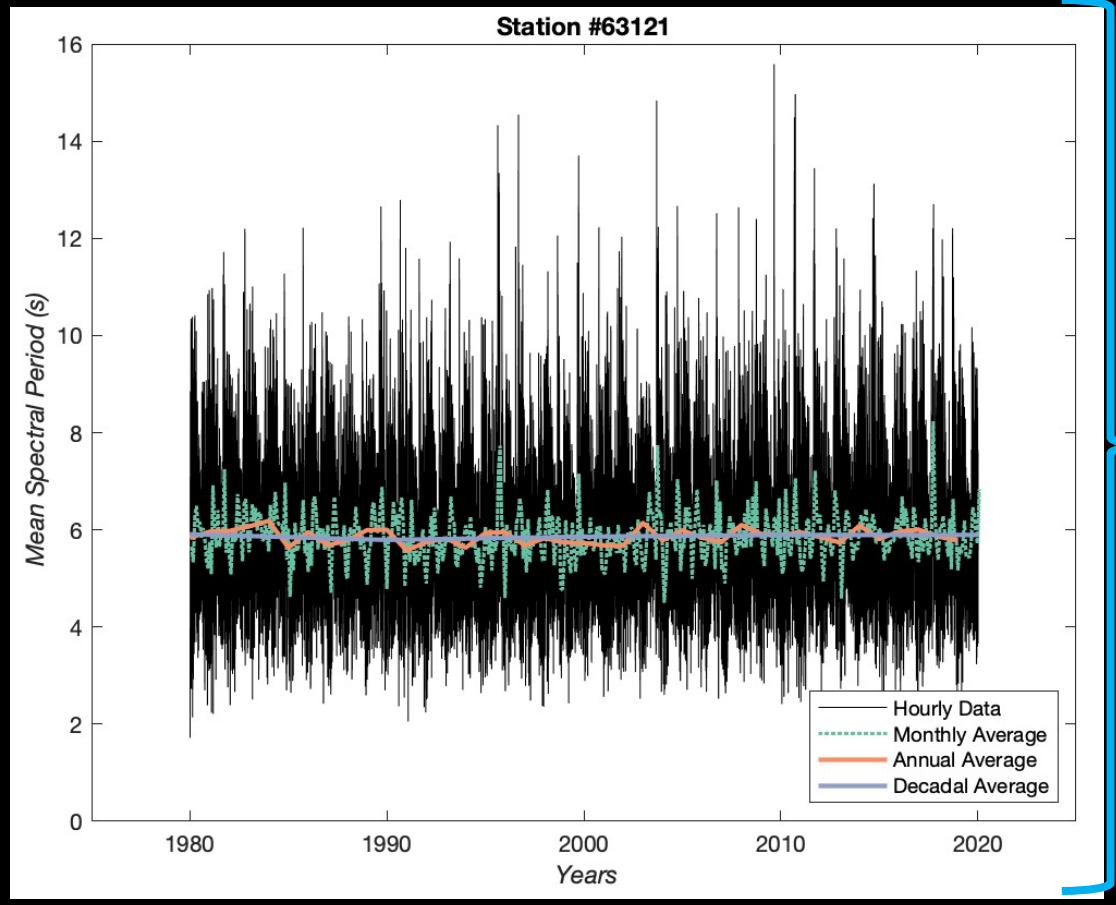


Rockaway Peninsula, NY

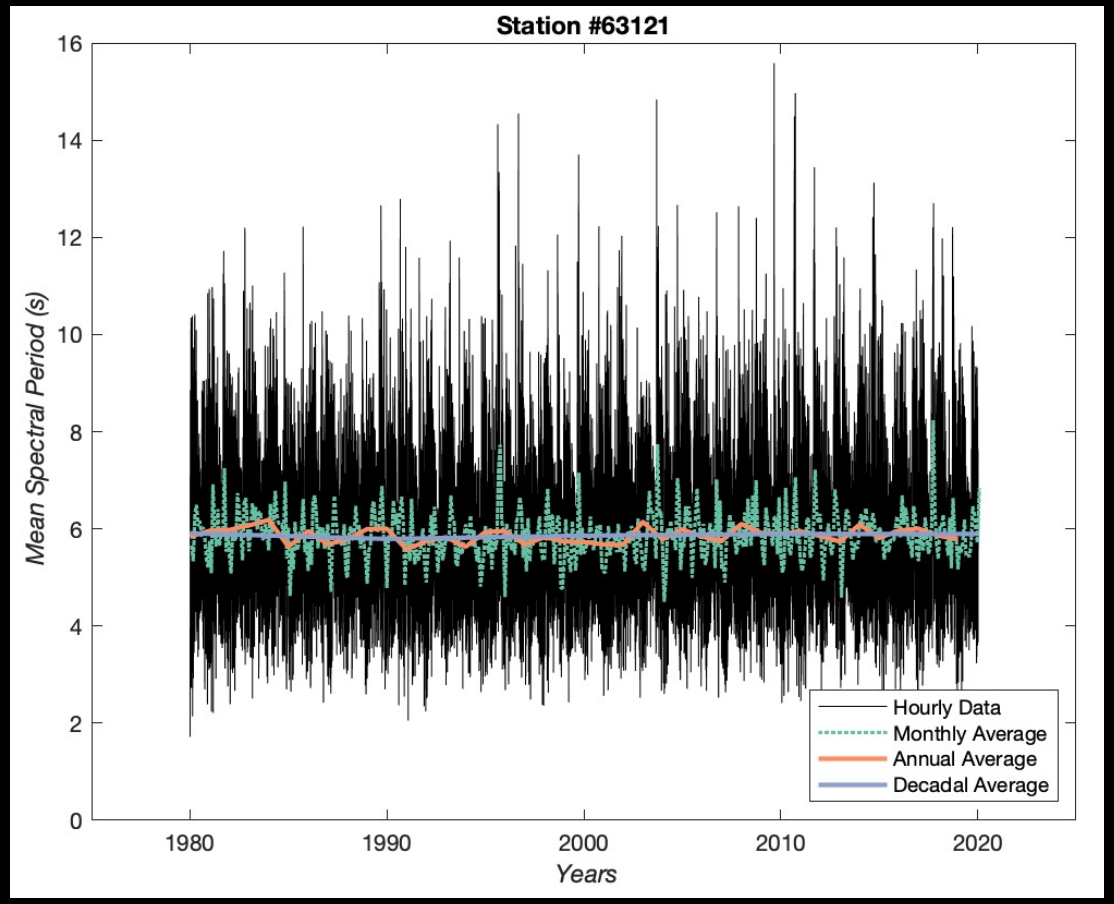
$$Q_s = K\left(\frac{{u_0}^3}{W_s}\right)\left[-5u_1 - 3u_2 + \frac{\beta(x)}{W_s}{u_0}^2\right]$$

Average T_m, H_s

$$\beta_e(z(x)) = \frac{W_{se}}{{u_0}^2}\left[5u_1 + 3u_2\right]$$

WIS Buoy Transport and Profiles

(Ortiz & Ashton 2016; Derived from Bagnold 1963, Bowen 1980, Stive & deVriend 1995)



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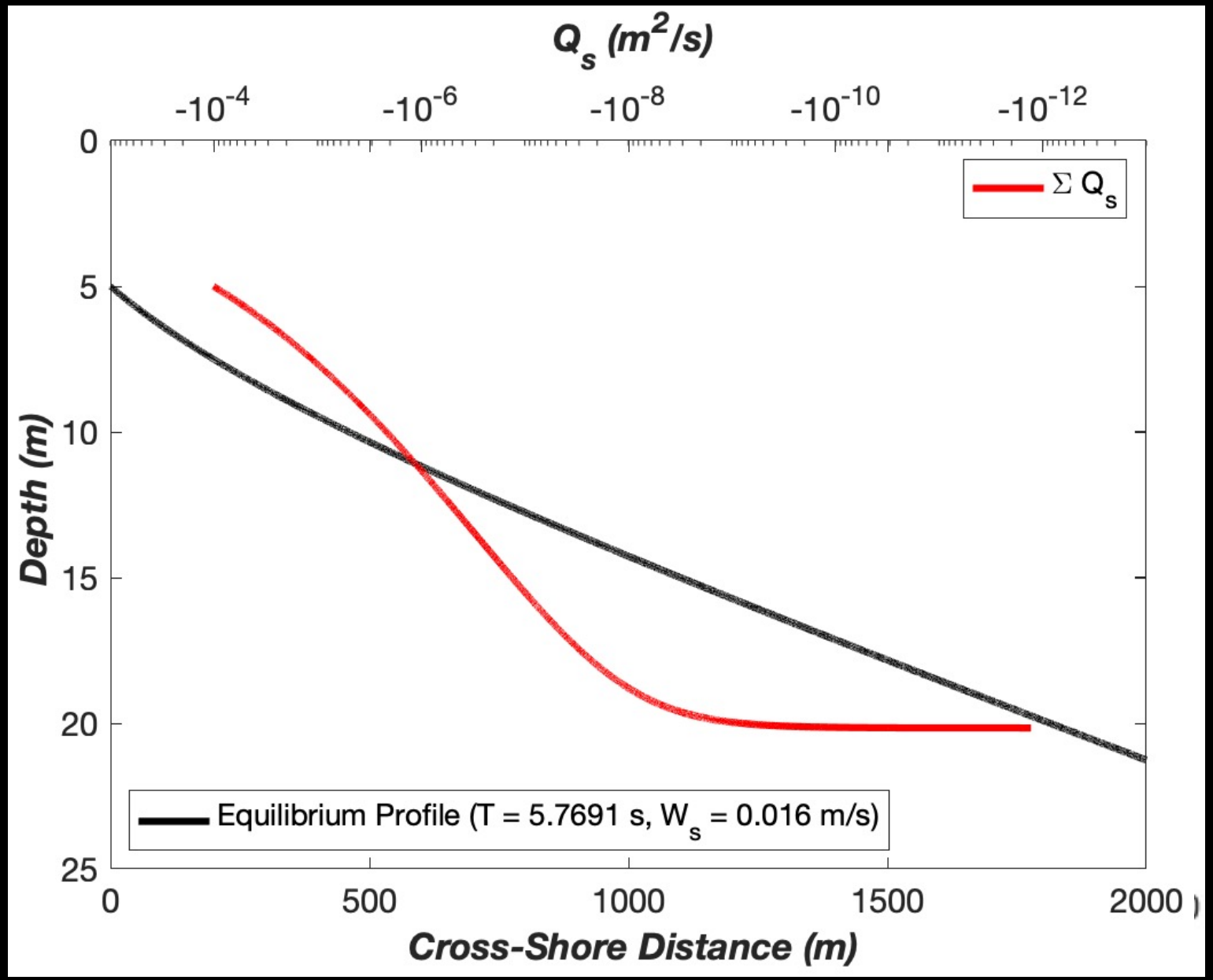
$$Q_s = K\left(\frac{{u_0}^3}{W_s}\right)\left[-5u_1 - 3u_2 + \frac{\beta(x)}{W_s}{u_0}^2\right]$$

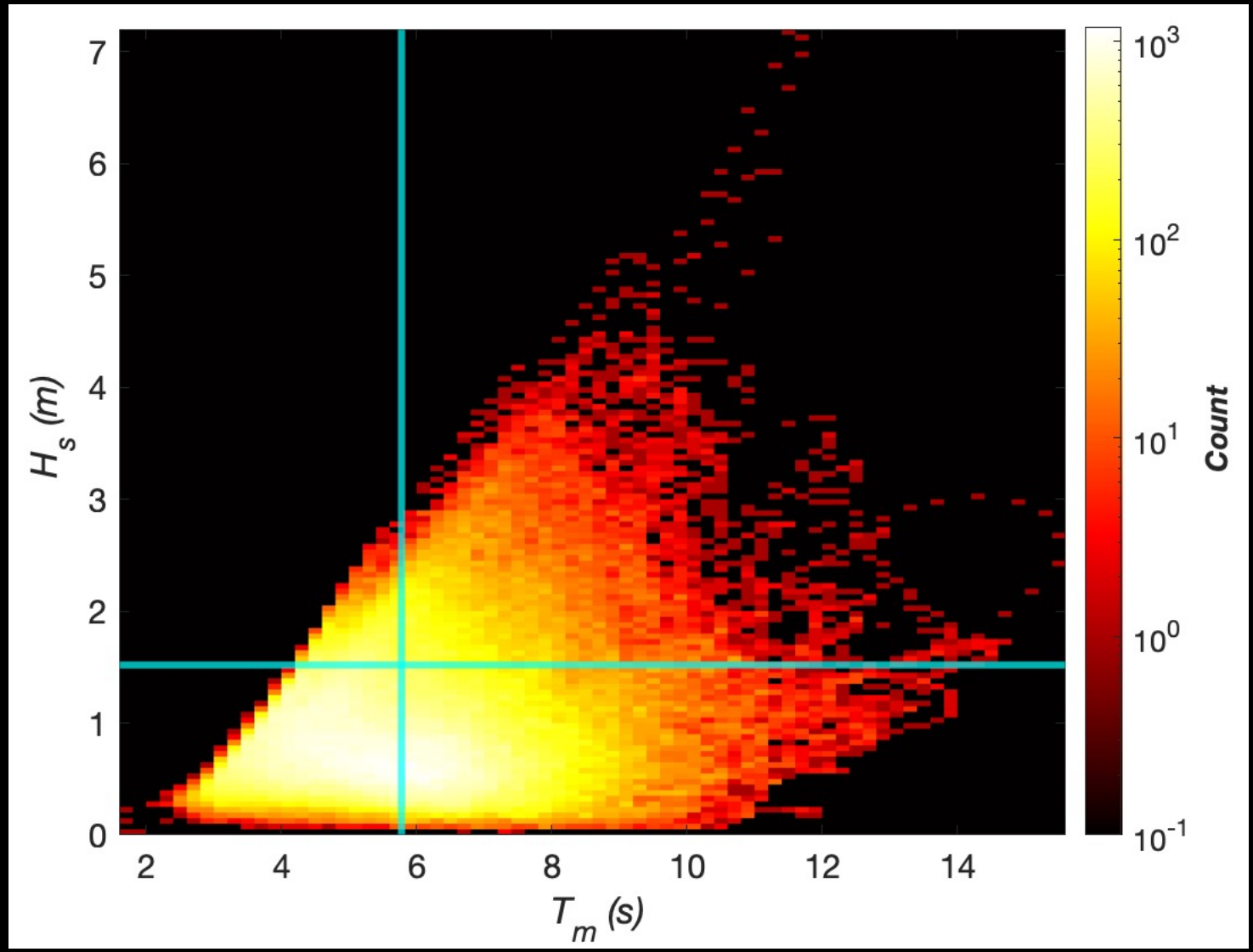
$$Q_{s_i}(T_{m_i}, H_{s_i}) \text{ @ time } i$$

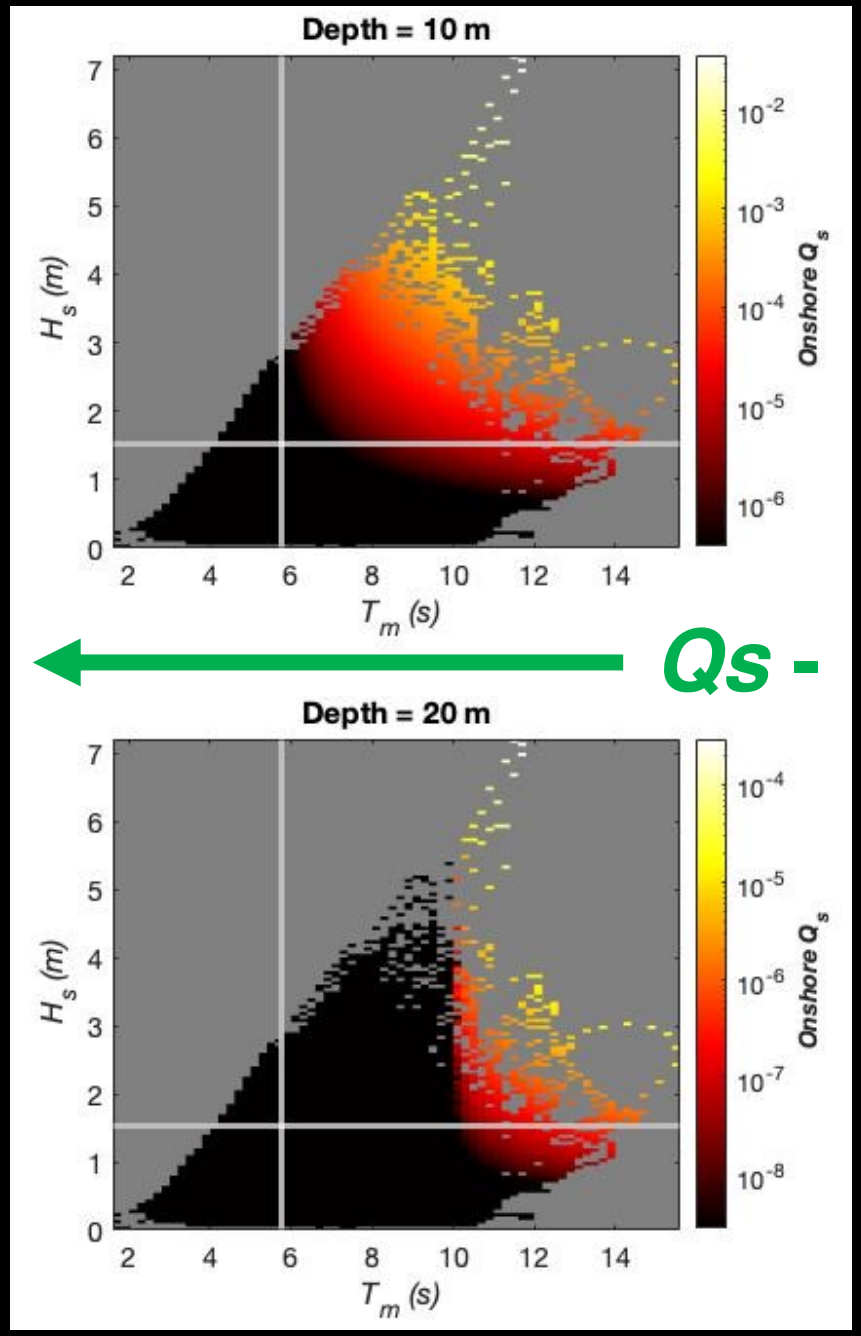
$$Q_{s_e} = \frac{\sum_{i=1}^{n} Q_s * \Delta t}{D}$$

WIS Buoy Transport and Profiles

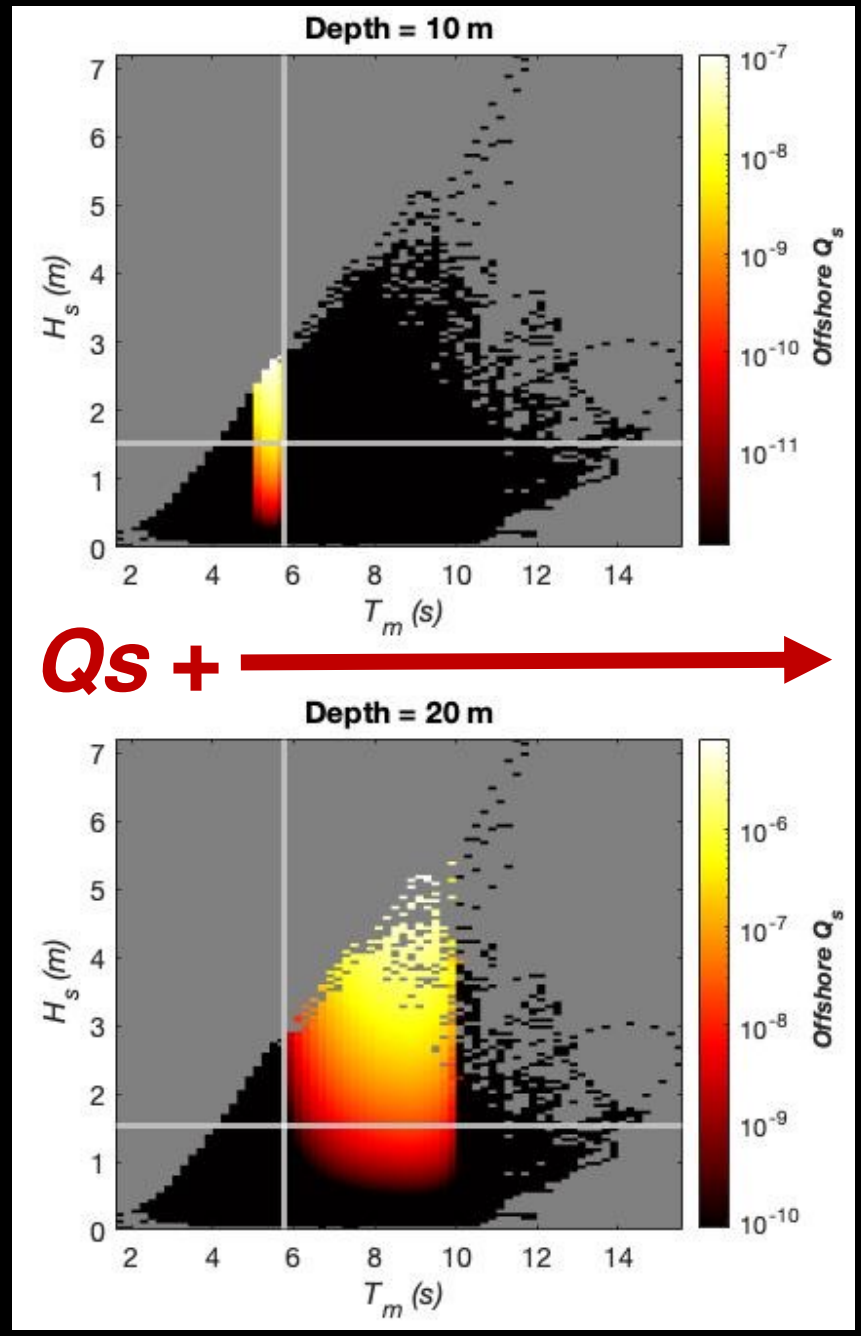


$\sum Q_s$ Transport over Avg. Profile

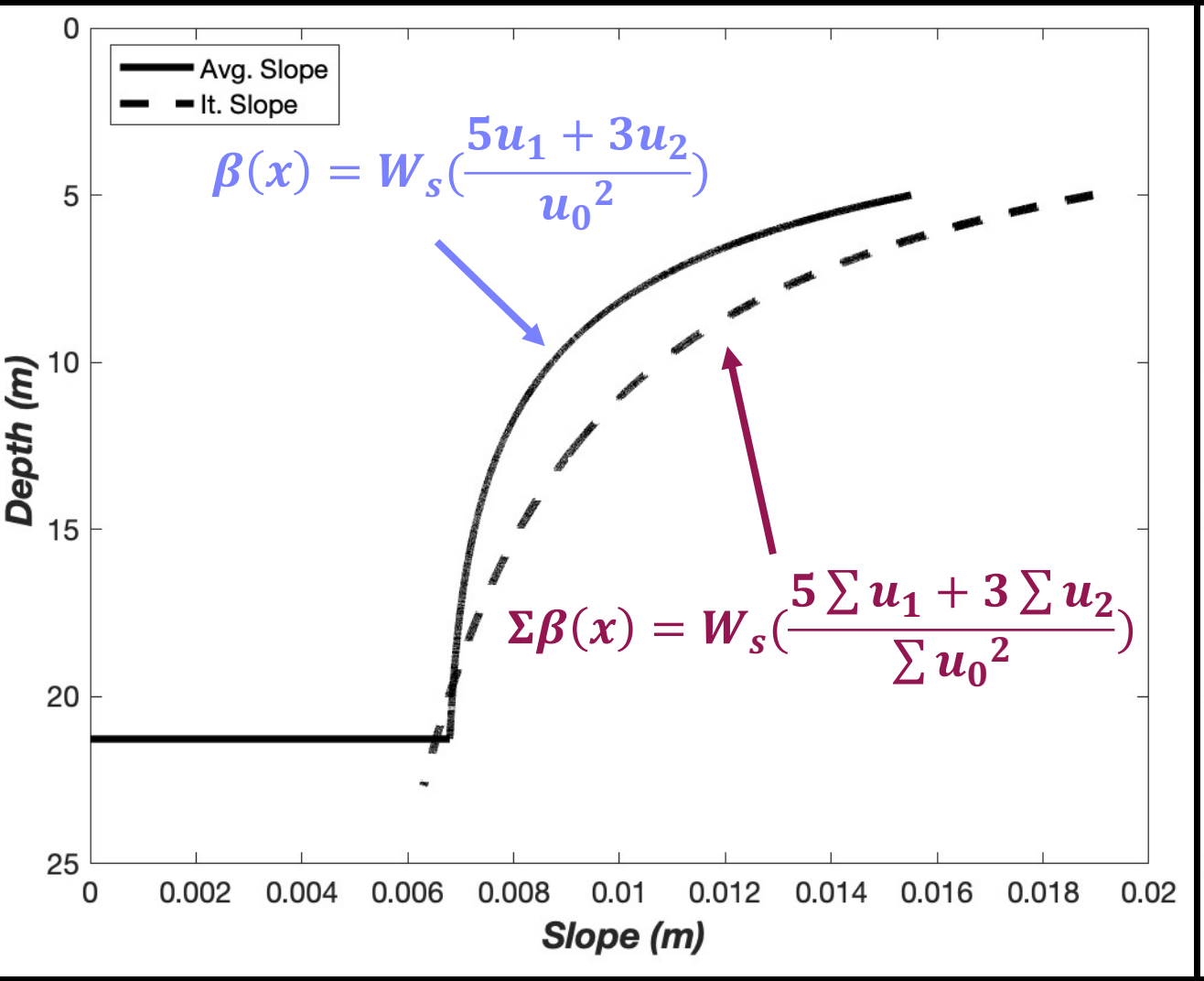

7
6
5
4
3
2
1
0
H_s (m)
2
4
6
8
10
12
14
T_m (s)
10^3
10^2
10^1
10^0
10^{-1}
Count

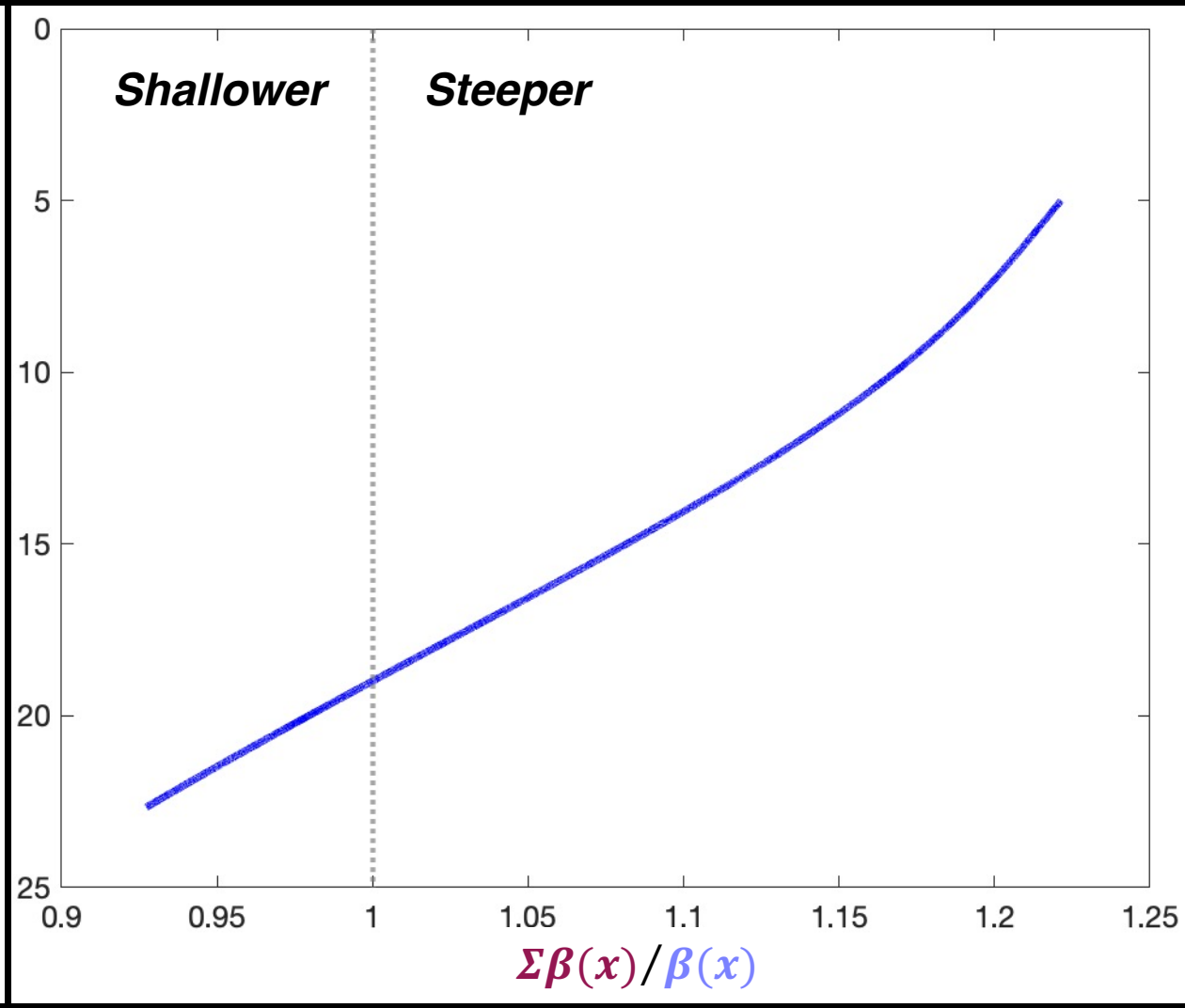

Depth = 10 m
H_s (m)
T_m (s)
Onshore Q_s
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Depth = 20 m
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}

Qs -


Depth = 10 m
H_s (m)
T_m (s)
Offshore Q_s
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Depth = 20 m
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}

Qs +


Avg. Slope
It. Slope
$\beta(x) = W_s(\frac{5u_1 + 3u_2}{u_0{}^2})$
$\Sigma\beta(x) = W_s(\frac{5\sum u_1 + 3\sum u_2}{\sum u_0{}^2})$
Depth (m)
Slope (m)
0
5
10
15
20
25
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02


Shallower
Steeper
$\Sigma\beta(x)/\beta(x)$
0
5
10
15
20
25
0.9
0.95
1
1.05
1.1
1.15
1.2
1.25

Summary

- Shoreface sediment transport is sensitive to variations in wave climate and geology
- Energetics approach can model shoreface change in response to SLR
- Different averaging techniques yield different profiles for WIS time series data

Massachusetts Institute of Technology

WOODS HOLE OCEANOGRAPHIC INSTITUTION

USGS science for a changing world

USCRP US COASTAL RESEARCH PROGRAM

Thank you!

mgillen@mit.edu

This research was conducted on ancestral Wampanoag and Massachusett lands. AGU is being held on ancestral Chitimacha land. The indigenous peoples from these tribes have and continue to suffer countless losses, exploitation, forced removal from imperialist and native erasure efforts by white settlers. These communities have endured and are continuing to experience violence and oppression. Land where work has been conducted and information is being disseminated has been, is, and will ALWAYS be ancestral indigenous land.

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https://roadtrippers.com/magazine/virginia-barrier-islands/

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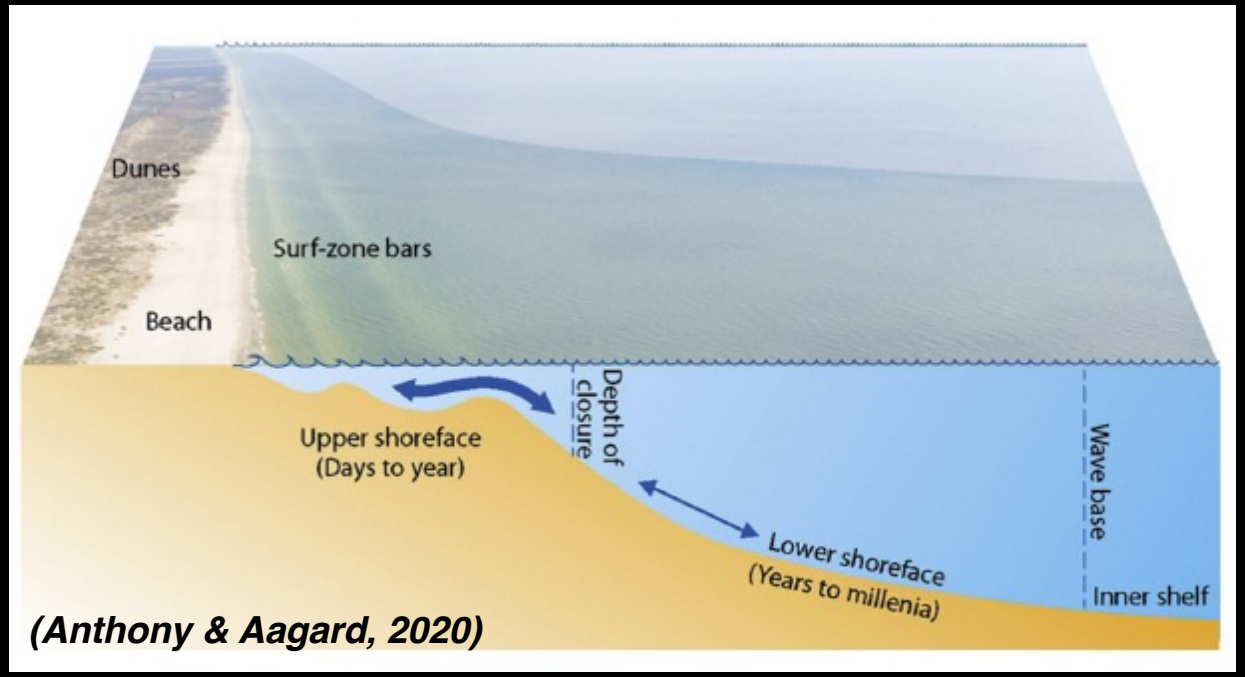
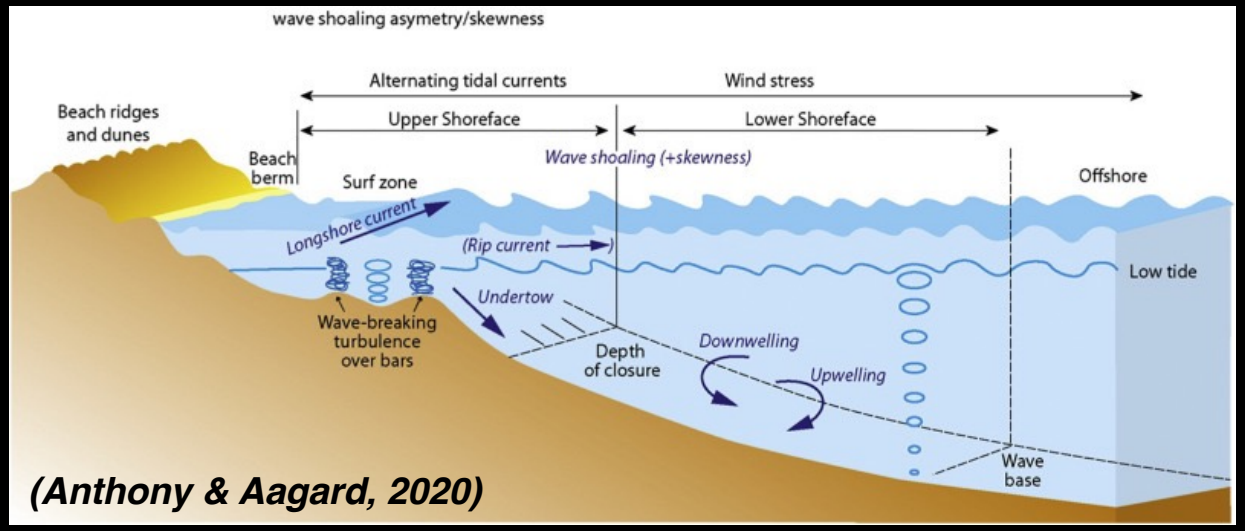


(Anthony & Aagard, 2020)



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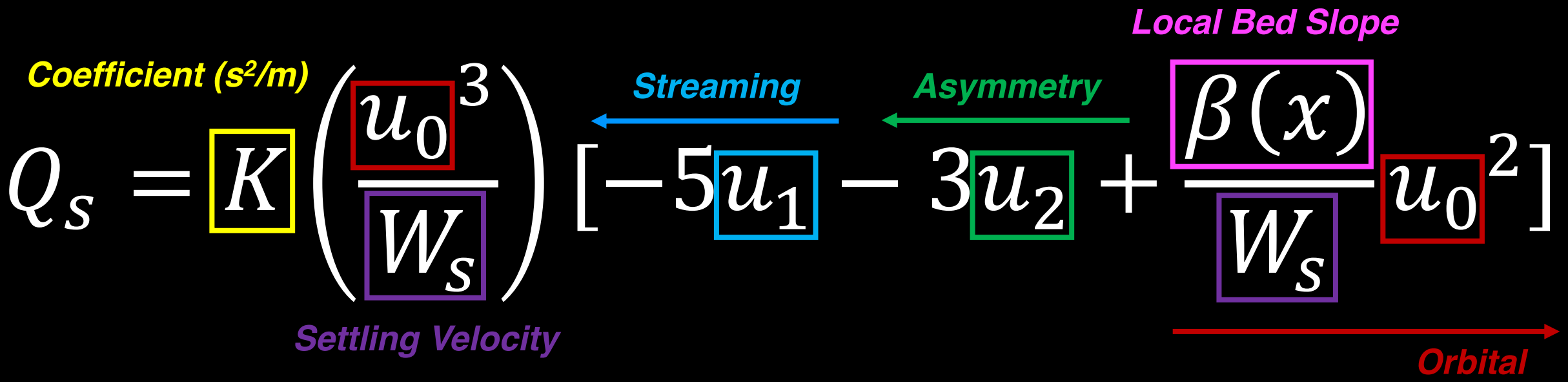

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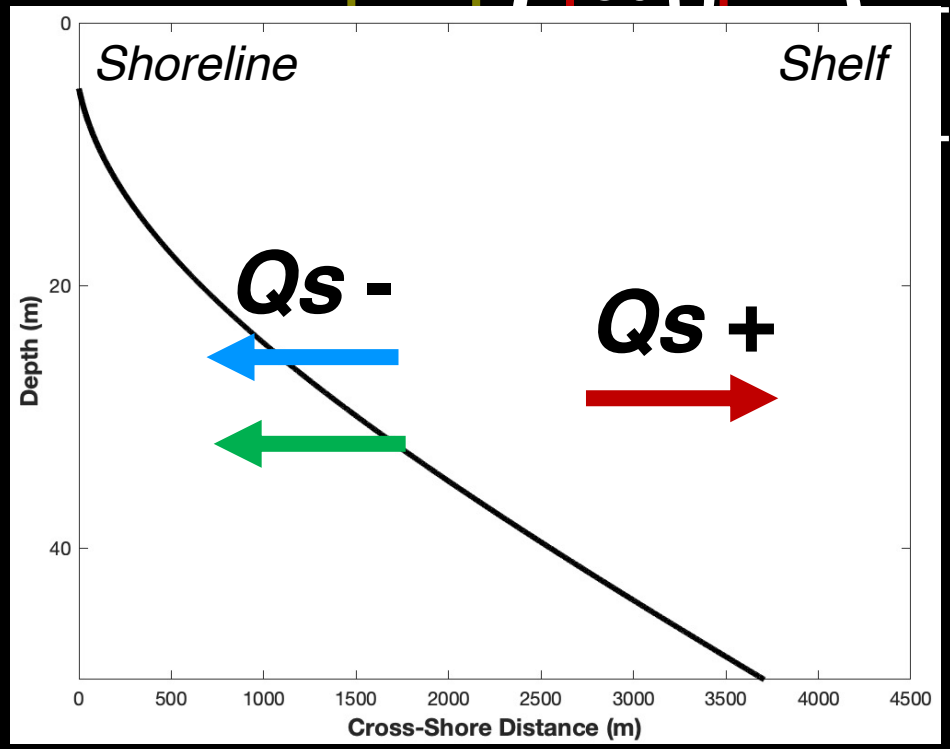

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Energetics Transport Equation

Coefficient (s^2/m)

Settling Velocity

Streaming

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Equilibrium Slope

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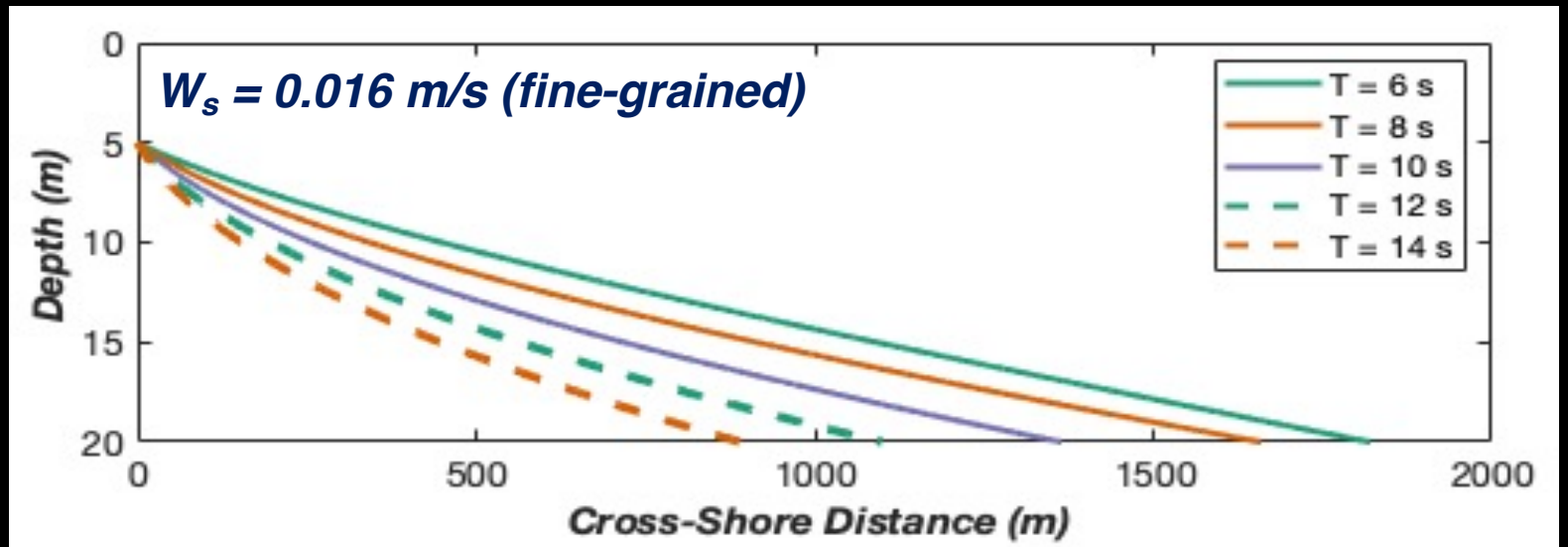
Modified from Ortiz & Ashton 2016

Wave Period



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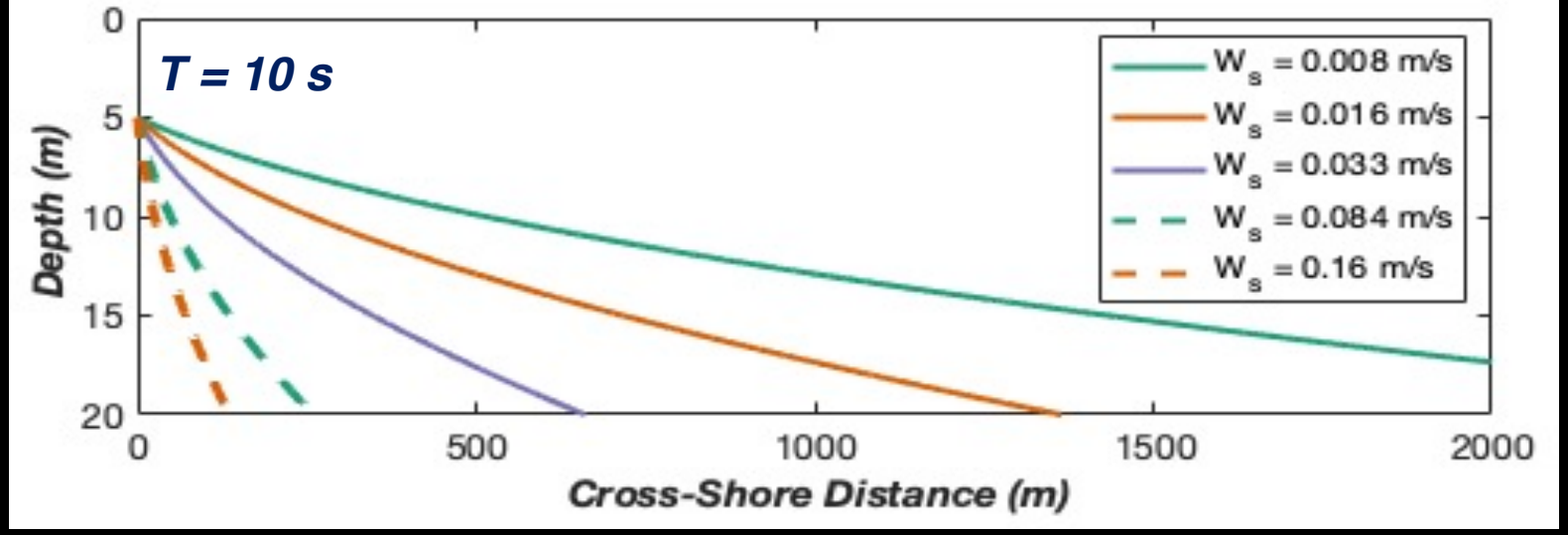
Settling Velocity



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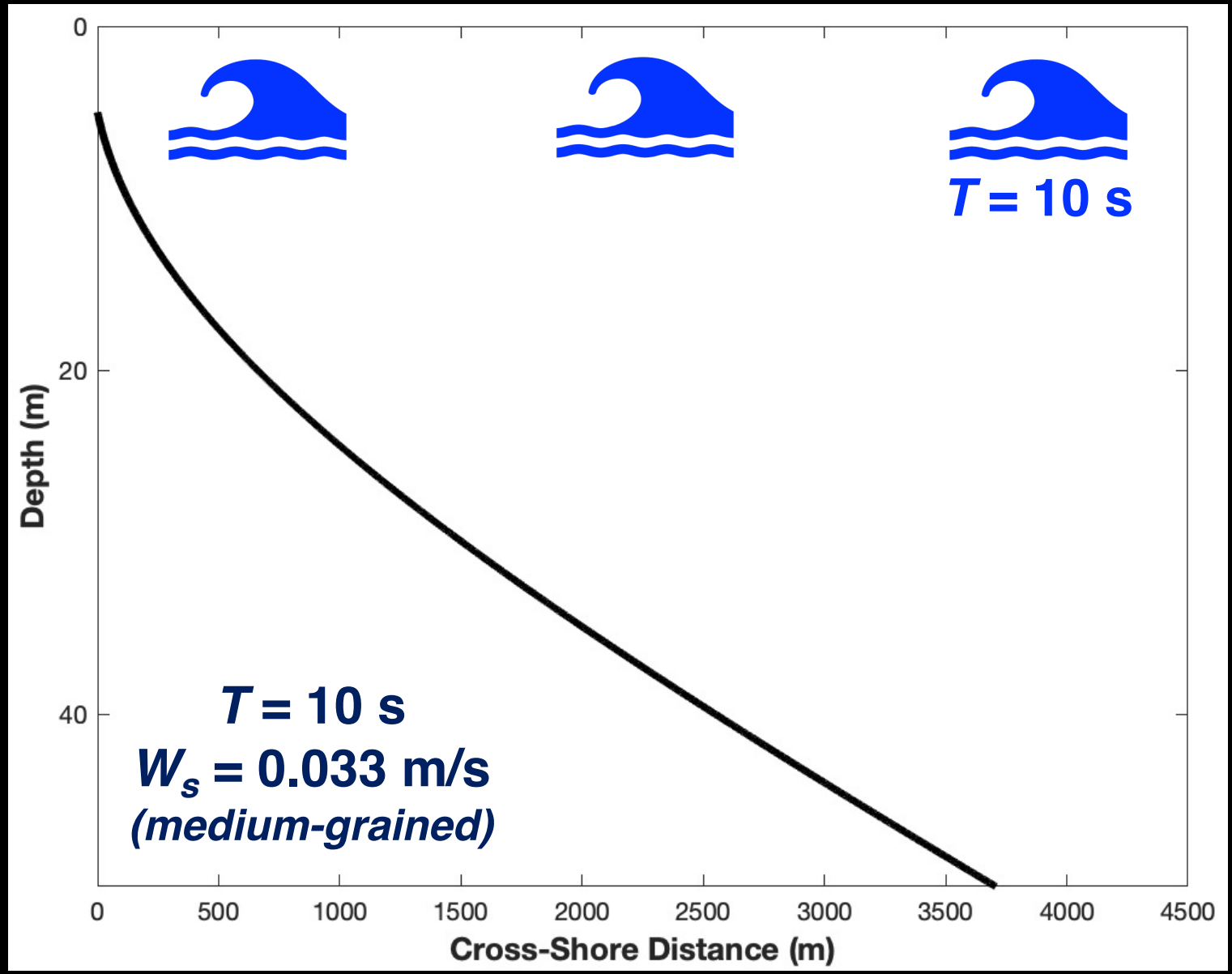
0
20
40
Depth (m)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
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T = 10 s
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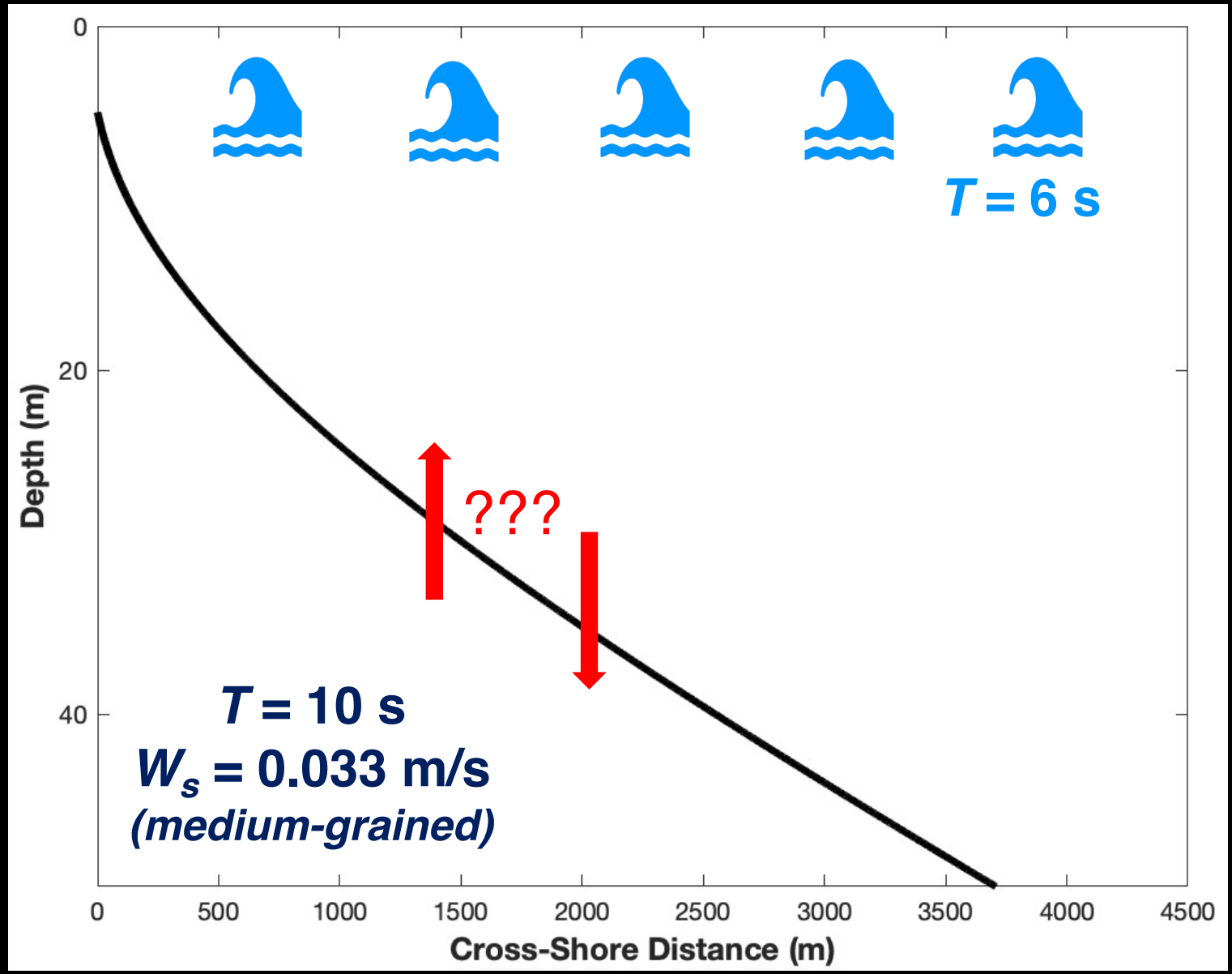
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3500
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4500
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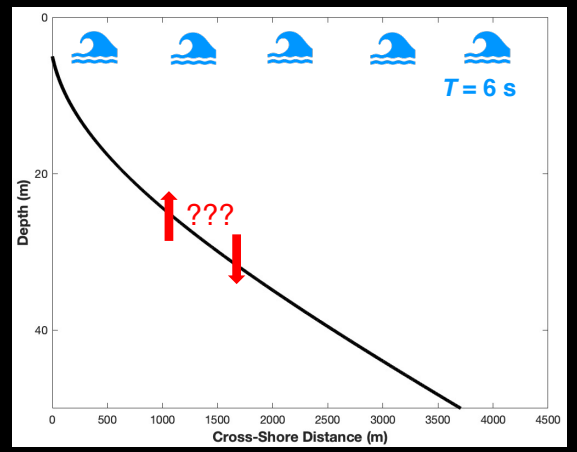

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$T = 6\ s$
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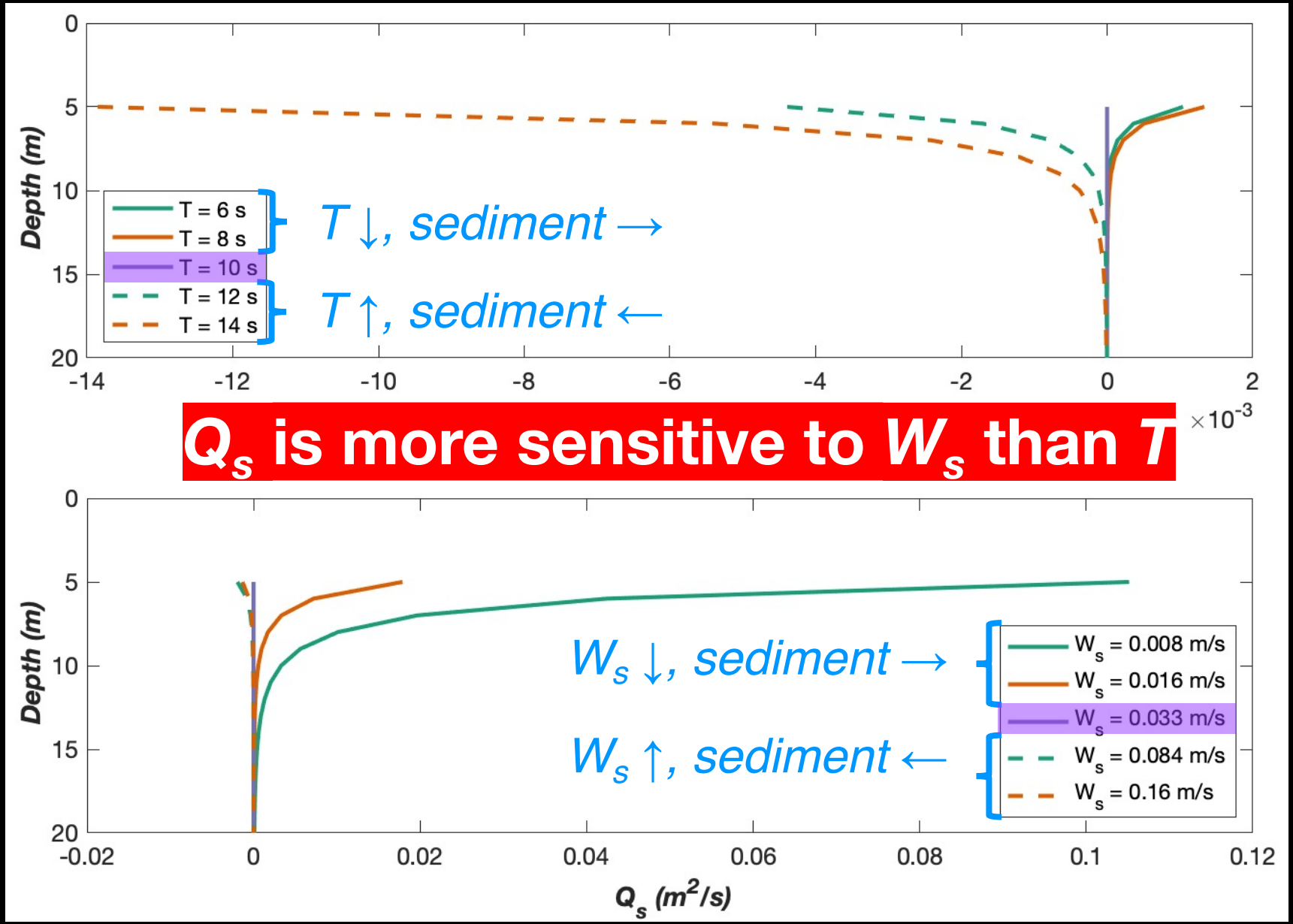
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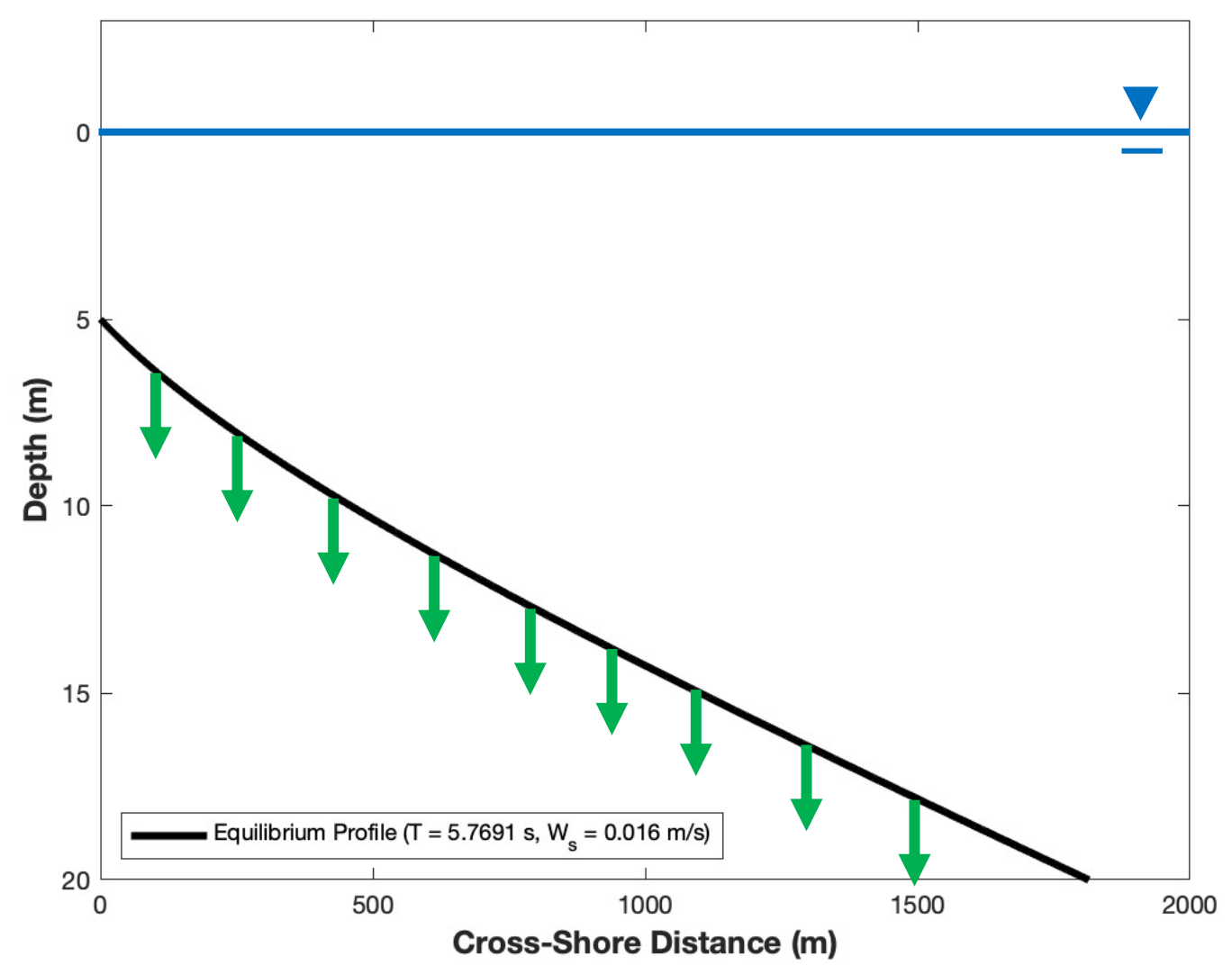
Q_s (m^2/s)

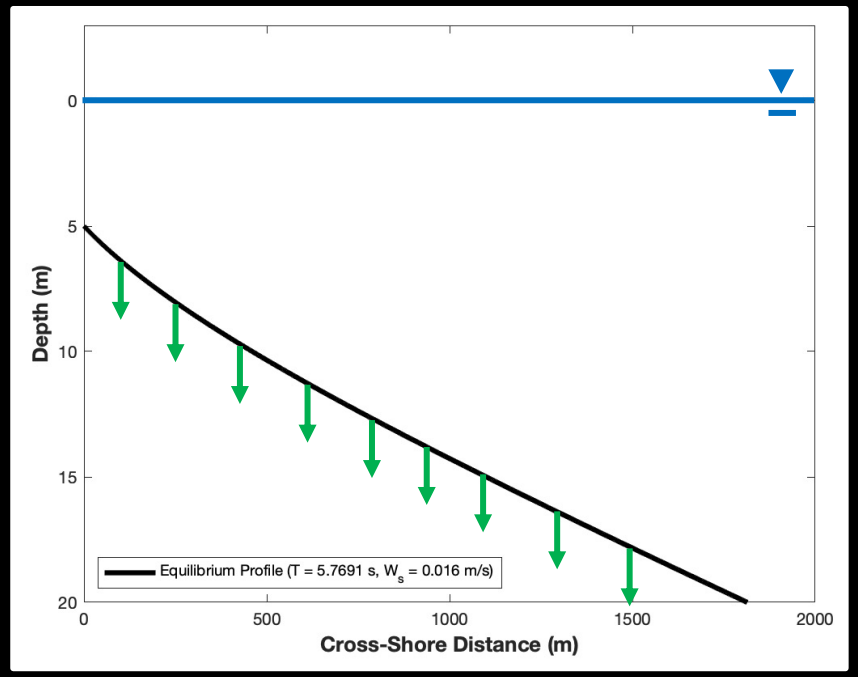
Sea-level Rise (SLR)

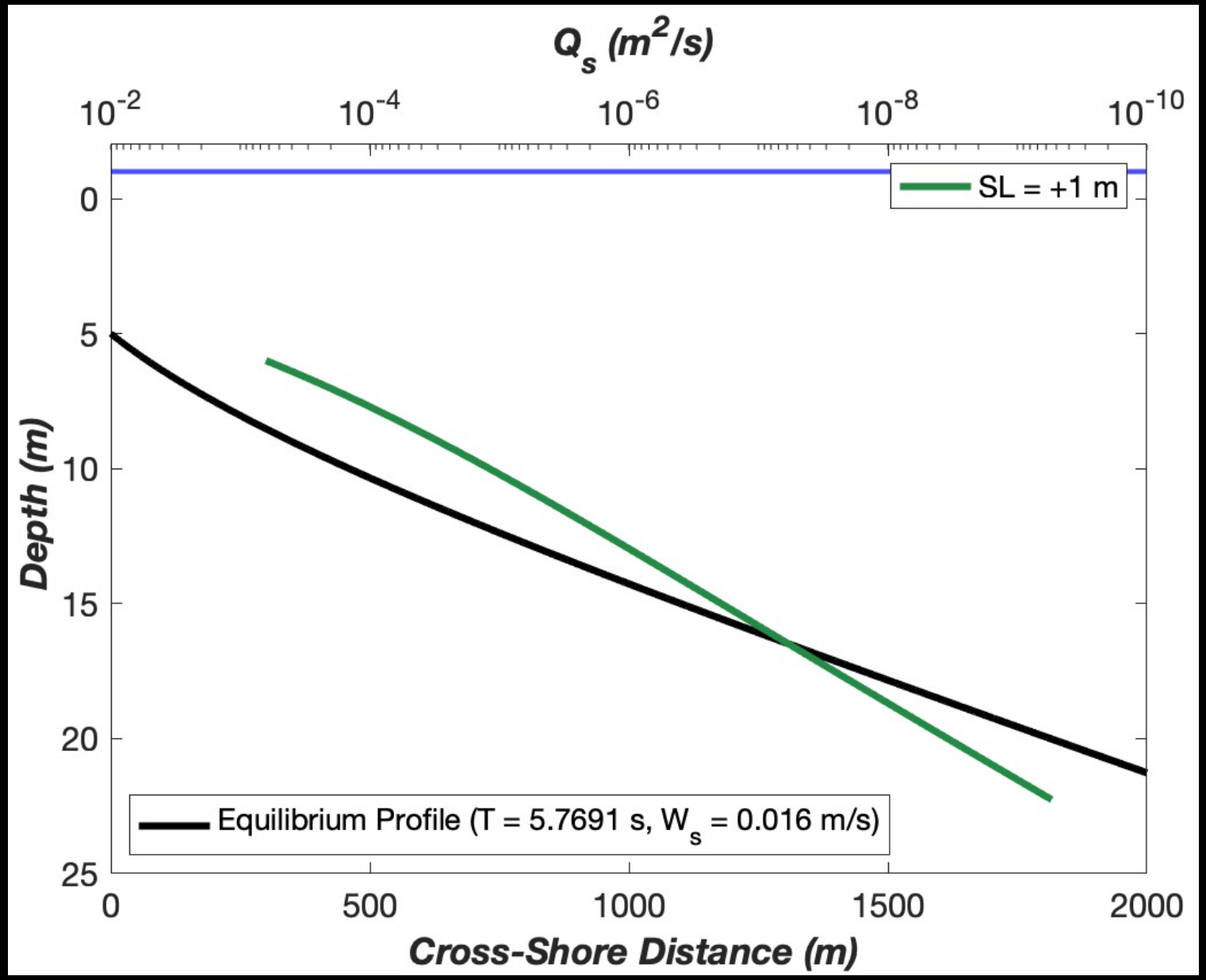


(Ortiz & Ashton 2016; Derived from Bagnold 1963 & Bowen 1980)

SLR Transport & Timescales

$$Q_s(z+1) = K\left(\frac{{u_0}^3}{W_s}\right)\left[-5u_1 - 3u_2 + \frac{\beta_e(x(z_o))}{W_s}{u_0}^2\right]$$



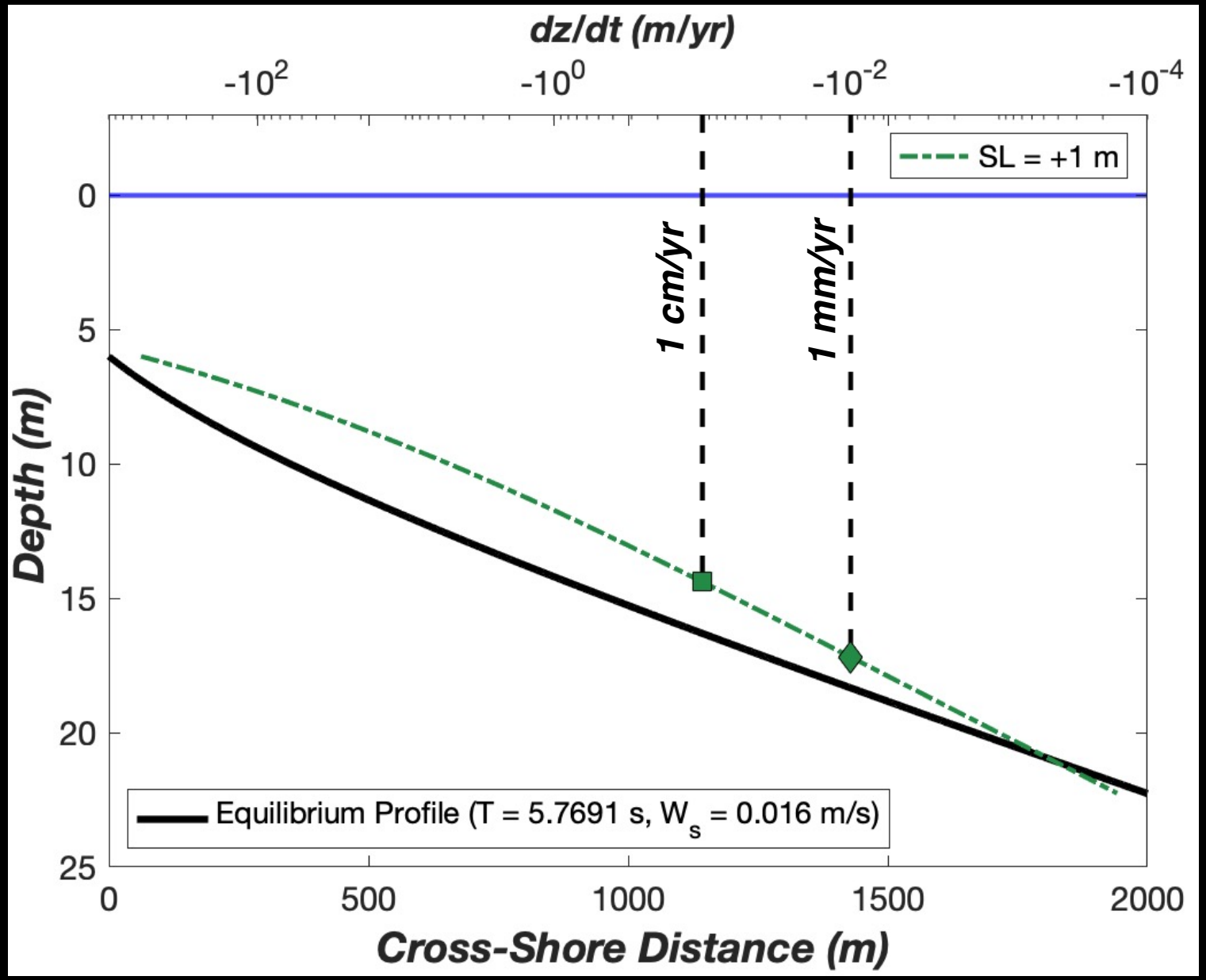


SLR Timescale

$$\frac{\partial z}{\partial t} = \frac{1}{\varepsilon}\frac{\partial Q_s}{\partial x}$$

H_{eff}: 4.1 m

(Fire Island, NY est.; Ortiz & Ashton 2016)



SLR Timescale

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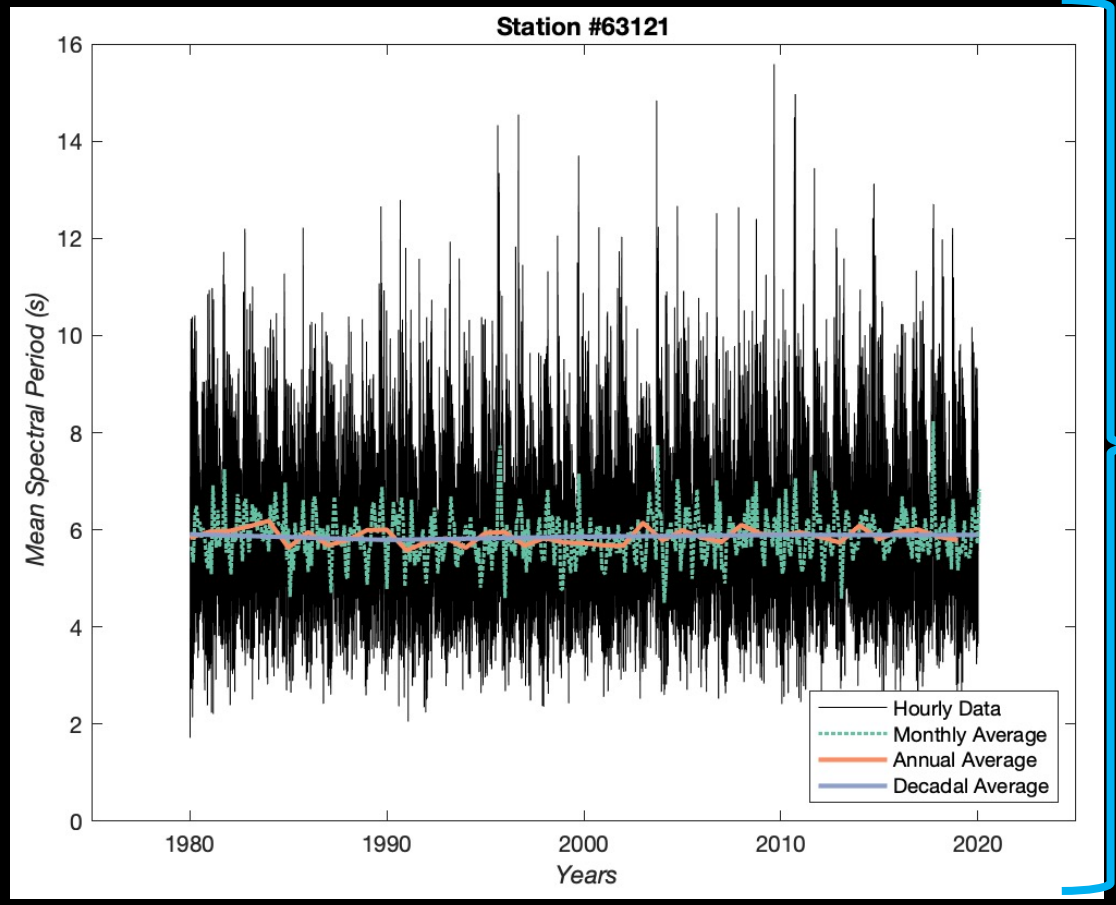


Rockaway Peninsula, NY

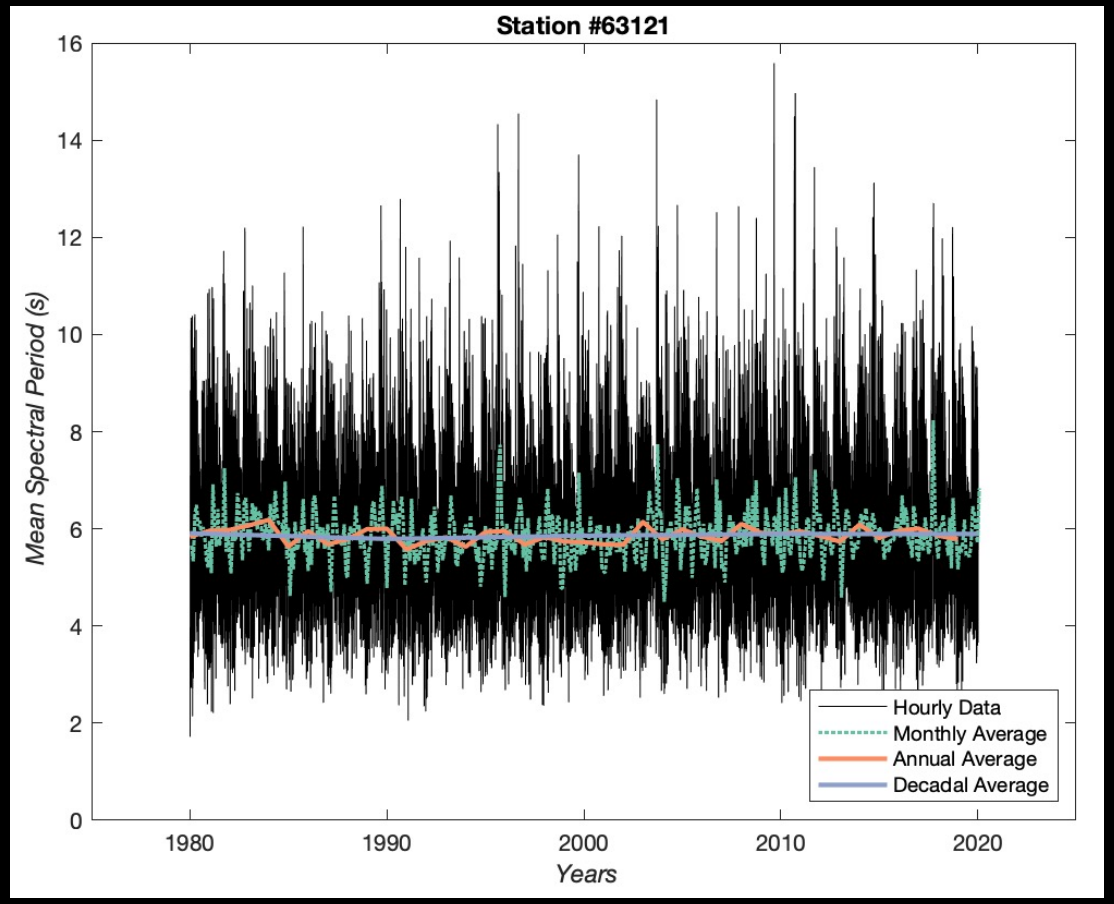
$$Q_s = K\left(\frac{{u_0}^3}{W_s}\right)\left[-5u_1 - 3u_2 + \frac{\beta(x)}{W_s}{u_0}^2\right]$$

Average T_m, H_s

$$\beta_e(z(x)) = \frac{W_{se}}{{u_0}^2}\left[5u_1 + 3u_2\right]$$

WIS Buoy Transport and Profiles

(Ortiz & Ashton 2016; Derived from Bagnold 1963, Bowen 1980, Stive & deVriend 1995)



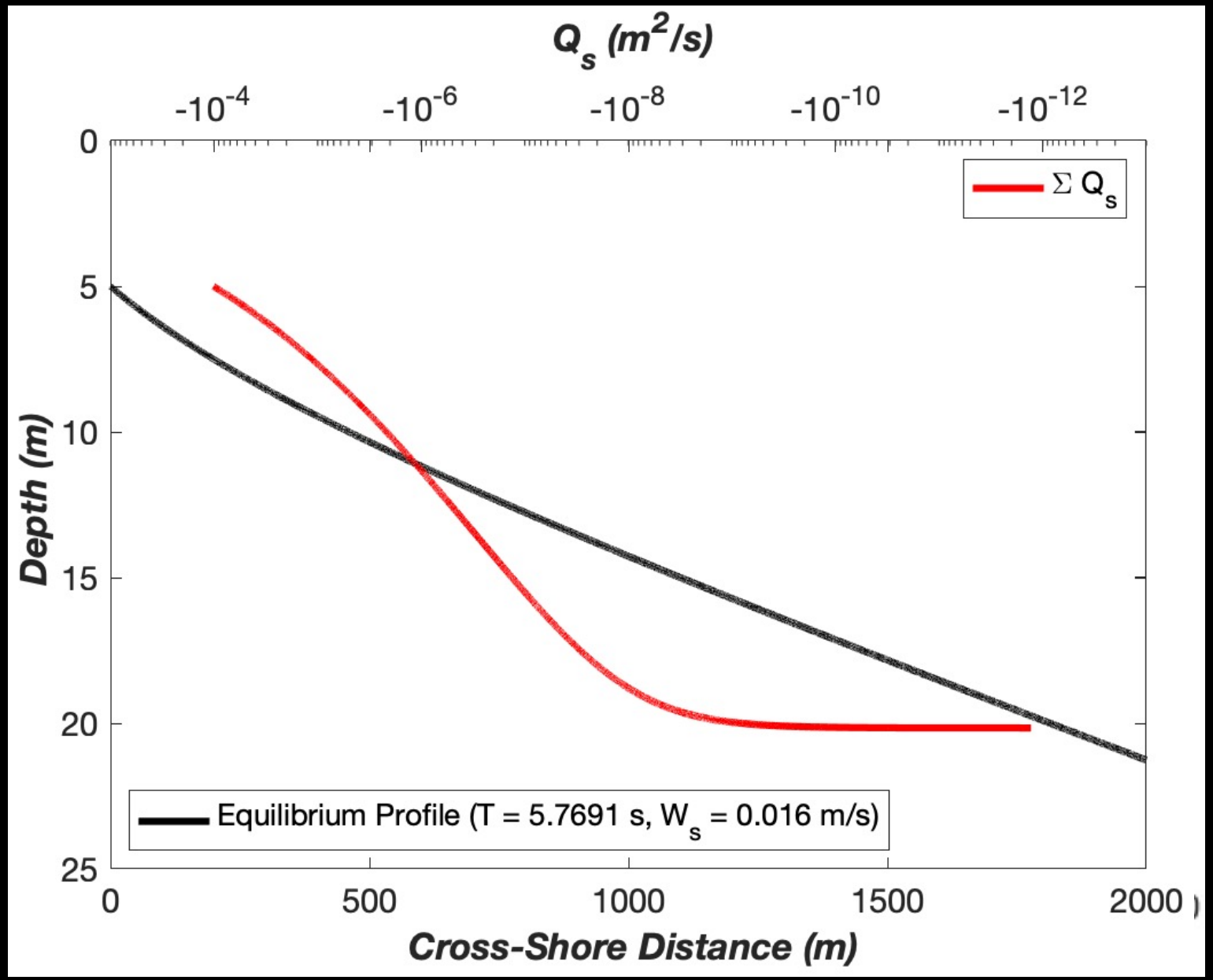
Rockaway Peninsula, NY

$$Q_s = K\left(\frac{{u_0}^3}{W_s}\right)\left[-5u_1 - 3u_2 + \frac{\beta(x)}{W_s}{u_0}^2\right]$$

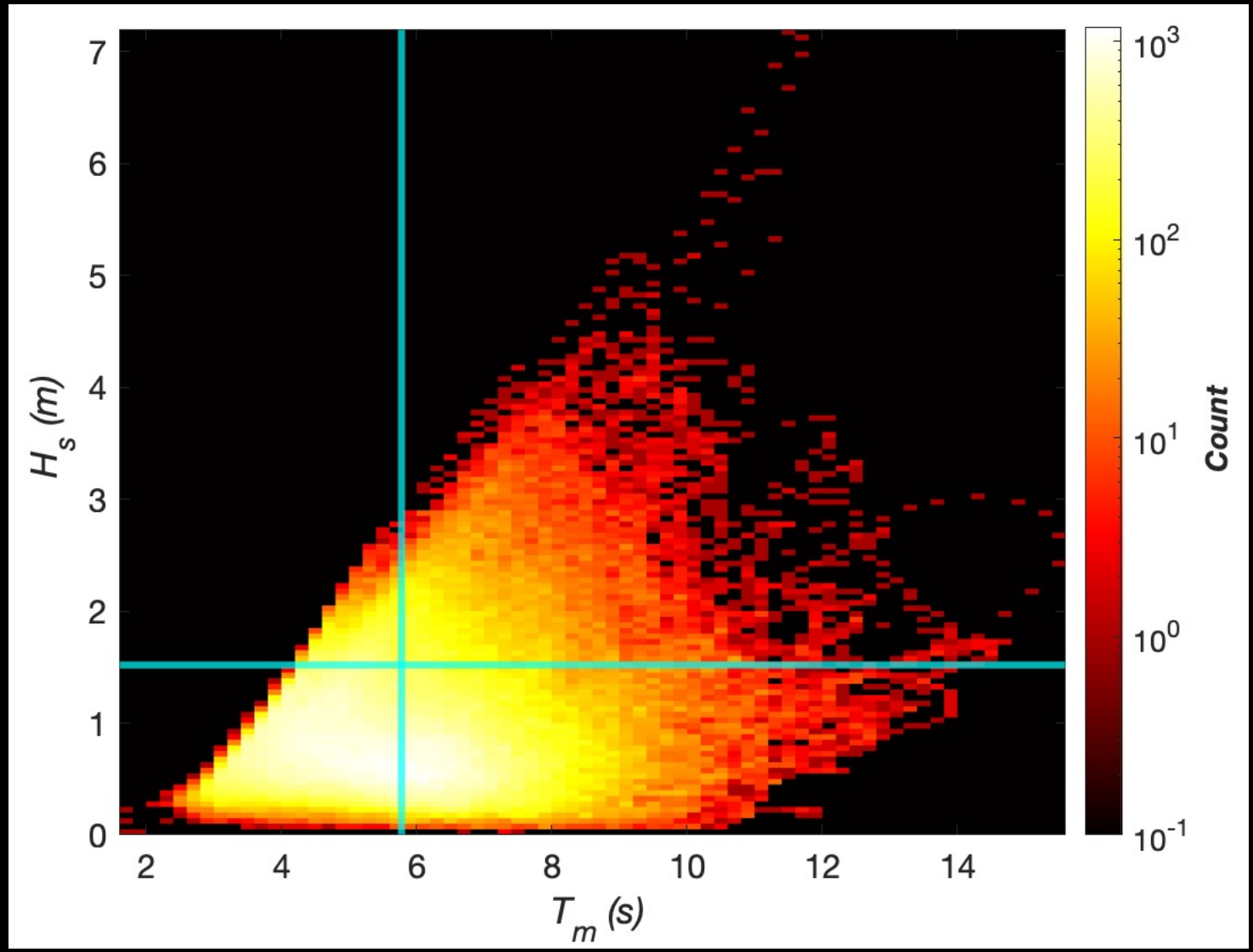
$$Q_{s_i}(T_{m_i}, H_{s_i}) \text{ @ time } i$$

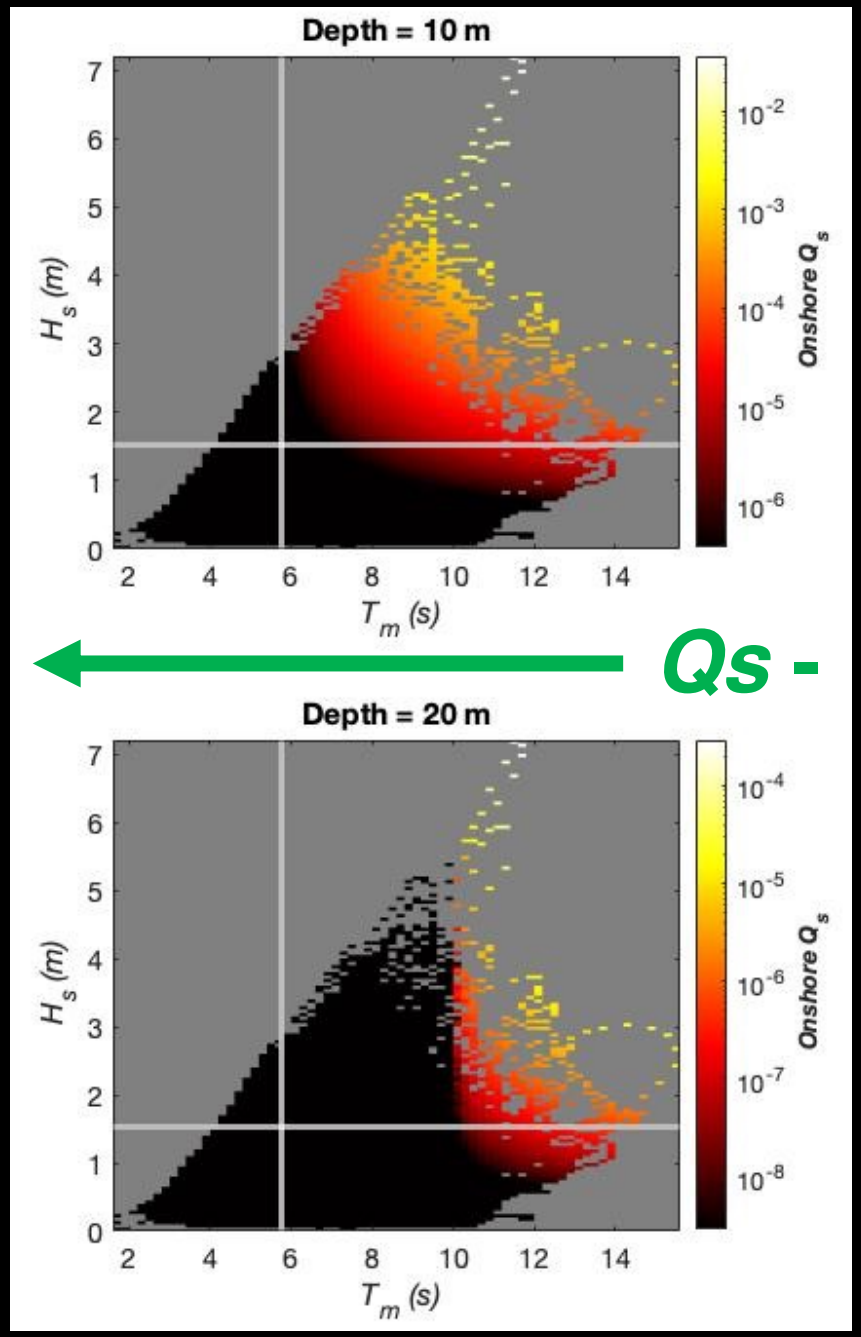
$$Q_{s_e} = \frac{\sum_{i=1}^{n} Q_s * \Delta t}{D}$$

WIS Buoy Transport and Profiles

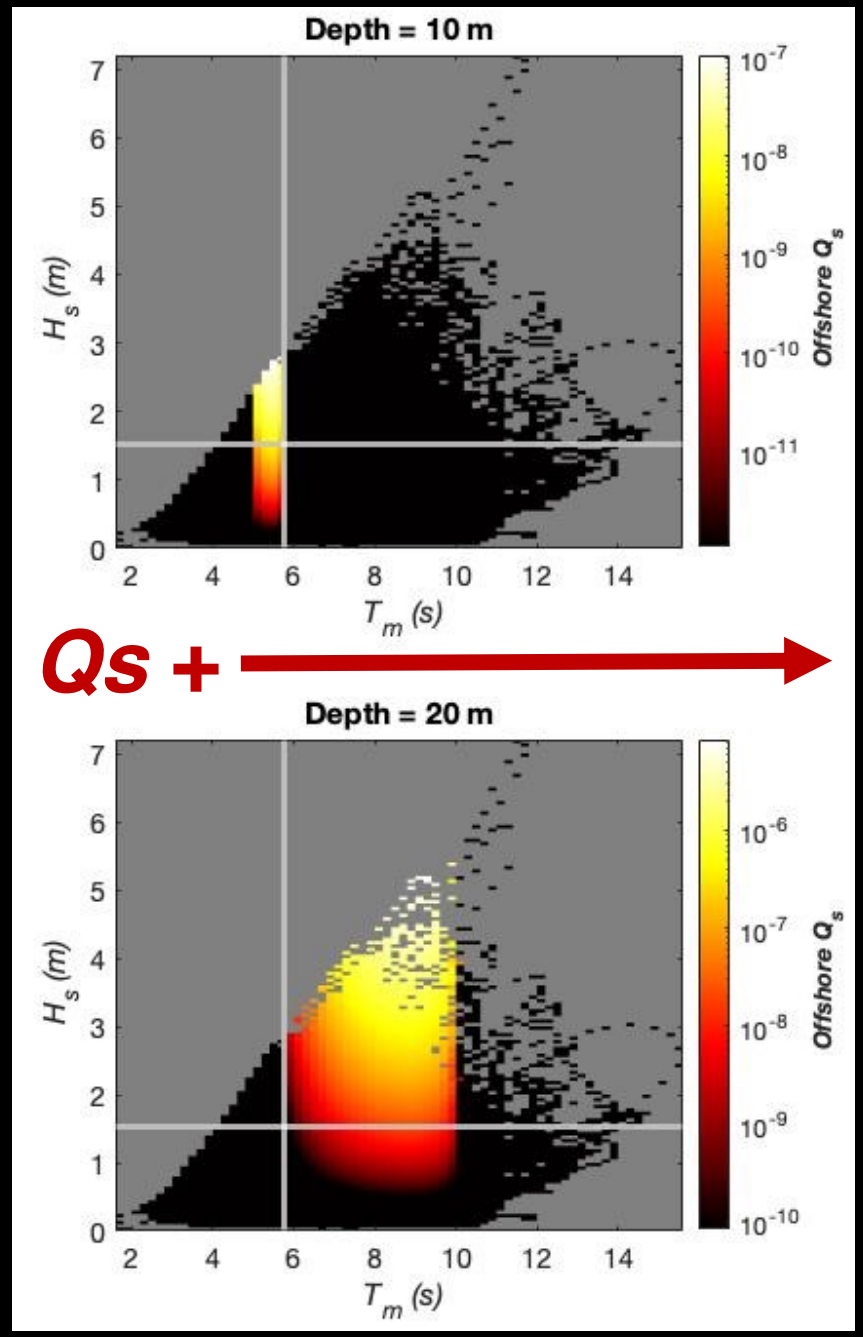


$\sum Q_s$ Transport over Avg. Profile

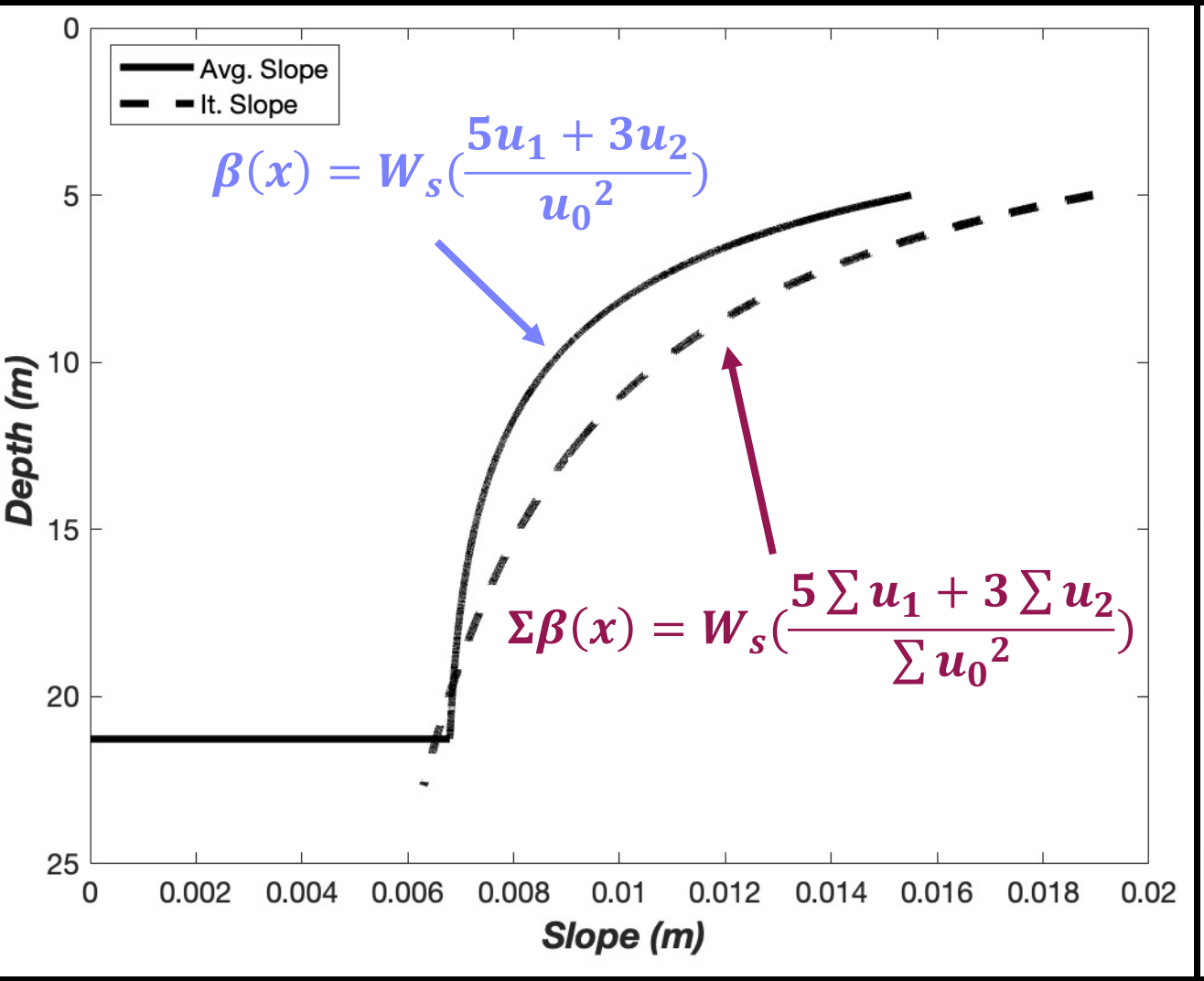

7
6
5
4
3
2
1
0
H_s (m)
2
4
6
8
10
12
14
T_m (s)
10^3
10^2
10^1
10^0
10^{-1}
Count

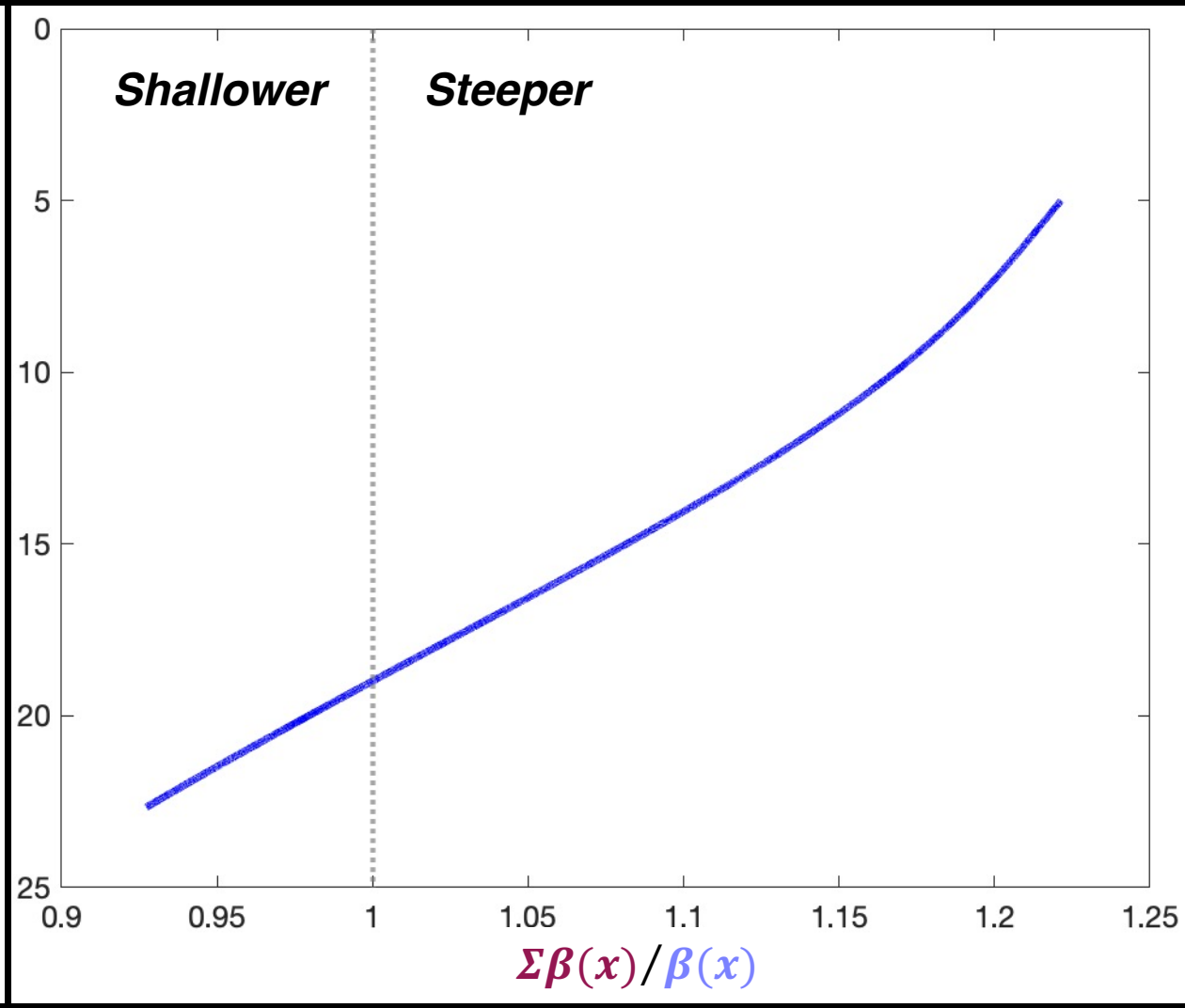

Depth = 10 m
H_s (m)
T_m (s)
Onshore Q_s
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Depth = 20 m
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}

Qs -


Depth = 10 m
H_s (m)
T_m (s)
Offshore Q_s
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Depth = 20 m
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}

Qs +


Avg. Slope
It. Slope
$\beta(x) = W_s(\frac{5u_1 + 3u_2}{u_0{}^2})$
$\Sigma\beta(x) = W_s(\frac{5\sum u_1 + 3\sum u_2}{\sum u_0{}^2})$
Depth (m)
Slope (m)
0
5
10
15
20
25
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02


Shallower
Steeper
$\Sigma\beta(x)/\beta(x)$
0
5
10
15
20
25
0.9
0.95
1
1.05
1.1
1.15
1.2
1.25

Summary

- Shoreface sediment transport is sensitive to variations in wave climate and geology
- Energetics approach can model shoreface change in response to SLR
- Different averaging techniques yield different profiles for WIS time series data

Massachusetts Institute of Technology

WOODS HOLE OCEANOGRAPHIC INSTITUTION

USGS science for a changing world

USCRP US COASTAL RESEARCH PROGRAM

Thank you!

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This research was conducted on ancestral Wampanoag and Massachusett lands. AGU is being held on ancestral Chitimacha land. The indigenous peoples from these tribes have and continue to suffer countless losses, exploitation, forced removal from imperialist and native erasure efforts by white settlers. All co-authors acknowledge the horrific violence these communities have endured and will continue to experience. Land where work has been conducted and information is being disseminated has been, is, and will ALWAYS be ancestral indigenous land.