Damping of turbulence by suspended sediment: fundamental ramifications for sediment dynamics

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Damping of Turbulence by Suspended Sediment: Fundamental Ramifications for Sediment Dynamics

Carl Friedrichs, Virginia Institute of Marine Science

Outline of Presentation:

• Richardson number influence on coastal/estuarine mixing
• Derivation of stratified “overlap” layer structure
• Under-saturated (weakly stratified) sediment suspensions
• Critically saturated ($Ri_{cr}$-controlled) sediment suspensions
• Hindered settling, over-saturation, and collapse of turbulence

Presented at University of Delaware, 9/27/11

Time-series of suspended sediment in York River estuary (Friedrichs et al. 2000)
Gradient Richardson Number (Ri) = \frac{\text{density stratification}}{\text{velocity shear}}

Shear instabilities occur for \( \text{Ri} < \text{Ri}_{cr} \)

“ “ suppressed for \( \text{Ri} > \text{Ri}_{cr} \)

\[
\text{Ri} = \frac{g \left( \frac{\partial \rho}{\partial z} \right)}{\rho \left( \frac{\partial u}{\partial z} \right)^2}
\]

\( \text{Ri}_{cr} \approx \frac{1}{4} \)

Hans Paerl et al. (2004) Neuse River Estuary observations from 2003

Density & Chl stratified when \( \text{Ri} > \frac{1}{4} \), mixed when \( \text{Ri} < \frac{1}{4} \)

OUTLINE: 1) \text{Ri} # importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
When strong currents are present, mud remains turbulent and in suspension at a concentration that gives $\text{Ri} \approx \text{Ri}_{cr} \approx 1/4$:

$$\text{Ri} = \frac{\text{Stratification}}{\text{Shear}}$$

$$\text{Ri} = \frac{-g_s \frac{\partial c}{\partial z}}{\rho_s \left(\frac{\partial u}{\partial z}\right)^2}$$

$g = \text{accel. of gravity}$
$s = (\rho_s - \rho)/\rho$
$c = \text{sediment mass conc.}$
$\rho_s = \text{sediment density}$

For $c > \sim 300 \text{ mg/liter}$

$$\text{Ri} \approx \text{Ri}_{cr} \approx O(1/4)$$

**Figure 5.** Sediment-based gradient Richardson number as a function of sediment concentration based on measurements throughout the entire water column in all of the profiles summarized in Table 1. The dashed curve corresponds to a gradient Richardson number of 1/4.

Amazon Shelf (Trowbridge & Kineke, 1994)

**OUTLINE:** 1) **Ri # importance**; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
Are there simple, physically-based relations to predict $c$ and $du/dz$ related to $Ri$?

Large supply of easily suspended sediment creates negative feedback:

$$Ri = \frac{\text{density stratification}}{\text{velocity shear}}$$

Shear instabilities occur for $Ri < Ri_{cr}$ and turbulence intensifies. Sediment re-enters base of boundary layer. Stratification is increased in lower boundary layer and $Ri$ returns to $Ri_{cr}$.

(a) If excess sediment enters bottom boundary layer or bottom stress decreases, $Ri$ \(\uparrow\) beyond $Ri_c$, critically damping turbulence. Sediment settles out of boundary layer. Stratification is reduced and $Ri$ returns to $Ri_c$.

(b) If excess sediment settles out of boundary layer or bottom stress increases, $Ri$ \(\downarrow\) below $Ri_c$ and turbulence intensifies. Sediment re-enters base of boundary layer. Stratification is increased in lower boundary layer and $Ri$ returns to $Ri_c$.

OUTLINE: 1) $Ri$ # importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
Consider Three Basic Types of Suspensions

1) Under-saturated -- Supply limited
2) Critically saturated load
3) Over-saturated -- Settling limited

OUTLINE: 1) Ri # importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
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Time-series of suspended sediment in York River estuary (Friedrichs et al. 2000)
Dimensionless analysis of bottom boundary layer in the absence of stratification:

\[ \frac{z}{u^*} \frac{du}{dz} = f \left( \frac{v}{z u^*}, \frac{z}{h} \right) \]

\( h \) = thickness of bottom boundary layer, \( v \) = kinematic viscosity, \( u^* = (\tau_b/\rho)^{1/2} \) = shear velocity

\(~ 10^{-6} \text{ m}^2/\text{s}\)

\(~ 1 \text{ cm/s}\)

\( h \sim 10 \text{ m} \uparrow \)

OUTLINE:

1) \( \text{Ri} \) # importance;
2) **Overlap layer**;
3) Under-saturation;
4) Critical Saturation;
5) Over-saturation
Dimensionless analysis of bottom boundary layer in the absence of stratification:

Variables

\[
\frac{z \ du}{u_* \ dz} = f \left( \frac{v}{z u_*}, \frac{z}{h} \right)
\]

\(h = \) thickness of bottom boundary layer, \(v = \) kinematic viscosity, \(u_* = (\tau_b/\rho)^{1/2} = \) shear velocity

\(~ 10^{-6} \text{ m}^2/\text{s} \quad \sim 1 \text{ cm/s}\)

\(h \sim 10 \text{ m} \uparrow\)

Outer Layer

\(\frac{v}{(zu_*)} \ll 1\), but \(z/h\) not small

“Overlap” Layer:

\(z/h \ll 1\) \& \(\frac{v}{(zu_*)} \ll 1\)

(a.k.a. “log-layer”)

\(\kappa \approx 0.41\) (Dyer, 1986)

Viscous Layer

\(\frac{z \ du}{u_* \ dz} = f \left( \frac{z}{h} \right)\)

\(\frac{z \ du}{u_* \ dz} = \text{Const.} = 1/\kappa\)

\(i.e., \quad \frac{\kappa z \ du}{u_* \ dz} = 1\)

\(u = \frac{u_*}{\kappa} \log \left( \frac{z}{z_0} \right)\)

OUTLINE: 1) Ri # importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
Bottom boundary layer often plotted on log(z) axis:

\[
\frac{z}{u_*} \frac{du}{dz} = f(z/h)
\]

\[
\frac{z}{u_*} \frac{du}{dz} = \frac{1}{\kappa}
\]

\[
u/(zu_*) \ll 1
\]

\[
\frac{z}{u_*} \frac{du}{dz} = f(zu_*/\nu)
\]

(Wright, 1995)

OUTLINE: 1) Ri # importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
Dimensionless analysis of overlap layer with (sediment-induced) stratification:

Additional variable

\[ b = \frac{g_s <c'w'>}{\rho_s} \]

\[ s = (\rho_s - \rho)/\rho \approx 1.6 \]

\[ c = \text{sediment mass conc.} \]

\[ w = \text{vertical fluid vel.} \]

\[ \frac{\kappa z}{u_*} \frac{du}{dz} = 1 \]

\[ \frac{\kappa z}{u_*} \frac{du}{dz} = f\left(\frac{b\kappa z}{u_3^3}\right) \]

Dimensionless ratio

\[ \frac{b\kappa z}{u_3^3} \equiv \zeta = \text{“stability parameter”} \]

OUTLINE: 1) Ri # importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
Deriving impact of \( z \) on structure of overlap (a.k.a. “log” or “wall”) layer

\[
\frac{\kappa z}{u_*} \frac{du}{dz} = f \left( \frac{b\kappa z}{u_*^3} \right) \quad \Rightarrow \quad \frac{\kappa z}{u_*} \frac{du}{dz} = f (\zeta)
\]

Rewrite \( f(\zeta) \) as Taylor expansion around \( \zeta = 0 \):

\[
\frac{\kappa z}{u_*} \frac{du}{dz} = f (\zeta) = f \bigg|_{\zeta=0} + \zeta \frac{df}{d\zeta} \bigg|_{\zeta=0} \frac{\zeta^2}{2} \frac{d^2 f}{d\zeta^2} \bigg|_{\zeta=0} + \ldots
\]

\[
= 1 \quad = \alpha \quad \approx 0 \quad \approx 0
\]

\[
\frac{\kappa z}{u_*} \frac{du}{dz} = 1 + \alpha \zeta
\]

\[
u = \frac{u_*}{\kappa} \left[ \log \left( \frac{z}{z_0} \right) + \alpha \int_{z_0}^{z} \left( \frac{\zeta}{z} \right) d\zeta \right]
\]

From atmospheric studies, \( \alpha \approx 4 - 5 \)

If there is stratification (\( \zeta > 0 \)) then \( u(z) \) increases faster with \( \zeta \) than homogeneous case.

OUTLINE: 1) Ri # importance; 2) **Overlap layer**; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
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Presented at University of Delaware, 9/27/11

Time-series of suspended sediment in York River estuary  (Friedrichs et al. 2000)
\[ u = \frac{u_\ast}{K} \left[ \log \left( \frac{z}{z_0} \right) + \alpha \int \frac{\zeta}{z} \, dz \right] \]  
\text{Eq. (1)}

-- Case (i): No stratification near the bed ($\zeta = 0$ at $z = z_0$). Stratification and $\zeta$ increase with increased $z$.
-- Eq. (1) gives $u$ increasing faster and faster with $z$ relative to classic well-mixed log-layer.
(e.g., halocline being mixed away from below)

-- Case (ii): Stratified near the bed ($\zeta > 0$ at $z = z_0$). Stratification and $\zeta$ decreases with increased $z$.
-- Eq. (1) gives $u$ initially increasing faster than $u$, but then matching $du/\,dz$ from neutral log-layer.
(e.g., fluid mud being entrained by wind-driven flow)

-- Case (iii): uniform $\zeta$ with $z$. Eq (1) integrates to
\[ u = \frac{u_\ast}{K} (1 + \alpha \zeta) \log \left( \frac{z}{z_0} \right) \]
-- $u$ remains logarithmic, but shear is increased buy a factor of $(1+\alpha\zeta)$

(Friedrichs et al, 2000)

OUTLINE: 1) Ri # importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
Effect of stratification (via $\zeta$) on eddy viscosity ($A_z$)

$$\frac{\kappa z}{u_*} \frac{du}{dz} = 1 + \alpha \zeta$$  
Overlap layer scaling  
modified by buoyancy flux  
$$u_*^2 = A_z \frac{du}{dz}$$  
Definition of eddy viscosity

Eliminate $du/dz$ and get

$$A_z = \frac{\kappa u_* z}{(1 + \alpha \zeta)}$$

-- As stratification increases (larger $\zeta$), $A_z$ decreases

-- If $\zeta = \text{const. in } z$, $A_z$ increases like $u_* z$, and the result is still a log-profile.

Connect stability parameter, $\zeta$, to shape of concentration profile, $c(z)$:

Definition of $\zeta$:

$$\zeta = \frac{b \kappa z}{u_*^3} = \frac{gs \langle c' w' \rangle \kappa z}{\rho_s u_*^3}$$
Rouse balance  
(Reynolds flux = settling):

$$gs \langle c' w' \rangle \kappa z = c w_s$$

Combine to eliminate $\langle c' w' \rangle$:

$$\zeta = \left( \frac{gs w_s K}{\rho_s u_*^3} \right) c z \quad \zeta = \text{const. in } z \quad \text{if} \quad C \sim \zeta^{-1}$$
(Assuming $w_s$ is const. in $z$)

OUTLINE: 1) Ri # importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
If suspended sediment concentration, \( C \sim z^{-A} \)

Then \( A <,>,= 1 \) determines shape of \( u \) profile

\[
\zeta = \left( \frac{g s w_s K}{\rho_s u_*^3} \right) c z \quad \zeta = \text{const. in } z \quad \text{if } C \sim z^{-1}
\]

Fit a general power-law to \( c(z) \) of the form \( C \sim z^{-A} \)

Then \( \zeta \sim z^{(1-A)} \)

If \( A < 1 \), \( c \) decreases more slowly than \( z^{-1} \)
\( \zeta \) increases with \( z \), stability increases upward,
\( u \) is more concave-down than \( \log(z) \)

If \( A > 1 \), \( c \) increases more quickly than \( z^{-1} \)
\( \zeta \) decreases with \( z \), stability becomes less pronounced upward,
\( u \) is more concave-up than \( \log(z) \)

If \( A = 1 \), \( c \sim z^{-1} \)
\( \zeta \) is constant with elevation
stability is uniform in \( z \),
\( u \) follows \( \log(z) \) profile

\( \zeta \) is constant in \( z \)

OUTLINE: 1) Ri # importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
If suspended sediment concentration, $C \sim z^{-A}$

$A < 1$ predicts $u$ more concave-down than $\log(z)$

$A > 1$ predicts $u$ more concave-up than $\log(z)$

$A = 1$ predicts $u$ will follow $\log(z)$

Testing this relationship using observations from bottom boundary layers:

**Eckernförde Bay, Baltic Coast, Germany**

(Friedrichs & Wright, 1997; Friedrichs et al, 2000)

**STRATAFORM mid-shelf site, Northern California, USA**

**Inner shelf, Louisiana USA**

OUTLINE: 1) Ri # importance; 2) Overlap layer; 3) **Under-saturation**; 4) Critical Saturation; 5) Over-saturation
If suspended sediment concentration, \( C \sim z^{-A} \)

- \( A < 1 \) predicts u more concave-down than \( \log(z) \)
- \( A > 1 \) predicts u more concave-up than \( \log(z) \)
- \( A = 1 \) predicts u will follow \( \log(z) \)

**STATAFORM mid-shelf site, Northern California, USA, 1995, 1996**

**Inner shelf, Louisiana, USA, 1993**

\( A \approx 0.11 \)
\( A \approx 3.1 \)
\( A \approx 0.35 \)
\( A \approx 0.73 \)
\( A \approx 1.0 \)

(Friedrichs et al, 2000)

-- Smallest values of \( A < 1 \) are associated with concave-downward velocities on log-plot.
-- Largest value of \( A > 1 \) is associated with concave-upward velocities on log-plot.
-- Intermediate values of \( A \approx 1 \) are associated with straightest velocities on log-plot.

**OUTLINE:** 1) Ri # importance; 2) Overlap layer; 3) **Under-saturation**; 4) Critical Saturation; 5) Over-saturation
Eckernförde Bay, Baltic Coast, Germany, spring 1993

-- Salinity stratification that increases upwards cannot be directly represented by $c \sim z^A$. Friedrichs et al. (2000) argued that this case is dynamically analogous to $A \approx -1$.

OUTLINE: 1) Ri # importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
Observations showing effect of concentration exponent A on shape of velocity profile

A = -1, .11, .35

A < 1, concave-down velocity
A > 1, concave-up velocity
A ~ 1, straight velocity profile

OUTLINE: 1) Ri # importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
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Presented at University of Delaware, 9/27/11
Relate stability parameter, $\zeta$, to Richardson number:

$$ Ri = -\frac{gs (dc/dz)}{\rho_s (du/dz)^2} $$

Definition of gradient Richardson number associated with suspended sediment:

$$\zeta = \frac{gs <c'w'> \kappa z}{\rho_s u_*^3} \quad \frac{\kappa z}{u_*} \frac{du}{dz} = 1 + \alpha \zeta$$

Original definition and application of $\zeta$:

Relation found for eddy viscosity:

$$ A_z = \frac{\kappa u_* z}{(1 + \alpha \zeta)} $$

Definition of eddy diffusivity:

$$ -<c'w'> = K_z \frac{dc}{dz} $$

Assume momentum and mass are mixed similarly:

$$ A_z = K_z $$

Combine all these and you get:

$$ Ri = \frac{\zeta}{1 + \alpha \zeta} $$

So a constant $\zeta$ with height also leads to a constant $Ri$ with height.

Also, if $\zeta$ increases (or decreases) with height $Ri$ correspondingly increases (or decreases).

OUTLINE: 1) $Ri$ # importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
\[ \zeta = \left( \frac{gsw_s K}{\rho_s u^3_*} \right) c \zeta \]
\[ Ri = \frac{\zeta}{1 + \alpha \zeta} \]

\( \zeta \) and Ri const. in z if  \( c \sim z^{-1} \)

Define  \( c \sim z^{-A} \) then  \( \zeta \sim z^{(1-A)} \)

If  \( A < 1 \),  \( c \) decreases more slowly than  \( z^{-1} \)
\( \zeta \) and Ri increase with z, stability increases upward,
u is more concave-down than log(z)

If  \( A > 1 \),  \( c \) decreases more quickly than  \( z^{-1} \)
\( \zeta \) and Ri decrease with z, stability becomes less pronounced upward,
u is more concave-up than log(z)

If  \( A = 1 \),  \( c \sim z^{-1} \)
\( \zeta \) and Ri are constant with elevation
stability is uniform in z,
u follows log(z) profile

If suspended sediment concentration,  \( C \sim z^{-A} \) then  \( A <,>,= 1 \) determines shape of u profile
and also the vertical trend in  \( \zeta \) and Ri

(Friedrichs et al, 2000)

**Current Speed**

**OUTLINE:**
1) Ri # importance; 2) Overlap layer; 3) Under-saturation; 4) **Critical Saturation**; 5) Over-saturation
Now focus on the case where $R_i = R_{i_{cr}}$ (so $R_i$ is constant in $z$ over “log” layer).

OUTLINE: 1) $R_i$ # importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
Connection between structure of sediment settling velocity to structure of “log-layer” when $Ri = Ri_{cr}$ in $z$ (and therefore $\zeta$ is constant in $z$ too).

Rouse Balance: 

$$w_s C = K_z \frac{dc}{dz}$$

Earlier relation for eddy viscosity:

$$K_z = \frac{Ku_* z}{(1 + \alpha \zeta)}$$

Eliminate $K_z$ and integrate in $z$ to get

$$\frac{C}{C_{ref}} = \left( \frac{z}{z_{ref}} \right)^{-\left[ \frac{w_s (1 + \alpha \zeta)}{Ku_*} \right]}$$

But we already know $C \sim z^{-1}$ when $Ri = \text{const.}$

So

$$\frac{w_s (1 + \alpha \zeta)}{Ku_*} = 1$$

and

$$1 + \alpha \zeta = \frac{Ku_*}{w_s}$$

when $Ri = Ri_{cr}$

OUTLINE: 1) $Ri$ # importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
\[ 1 + \alpha \zeta = \frac{\kappa u_*}{w_s} \]

when \( \text{Ri} = \text{Ri}_{\text{cr}} \). This also means that when \( \text{Ri} = \text{Ri}_{\text{cr}} \):

\[ \text{Ri} = \frac{\zeta}{1 + \alpha \zeta} \quad \rightarrow \quad \text{Ri}_{\text{cr}} = \frac{w_s \zeta}{\kappa u_*} \]

\[ A_z = K_z = \frac{\kappa u_* z}{(1 + \alpha \zeta)} \quad \rightarrow \quad A_z = K_z = w_s z \]

\[ \frac{du}{dz} = \frac{u_*}{\kappa z} (1 + \alpha \zeta) \quad \rightarrow \quad \frac{du}{dz} = \frac{u_*^2}{w_s z} \]

\[ u = \frac{u_*}{\kappa} (1 + \alpha \zeta) \log \left( \frac{z}{z_0} \right) \quad \rightarrow \quad u = \frac{u_*^2}{w_s} \log \left( \frac{z}{z_0} \right) \]

\[ \text{Ri} = -\frac{g_s (dc/dz)}{\rho_s (du/dz)^2} \quad \rightarrow \quad c = \frac{\text{Ri}_{\text{cr}} \rho_s}{g_s} \left( \frac{u_*^2}{w_s} \right)^2 z^{-1} \]

OUTLINE: 1) Ri # importance; 2) Overlap layer; 3) Under-saturation; 4) **Critical Saturation**; 5) Over-saturation
OUTLINE: 1) Ri # importance; 2) Overlap layer; 3) Under-saturation; 4) **Critical Saturation**; 5) Over-saturation
(a) Eel shelf, 60 m depth, winter 1995-96
(Wright, Friedrichs, et al. 1999)

Velocity shear $du/dz$ (1/sec)

$10^{-4}$ to $10^{-1}$

$0$ to $0.4$

Sediment gradient Richardson number

(b) Waiapu shelf, NZ, 40 m depth, winter 2004
(Ma, Friedrichs, et al. in 2008)

$R_i_{cr} = 1/4$

18 - 40 cm

OUTLINE: 1) $R_i$ # importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
Application of $R_i_{cr}$ log-layer equations for Eel shelf, 60 m depth, winter 1995-96

\[ u = \frac{u_*^2}{w_s} \log \left( \frac{z}{z_0} \right) \]

\[ c = \frac{R_i_{cr} \rho_s}{g_s} \left( \frac{u_*^2}{w_s} \right)^2 z^{-1} \]

OUTLINE: 1) $R_i$ importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation

(Souza & Friedrichs, 2005)
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100 mg/l  Time-series of suspended sediment in York River estuary  (Friedrichs et al. 2000)
Now also consider over-saturated cases:

1) Under-saturated -- Supply limited

2) Critically saturated load

3) Over-saturated -- Settling limited

OUTLINE: 1) Ri # importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
More settling

at around 5 - 8 grams/liter, the return flow of water around settling flocs creates so much drag on neighboring flocs that \( w_s \) starts to decrease with additional increases in concentration.

At \( \sim 10 \) g/l, \( w_s \) decreases so much with increased C that the rate of settling flux decreases with further increases in C. This is “hindered settling” and can cause a strong lutecline (vertical sediment gradient) to form.

A lutecline with hindered settling can cause turbulent collapse. The sediment can’t leave the water column, so dC/dz keeps increasing, creating positive feedback. Ri increases further above \( Ri_{cr} \), and more sediment to settle. Then there is more hindered settling and a stronger lutecline, increases Ri further.

**Figure 4.12** A representative plot of settling velocity and associated settling flux variation with suspension concentration.

Starting at around 5 - 8 grams/liter, the return flow of water around settling flocs creates so much drag on neighboring flocs that \( w_s \) starts to decrease with additional increases in concentration.

At \( \sim 10 \) g/l, \( w_s \) decreases so much with increased C that the rate of settling flux decreases with further increases in C. This is “hindered settling” and can cause a strong lutecline (vertical sediment gradient) to form.

A lutecline with hindered settling can cause turbulent collapse. The sediment can’t leave the water column, so dC/dz keeps increasing, creating positive feedback. Ri increases further above \( Ri_{cr} \), and more sediment to settle. Then there is more hindered settling and a stronger lutecline, increases Ri further.

**OUTLINE:** 1) Ri # importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
Fine sediment transport by tidal asymmetry in the high-concentrated Ems River: indications for a regime shift in response to channel deepening (Winterwerp, 2011)

\[ \text{Ri} = \frac{g_s \partial c/\partial z}{\rho_s (\partial u/\partial z)^2} \]

\( \text{Ri} \approx \text{Ri}_{cr} \) at peak ebb

\( \text{Ri} \approx \text{Ri}_{cr} \) at peak ebb

\( \text{Ri} >\text{Ri}_{cr} \) around slack

\( \text{Ri} \leq \text{Ri}_{cr} \) during flood

\( \text{Ri} \gg \text{Ri}_{cr} \) during flood

Observed

Modeled

Fig. 6 Measured isolutals at Station 2, June 19, 1990. Note rapid settling just prior to high water and pronounced stratification during ebb (after Van Leussen 1994)

Fig. 7 Computed isolutals at Station 2, June 19, 1990. Note rapid settling just prior to high water and pronounced stratification during ebb

-- 1-DV k-ε model based on components of Delft 3D
-- Sediment in density formulation
-- Flocculation model
-- Hindered settling model

OUTLINE: 1) Ri # importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
A numerical investigation of lutocline dynamics and saturation of fine sediment in the oscillatory boundary layer

U ~ 60 cm/s
C ~ 10 g/liter
“large eddy simulation” model
Fixed sediment supply

OUTLINE: 1) Ri # importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
Profiles of flux Richardson number at time of max free stream $U$

The Richardson number is of "order" critical (relatively close to 0.25) near top of suspended layer

OUTLINE: 1) Ri # importance; 2) Overlap layer; 3) Under-saturation; 4) Critical Saturation; 5) Over-saturation
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Conclusions:

• Negative feedback favors sediment $Ri \approx Ri_{cr}$ in the BBL.
• $Ri < 1/4$ (vs. $> 1/4$) implies supply (vs. settling) limitation.
• $Ri$ const. in $z$ implies $C \sim z^{-A}$, with $A \approx 1$ and $u \sim \log(z)$.
• If $Ri \uparrow$ (vs. $\downarrow$) in $z$, then $A < 1$ (vs. $> 1$), $u$ concave down (vs. up).
• $Ri \approx Ri_{cr}$ predicts max load independent of $w_s$ and erodibility.
• Time-scales of changes in $u$ determine whether turbulence and suspension will catastrophically collapse via positive feedback.

Presented at University of Delaware, 9/27/11