Internal Wave Beam Reflection Through Simulated Oceanic Pycnocline

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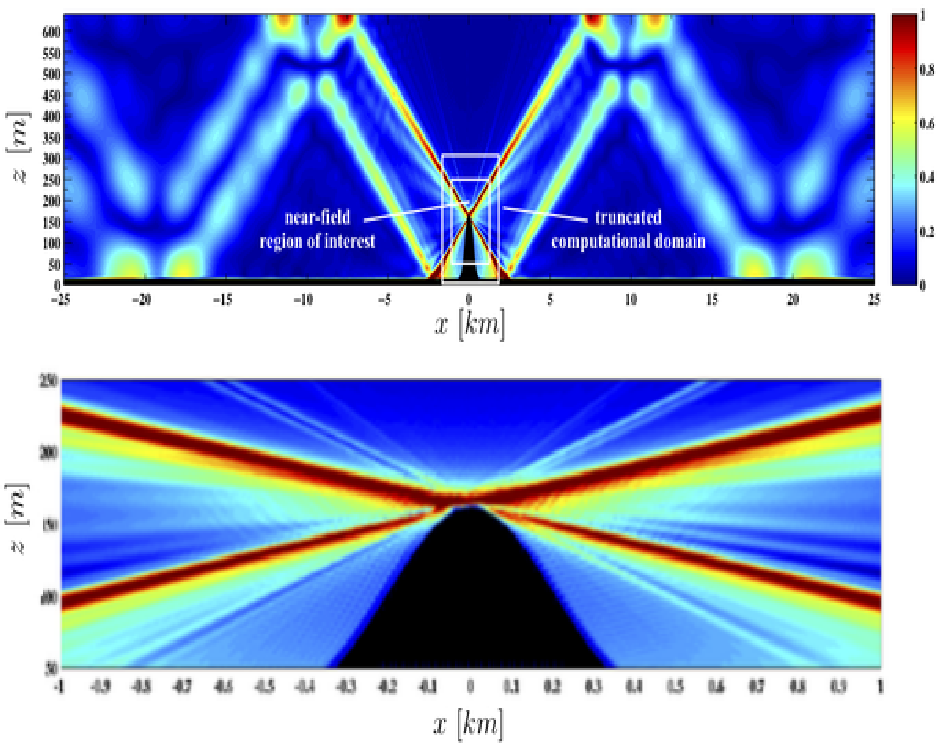
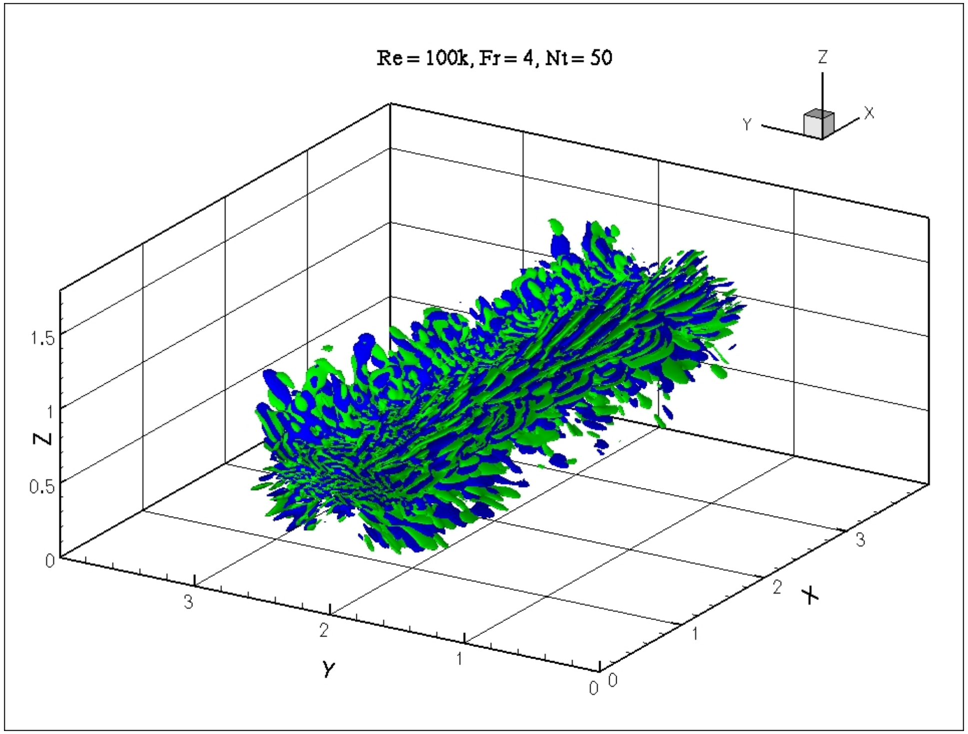
Motivation

- IW beam generated by ocean topography and turbulent wakes
- Reflection characteristics important to capture energy budgets in large scale oceanic models



Ocean Topography

(Kraig Winters, UCSD)



Submerged Turbulence

Objectives

To investigate IGW modulation, reflection, and ducting as it propagates across pycnoclines with a range of characteristics.

Parameters

$r = N_{max}/N_1$

h = Pycnocline width/ λ

Measure

Reflection Coef. for $|\langle p', \mathbf{u} \rangle|$ and ΔN^2

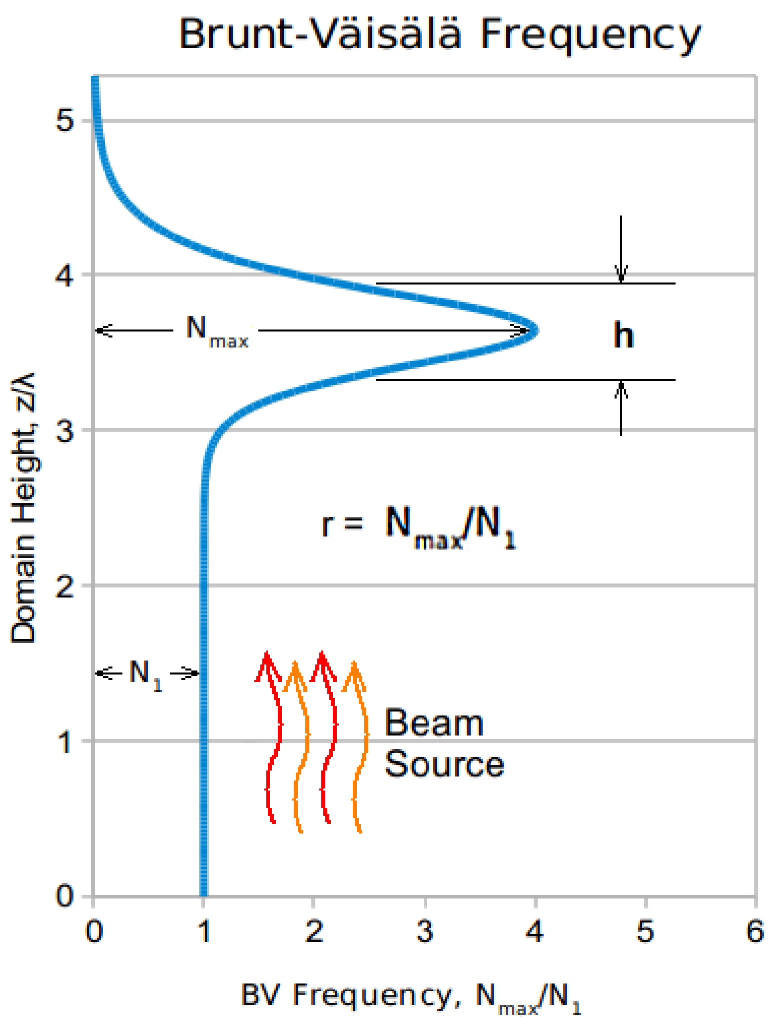
Compare/Complement

Laboratory experiments

(Wunsch et al., Johns Hopkins APL, 2010)

Finite-width transition theory

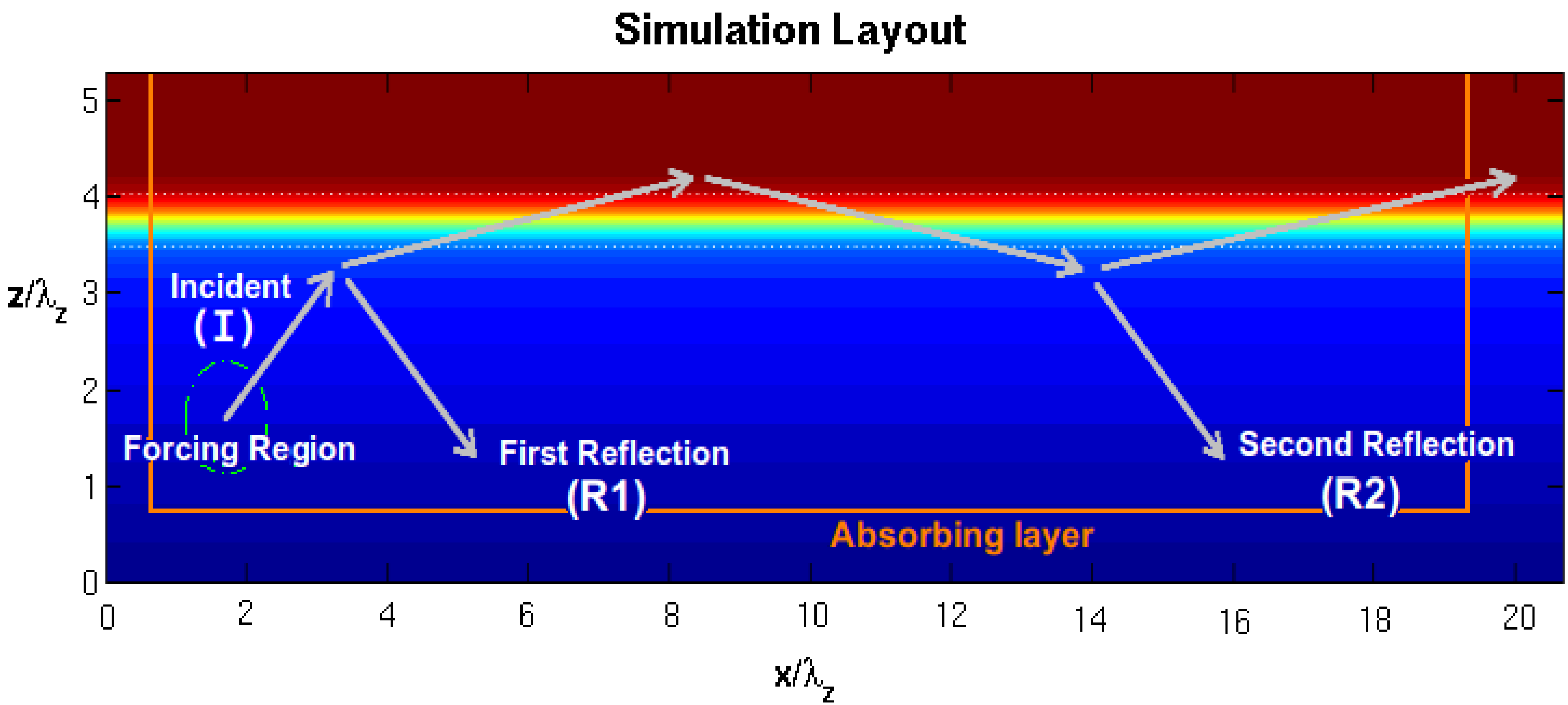
(Mathur, Peacock, MIT, 2009)



Simulation Layout

Wave steepness = 3%   Incident propagation angle = 45◦

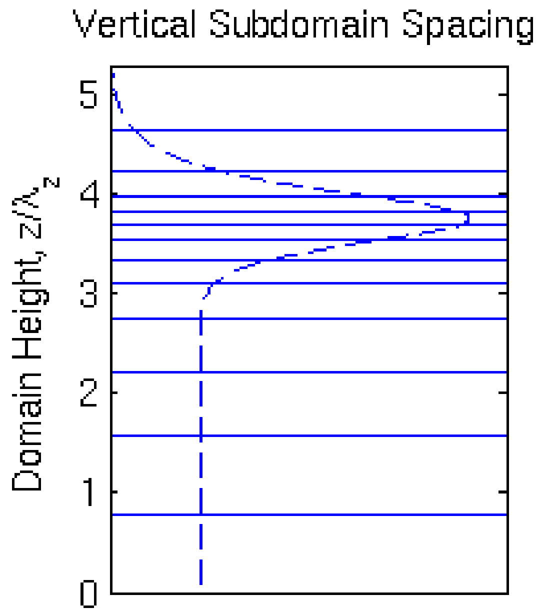
*Absorbing layers damp wave beams at domain boundaries

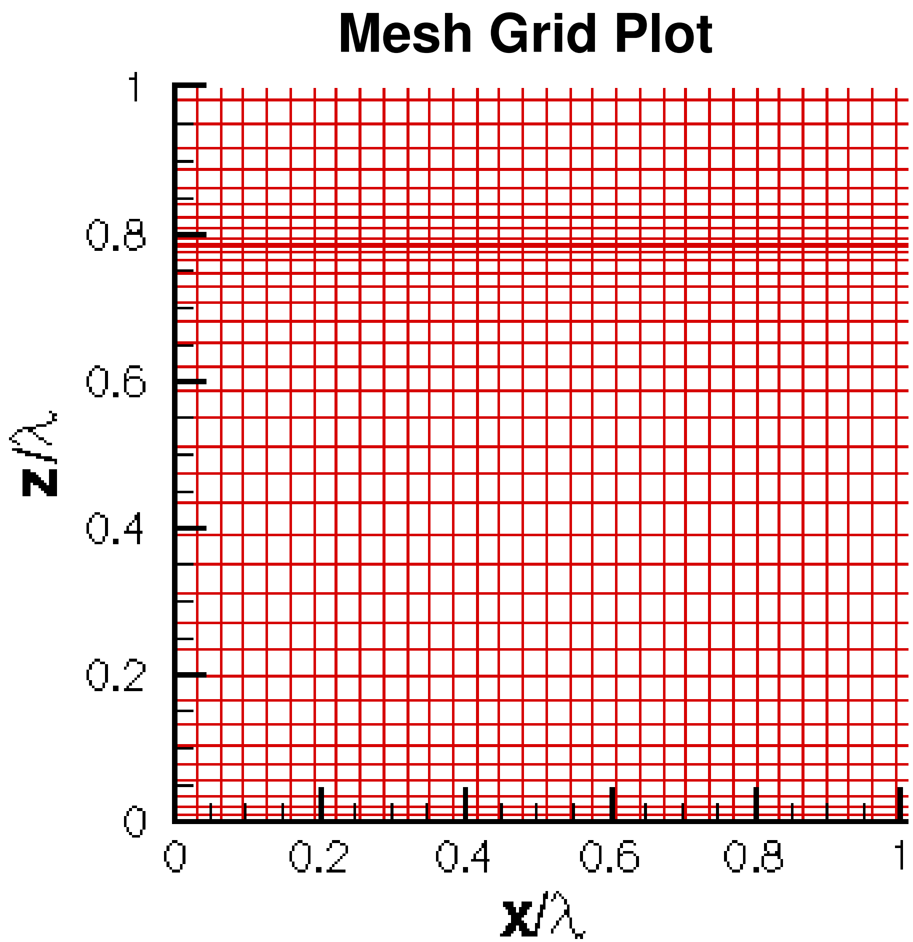


Computational Approach

2D Spectral Multi-domain Penalty Solver

(Diamessis et al. JCP 2005)





256 – 768 horizontal gridpoints

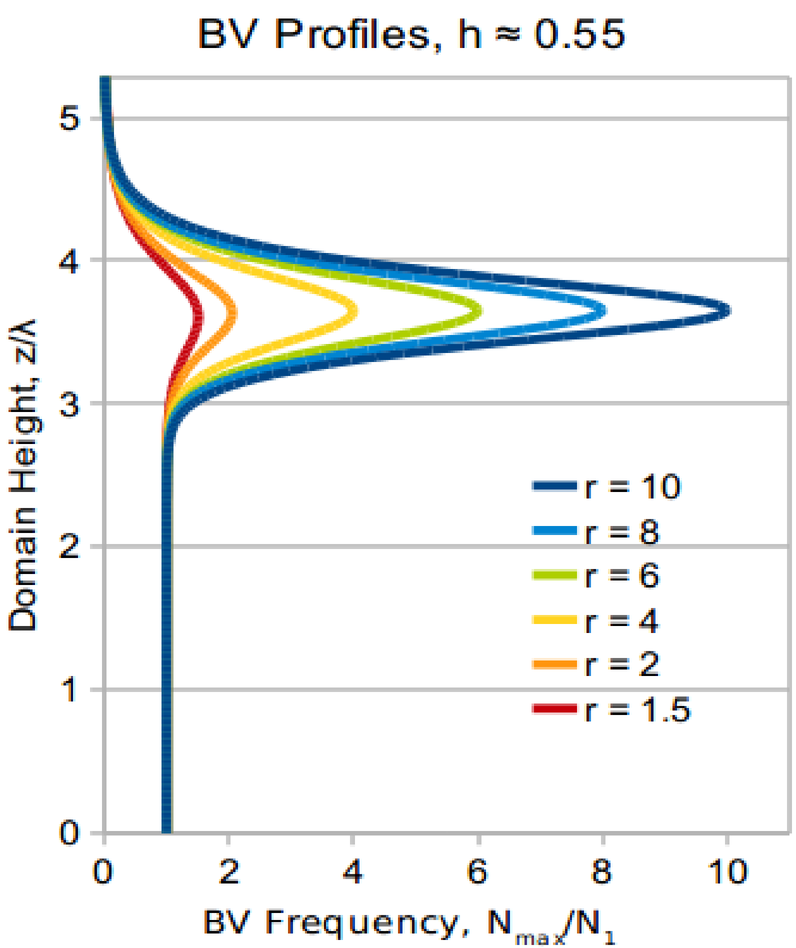
424 – 527 vertical gridpoints

~30 pts./lambda_x

~40 pts./lambda_z (everywhere)

Series 1 – Varying Pycnocline Strength

6 Cases: r -values - 1.5 2 4 6 8 10



- Fill in experimental gap for $2 < r < 6$

- Compare to finite-width transition linear theory

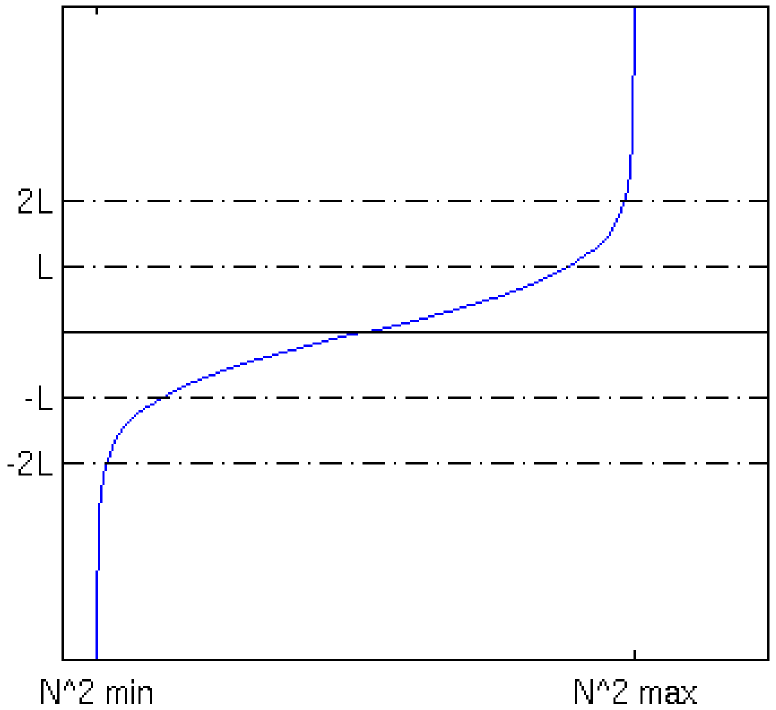
- $R2 = \dfrac{A_x \text{Ref.}}{A_x \text{Inc.}}$

Finite-width Transition Linear Theory

Inviscid solutions for transmission coefficients across a tanh(z) N^2 profile.

Near perfect transmission occurs when then largest vertical wavelength is much smaller than the transition length, L

$$L^*m >> 1$$



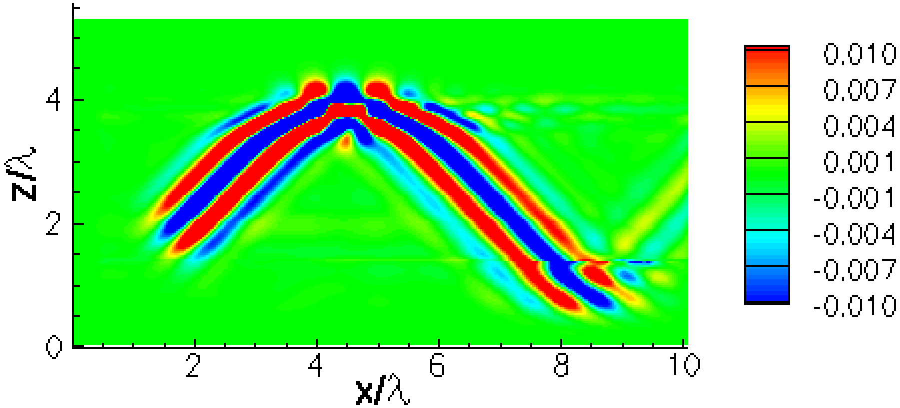
This is true for all Series 1 cases. We expect perfect transmission!

ΔN^2 Contour Plots

Pycnocline thickness, h = 0.55

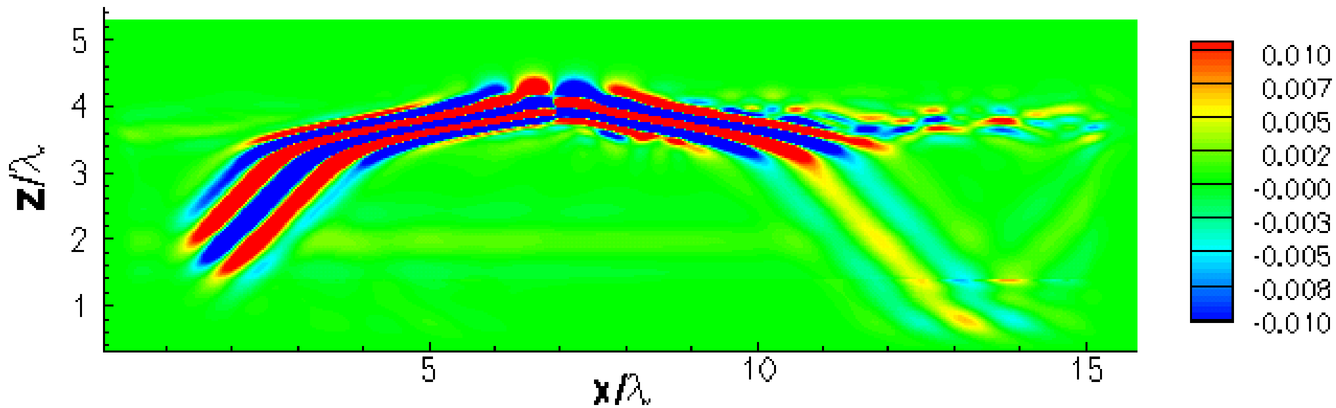
r = 1.5

t = 30*T



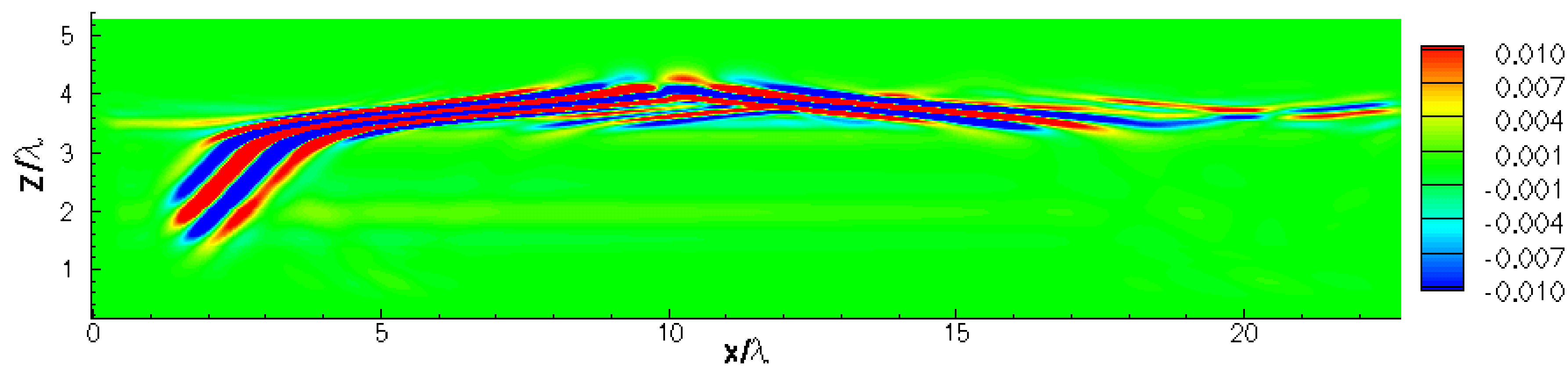
r = 4

t = 30*T



r = 8

t = 30*T



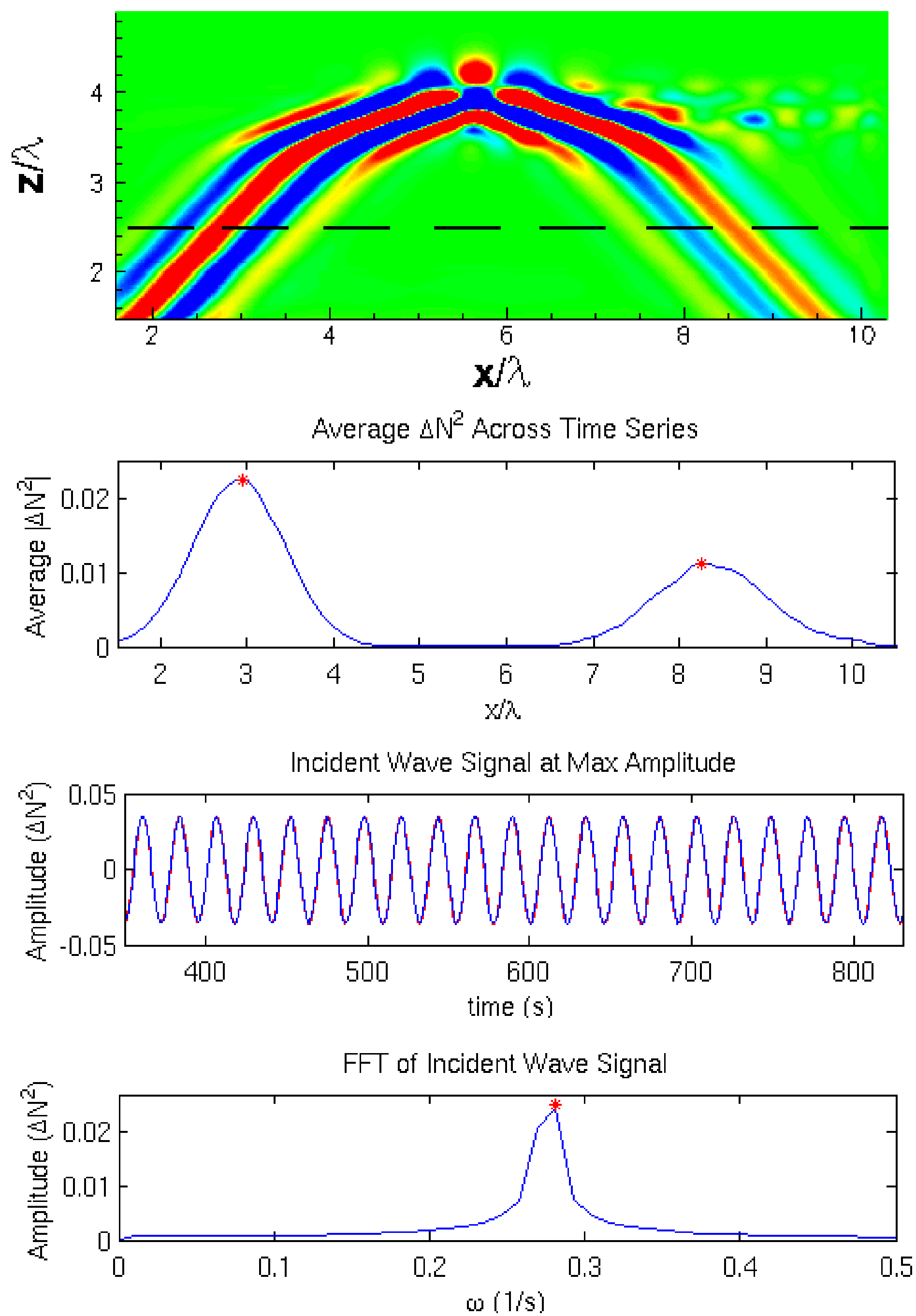
R2 Measurement Method

Horizontal cross-section for x-t samples

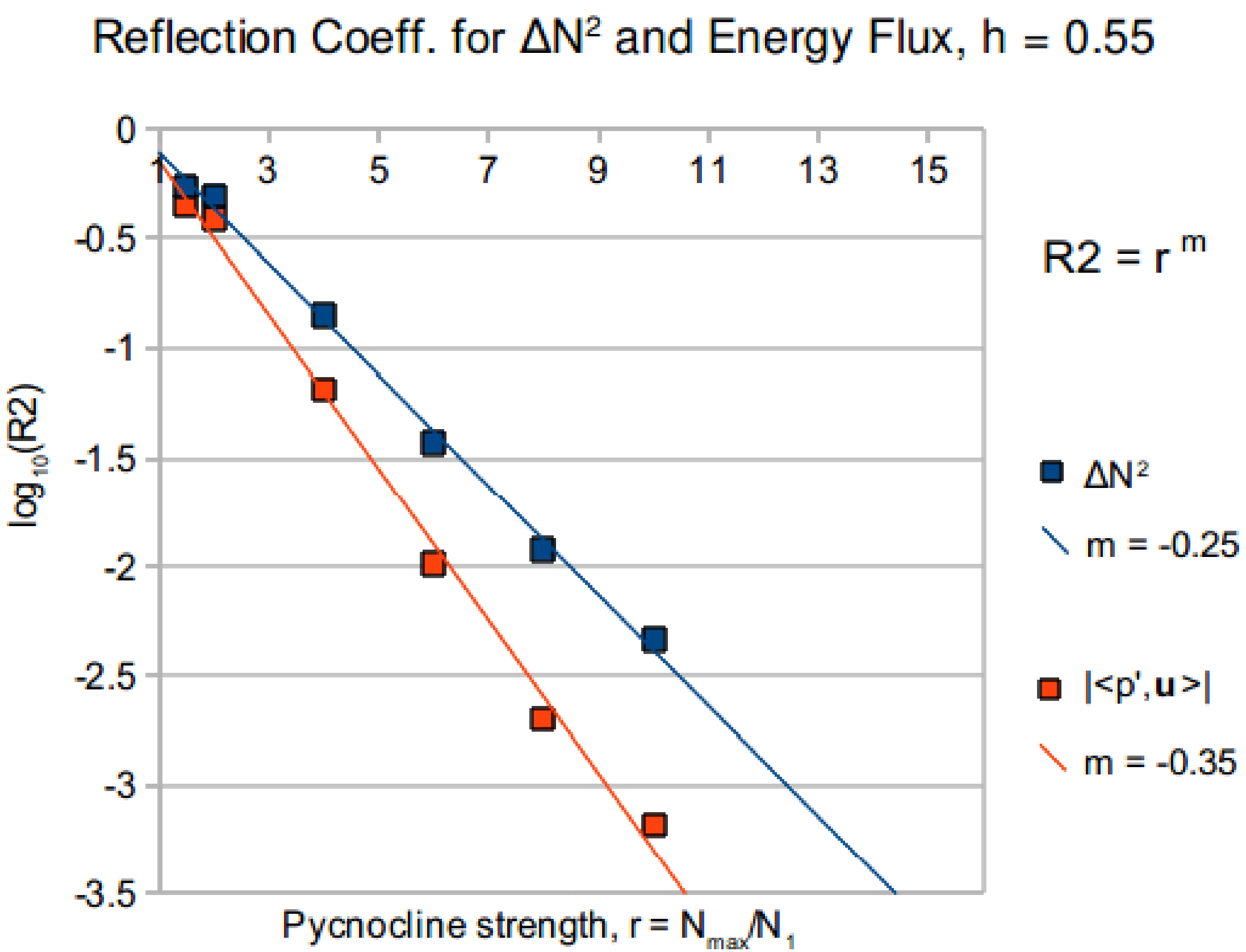
1. Take a time-series in the linearly stratified region across x

2. Find the x-location of max average wave amplitude

3. FFT signal at location of max amplitude to find RMS amplitude and frequency



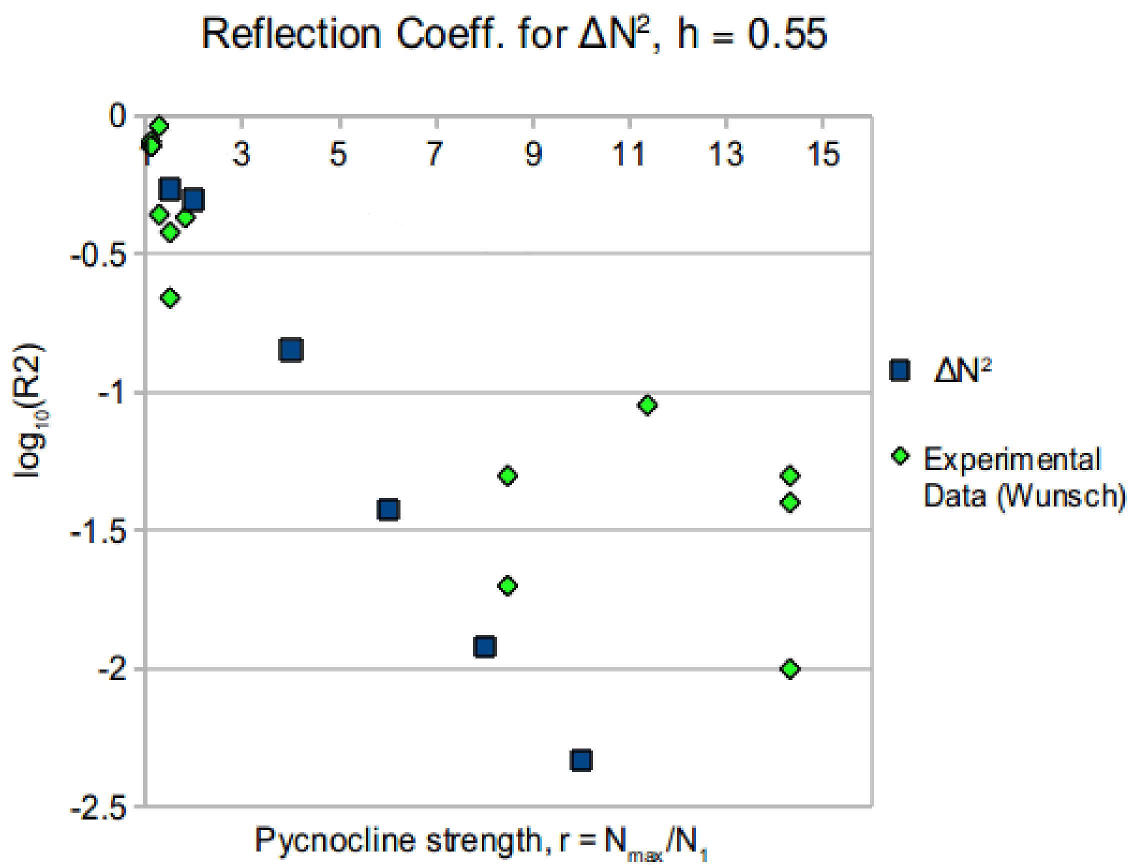
Measured Reflection Coefficients



Measured Reflection Coefficients

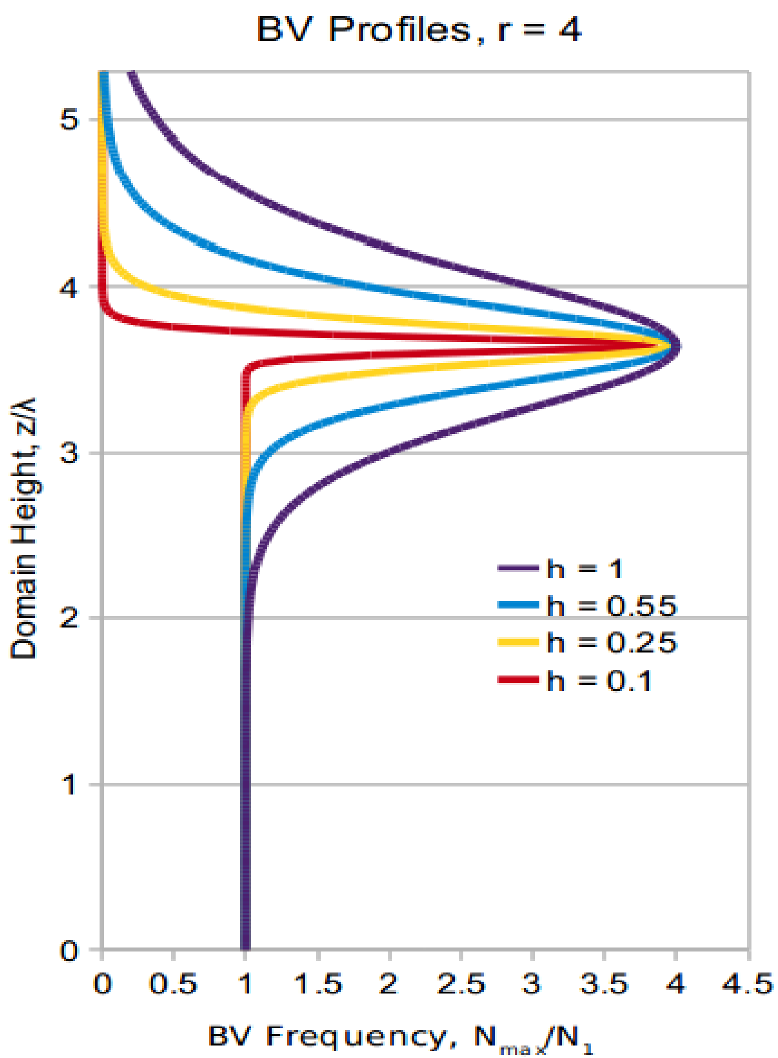
- At small r, results are comparable to laboratory findings

- At higher r, results differ from lab. Possibly due to experimental noise



Series 2 – Varying Pycnocline Thickness

4 Cases: h-values - 0.1 0.25 0.55 1



- Measure reflection coeff., R2, for **energy flux** and **ΔN^2**

- Explore qualitative beam structure inside pycnocline

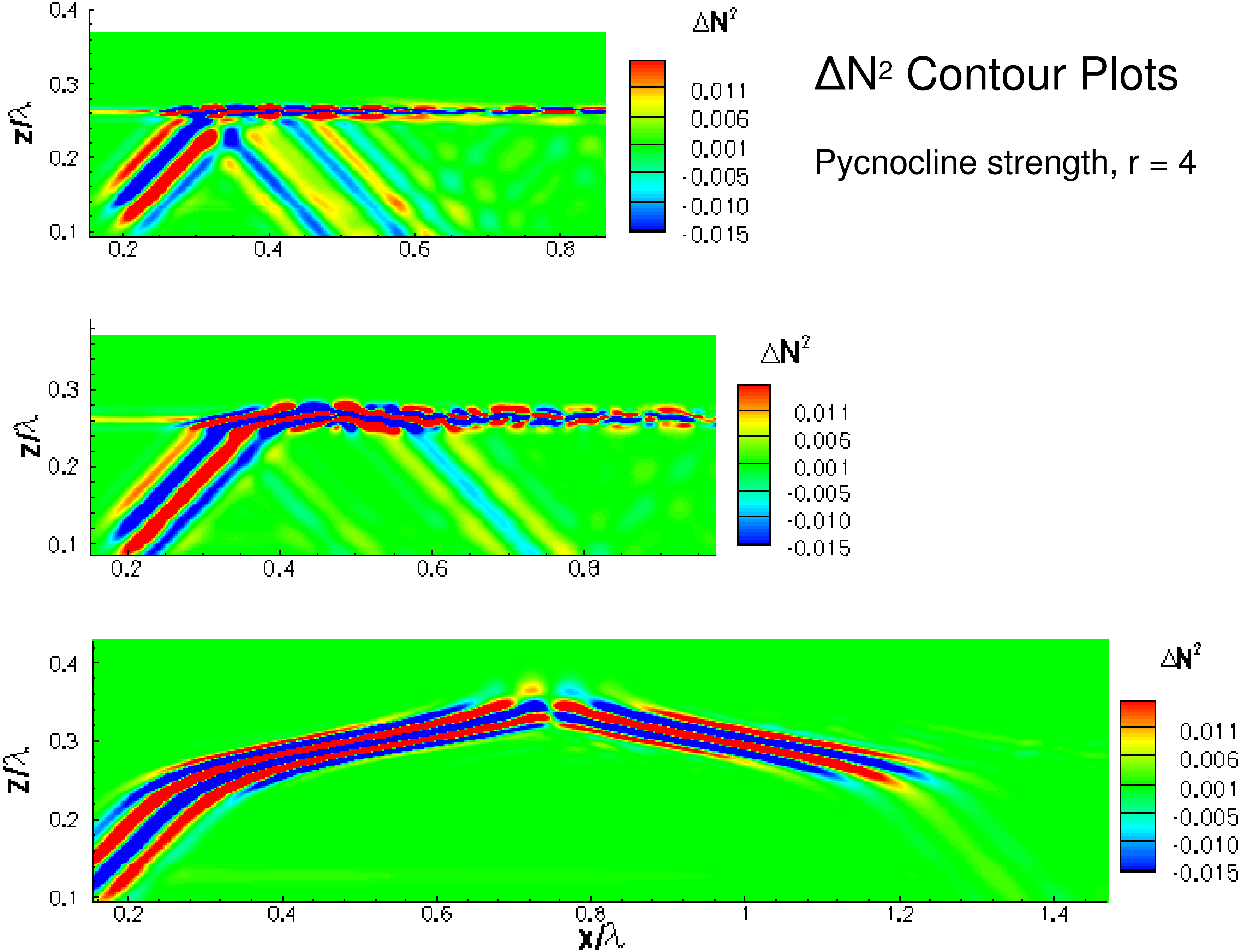
ΔN^2 Contour Plots

Pycnocline strength, r = 4

h = 0.1
t = 30*T

h = 0.25
t = 30*T

h = 1
t = 30*T



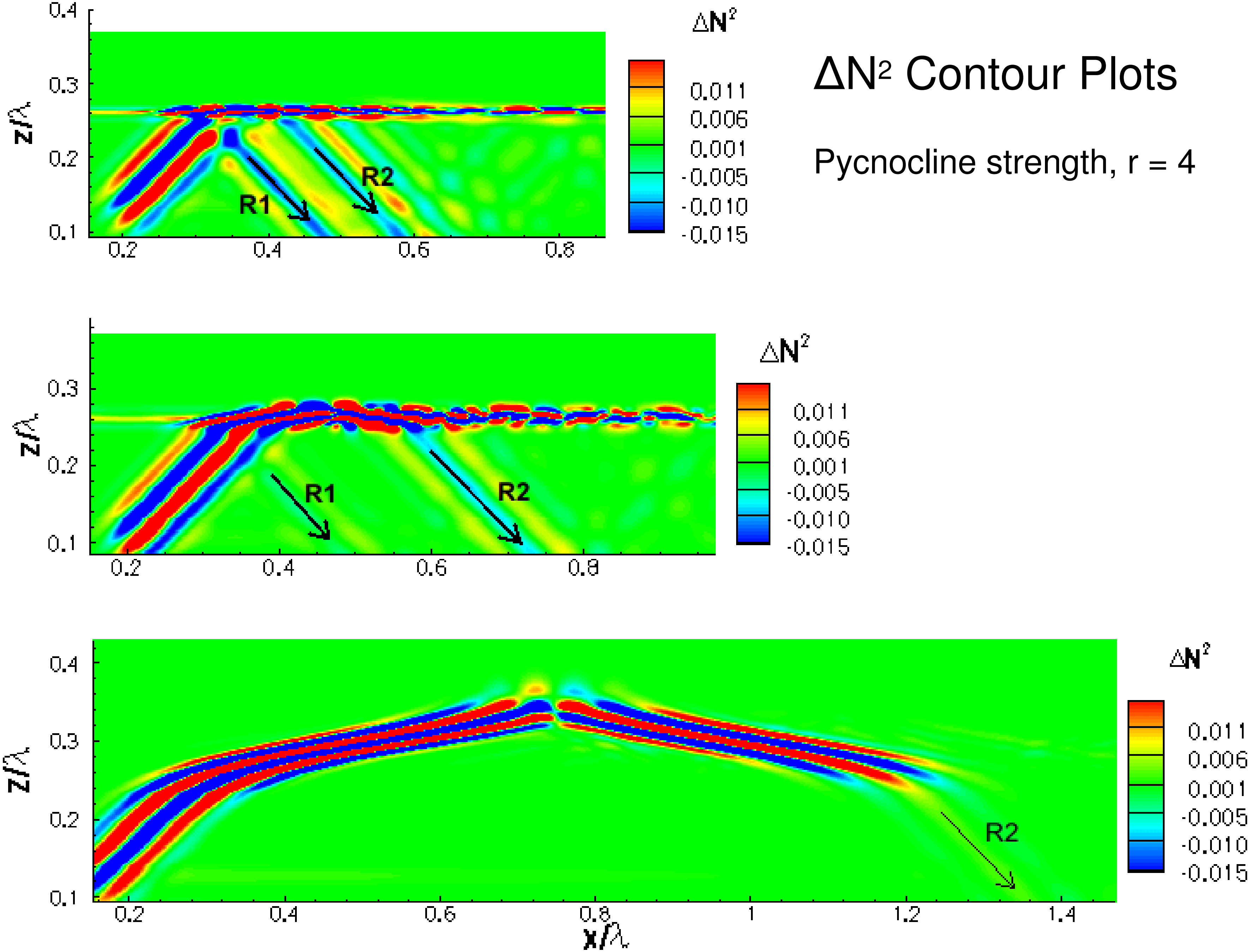
ΔN² Contour Plots

Pycnocline strength, r = 4

h = 0.1
t = 30*T

h = 0.25
t = 30*T

h = 1
t = 30*T



ΔN^2 Contour Plots

Pycnocline strength, r = 4

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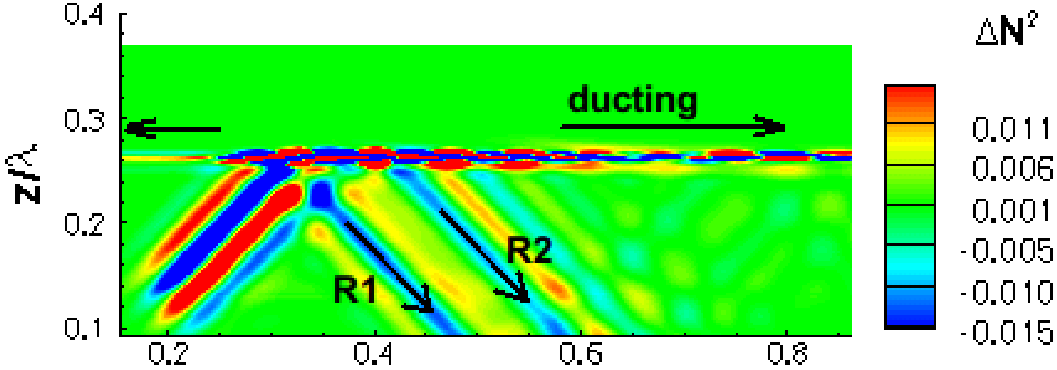
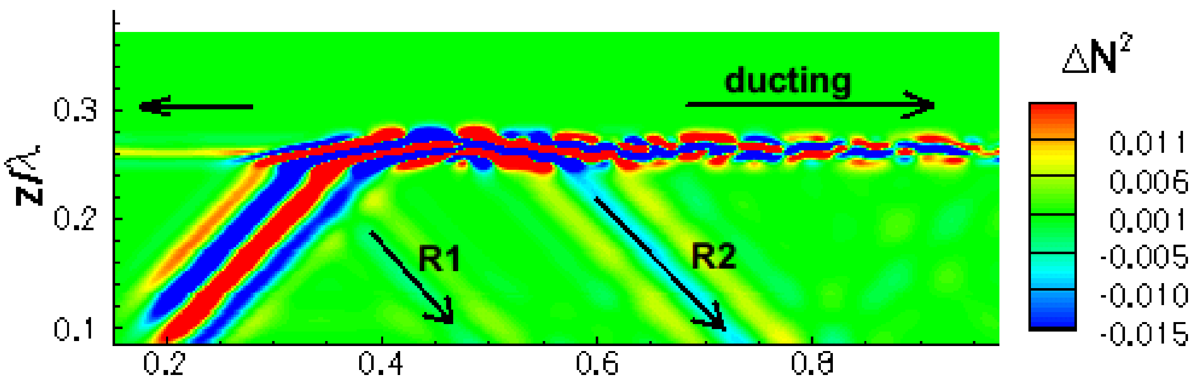


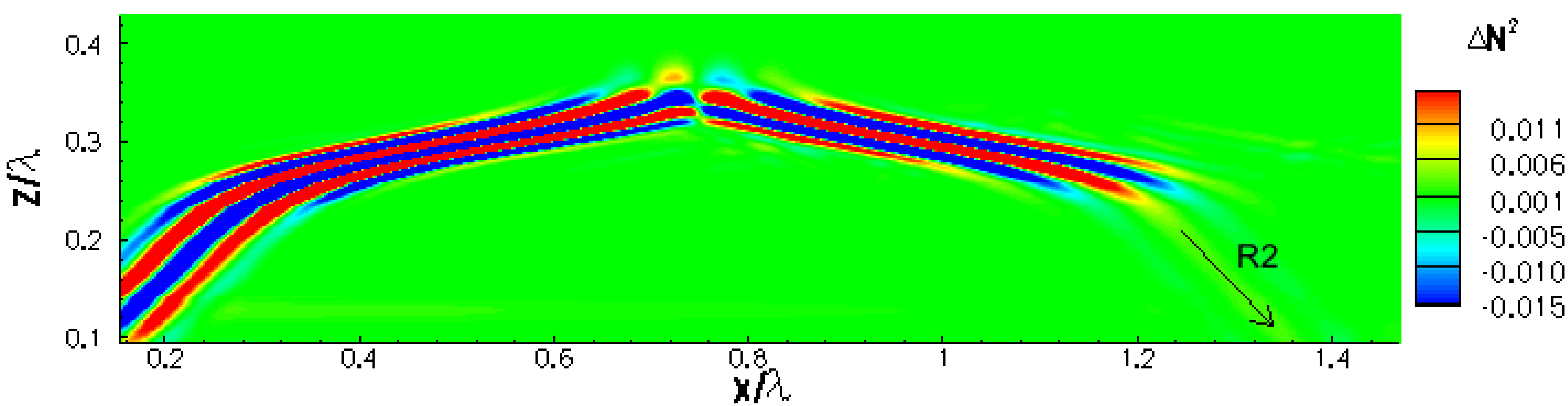
h = 0.25

t = 30*T

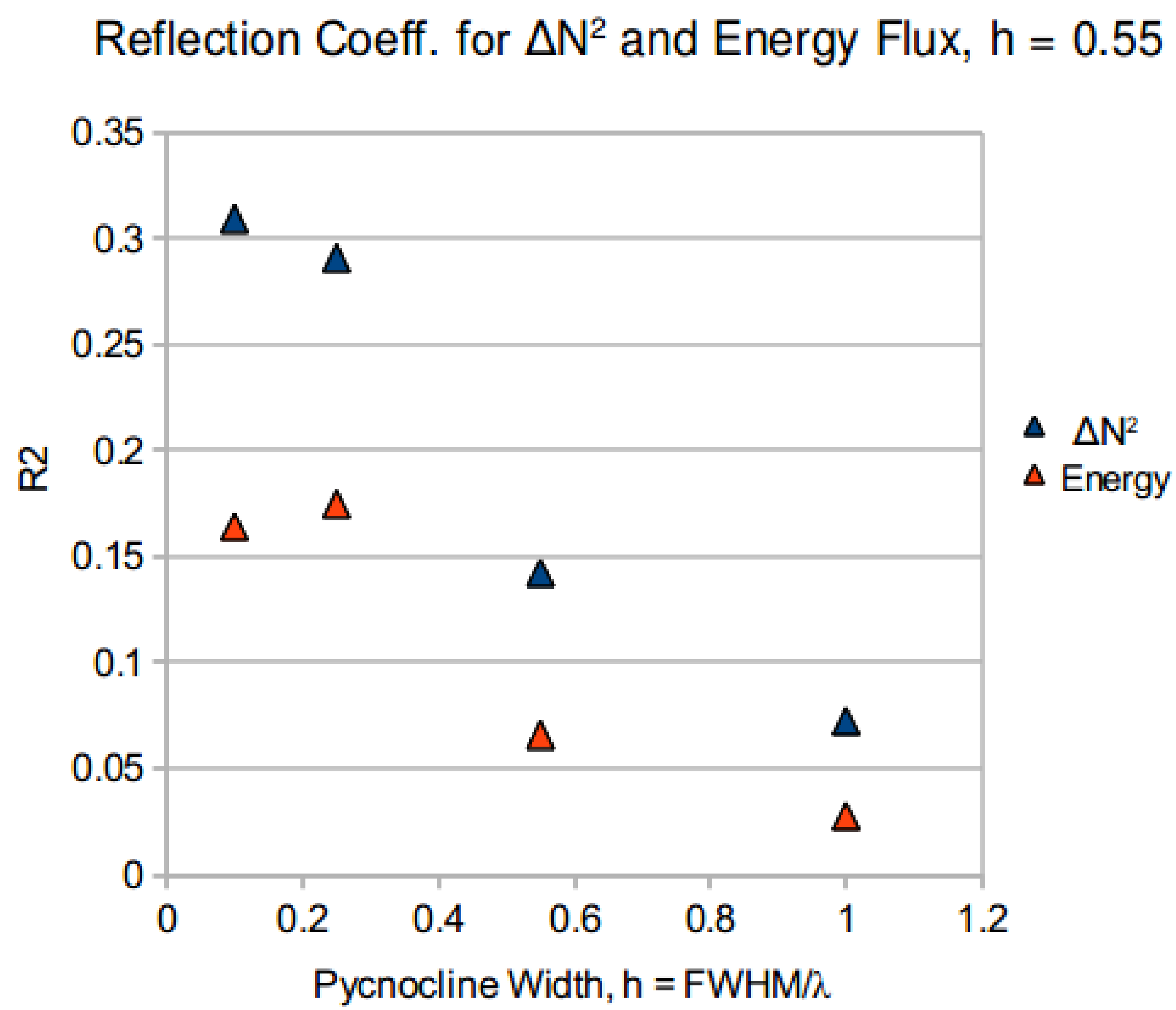


h = 1

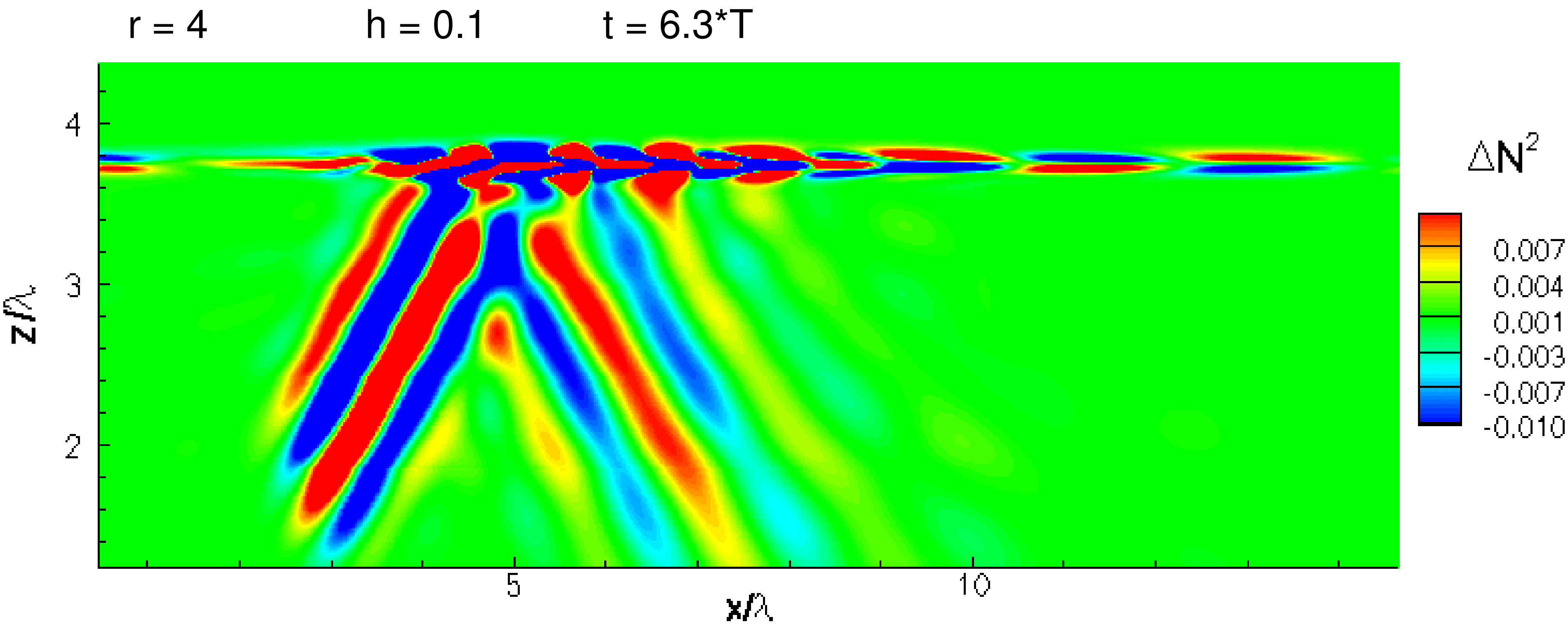
t = 30*T



Measured Reflection Coefficients



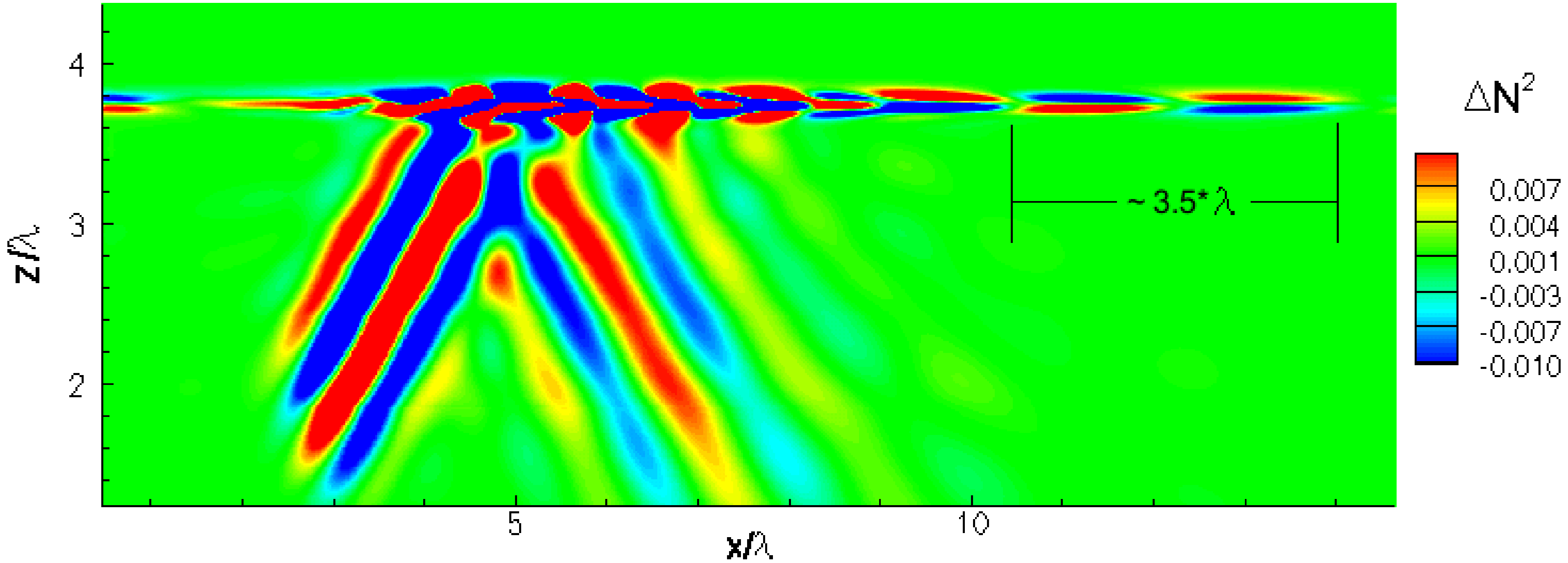
Curious Phenomena within Thin Pycnocline (h = 0.1)



Curious Phenomena within Thin Pycnocline (h = 0.1)

- Fast moving packets, large length scale

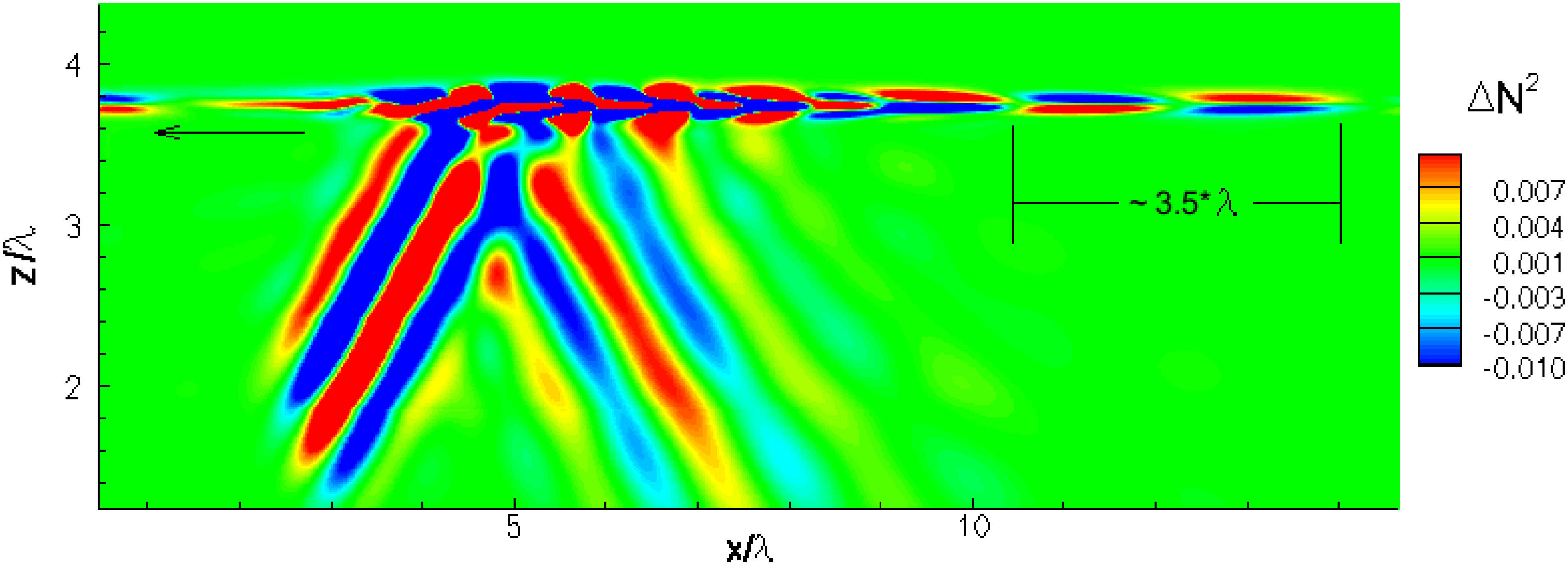
r = 4 h = 0.1 t = 6.3*T



Curious Phenomena within Thin Pycnocline (h = 0.1)

- Fast moving packets, large length scale
- Rearward modal structure

r = 4 h = 0.1 t = 6.3*T



Conclusions

- At a fixed pycnocline thickness, $h = 0.55$, reflection varies from strong reflection to full absorption from the range of $2 < r < 6$

- R2 decays to zero according to a power law

- Results differ from laboratory observations and from theory

- Variable pycnocline thickness reveals bidirectionally propagating vertical modal structure, and greater ducted energy

Next Steps

- Investigate wave decay inside pycnocline
    - Viscous dissipation?

- Investigate modal structure and quick beams in pycnocline

- Adjust transition length independently from pycnocline width
    - How does beam change as transition approaches a sharp gradient?

- Explore: High amplitude incident beams, shallow angle of incidence, high Reynolds number

- Model sub-critical shear flow inside pycnocline