Mesospheric bore evolution characteristics

Brian Laughman

NorthWest Research Assoicates

CEDAR Postdoc Report #2

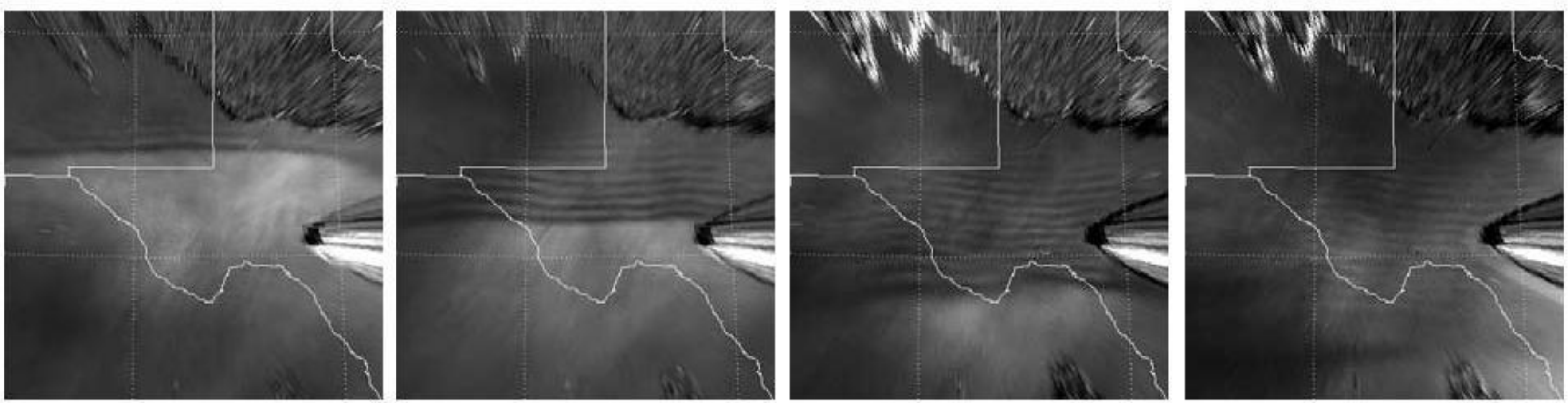
June 27th, 2012

Mesospheric Bore Evolution Characteristics

- What are Mesospheric Bores?
- Numerical Models
- BDO theory
- Results
  - Forcing dependence
  - Ducting environment dependence
- Conclusions

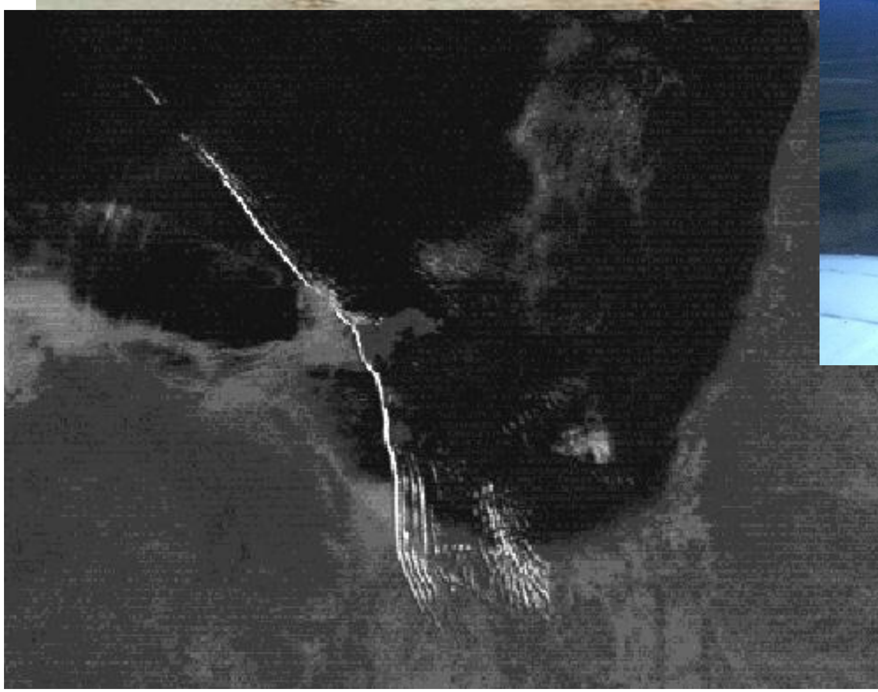
What are mesospheric bores?

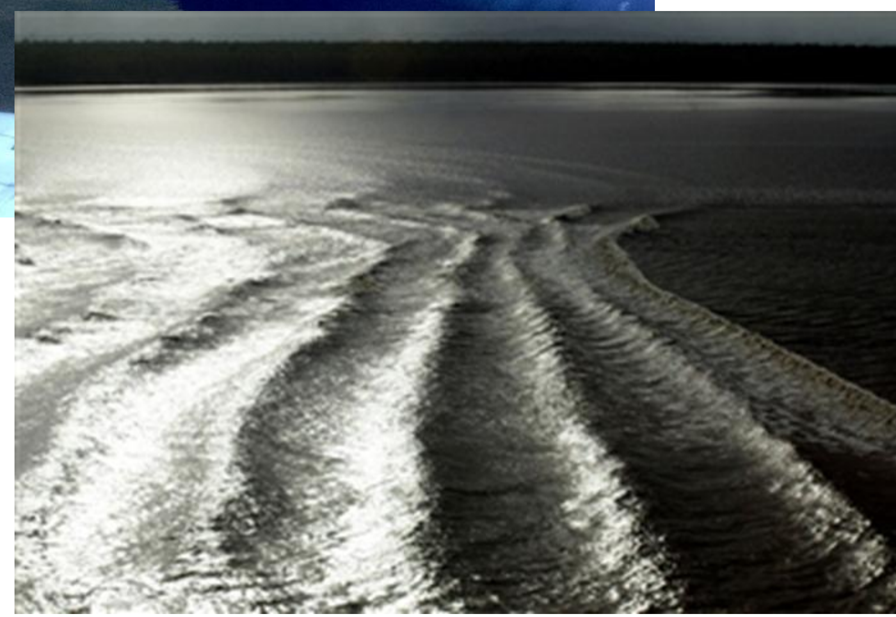
- Roughly 2D, weakly non-linear, ducted wave phenomenon
- Characterized by crest creation
- Observed at roughly 80 – 100 km
- Propagate at speed of ~ 75 m/s
- Length scales of ~ 20 km



4 time ordered images of a propagating bore courtesy of Steve Smith.
CSU lidar data shows a strong thermal inversion of 50 K between 85 and 90 km.

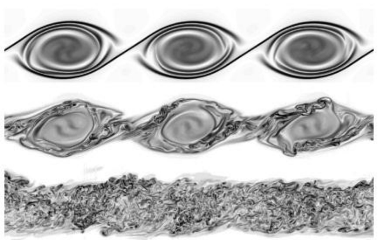
Other Bores





Navier-Stokes model

We numerically solve the Navier – Stokes equations

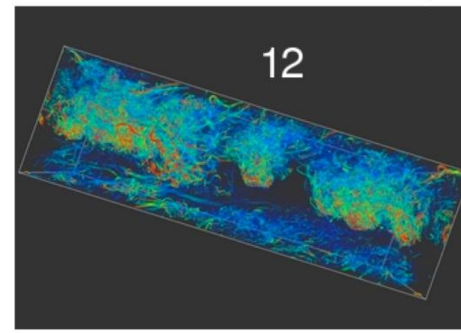


Momentum

Continuity

Heat Equation

Ideal Gas Law



- It is a DNS model – Direct Numerical Simulation
- It uses the Boussinesq Approximation – incompressible
- 2-D simulations evolve *potential temperature* and *vertical velocity*

BDO model : A useful approximation

The BDO equation makes two approximations.

1. Fairly-long wavelength → weak dispersion

$$c = c_0 (1 - \delta |k|)$$

2. Small-but-finite amplitude → weakly nonlinear effects:

- Steepening
- No breaking
- No recirculation

Evolves displacement:

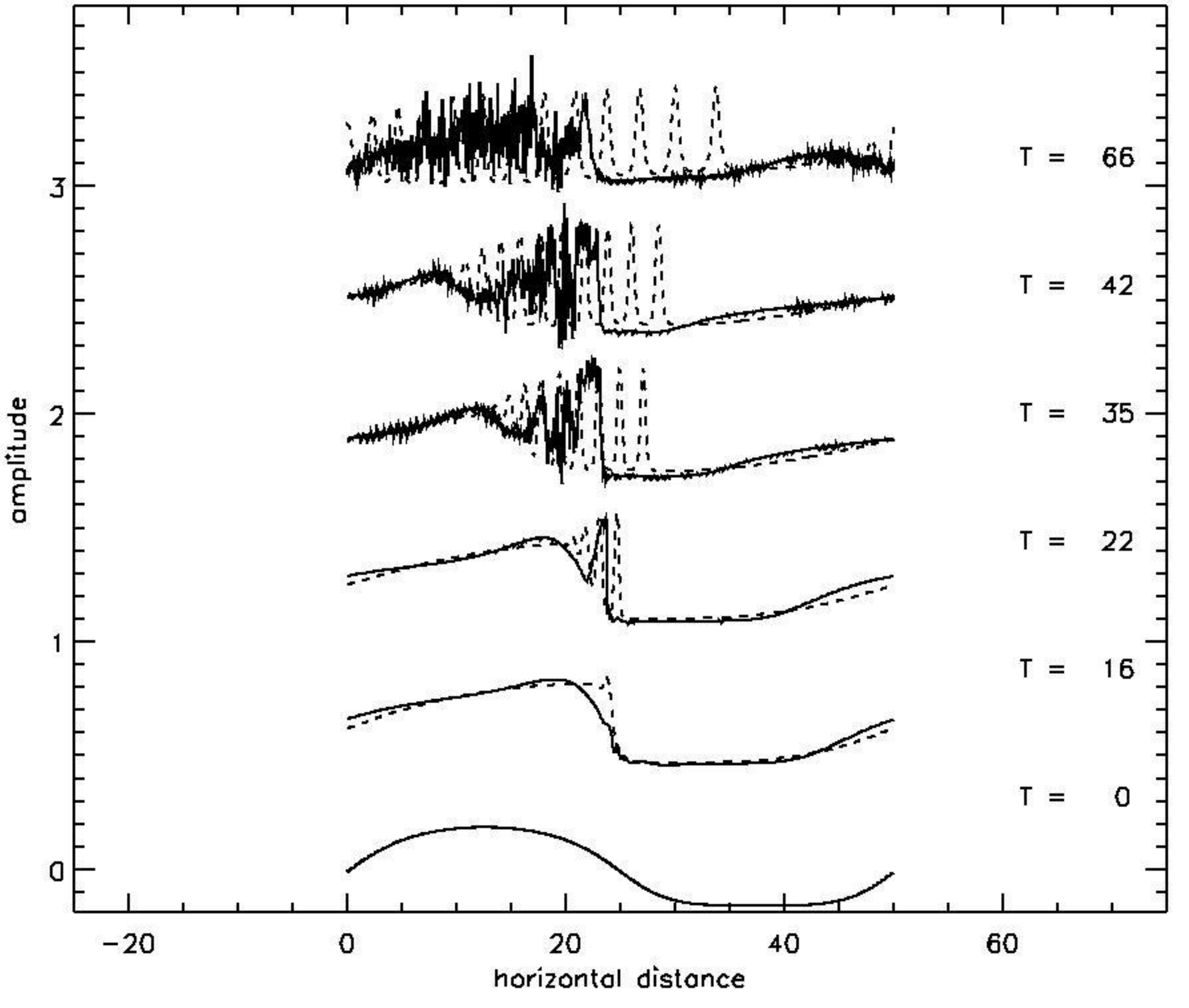
$$\eta(x,z,t) = A(x,t)\,\phi(z)$$

- Evolution equation ($A(x,t)$)
- Modal equation ($\phi(z)$)

Steady-state solution:

$$A(x,t) = \frac{a\lambda^2}{(x - c_b t)^2 + \lambda^2}, \qquad c_b = c_0 + \frac{\delta}{\lambda}, \qquad a\lambda = \frac{4\delta}{\alpha}$$

The BDO equation : large amplitude limit



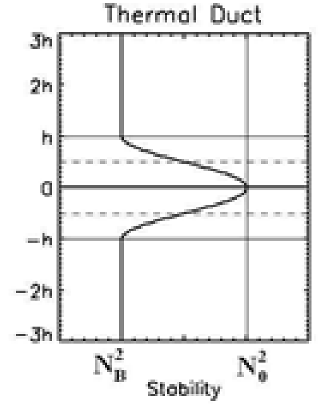
- BDO handles nonlinearity through crest creation
- NS model predicts breaking

Results

- Forcing geometry effects *(simple thermal duct)*

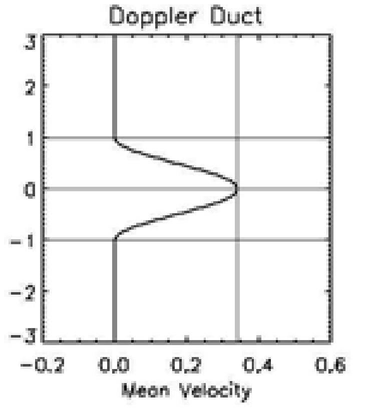
1. Wavelength effects
2. Amplitude effects

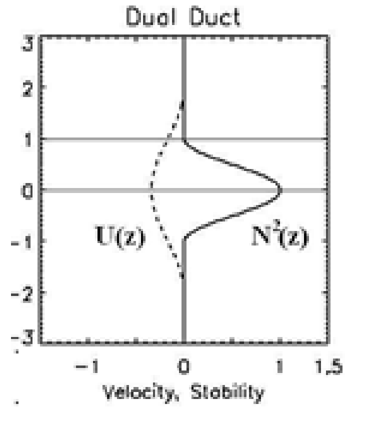
$$A(x,t_0) \sim \sin(\frac{2\pi}{\lambda_x} x)$$



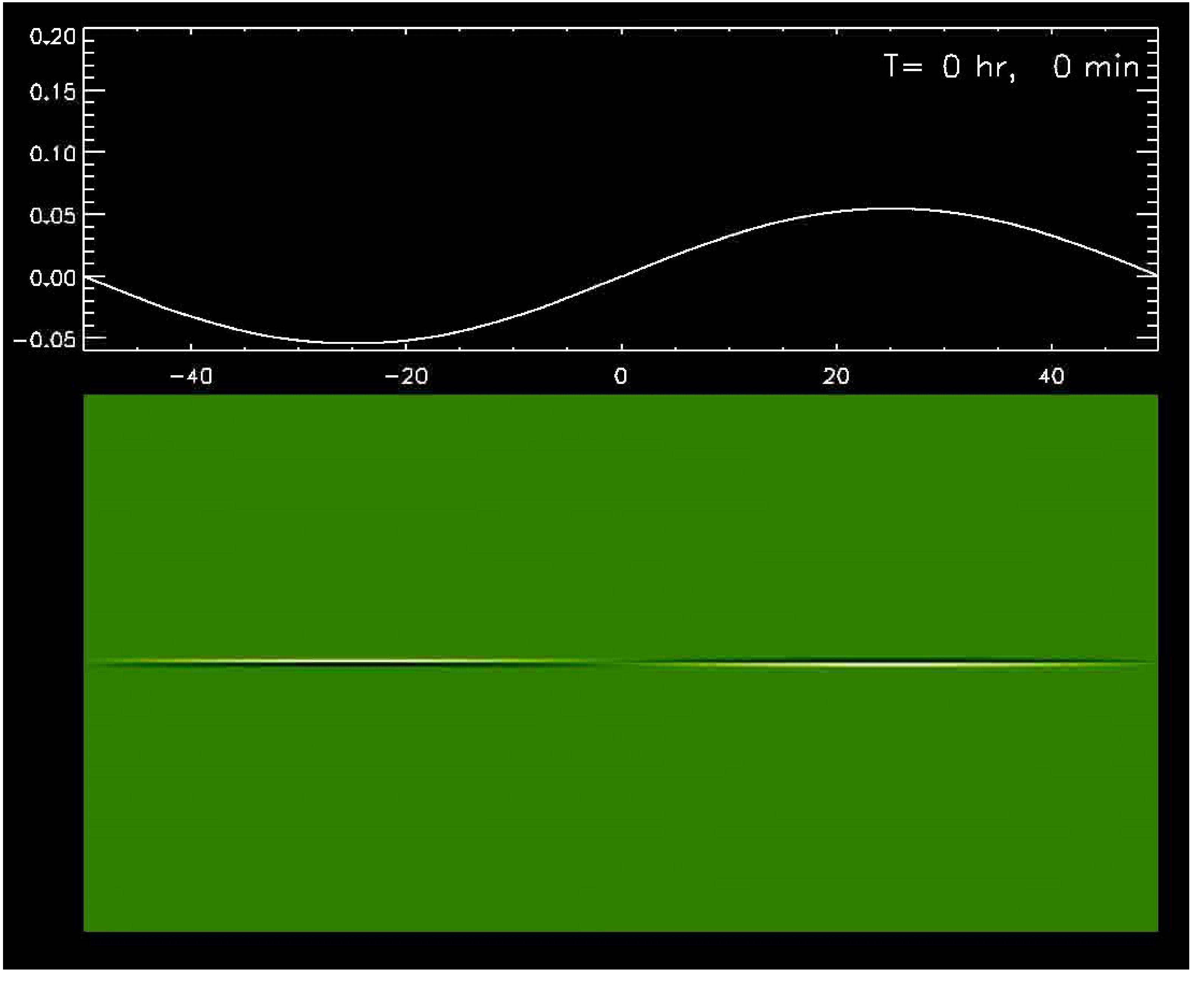
- Ducting environment effects

1. Duct shape (*cosine v. sech-squared*)
2. Duct thickness (*increased h*)
3. Viscous effects
4. Non-zero background stability
5. Isolated Doppler duct
6. Co-located ducts (*Headwinds/Tailwinds*)

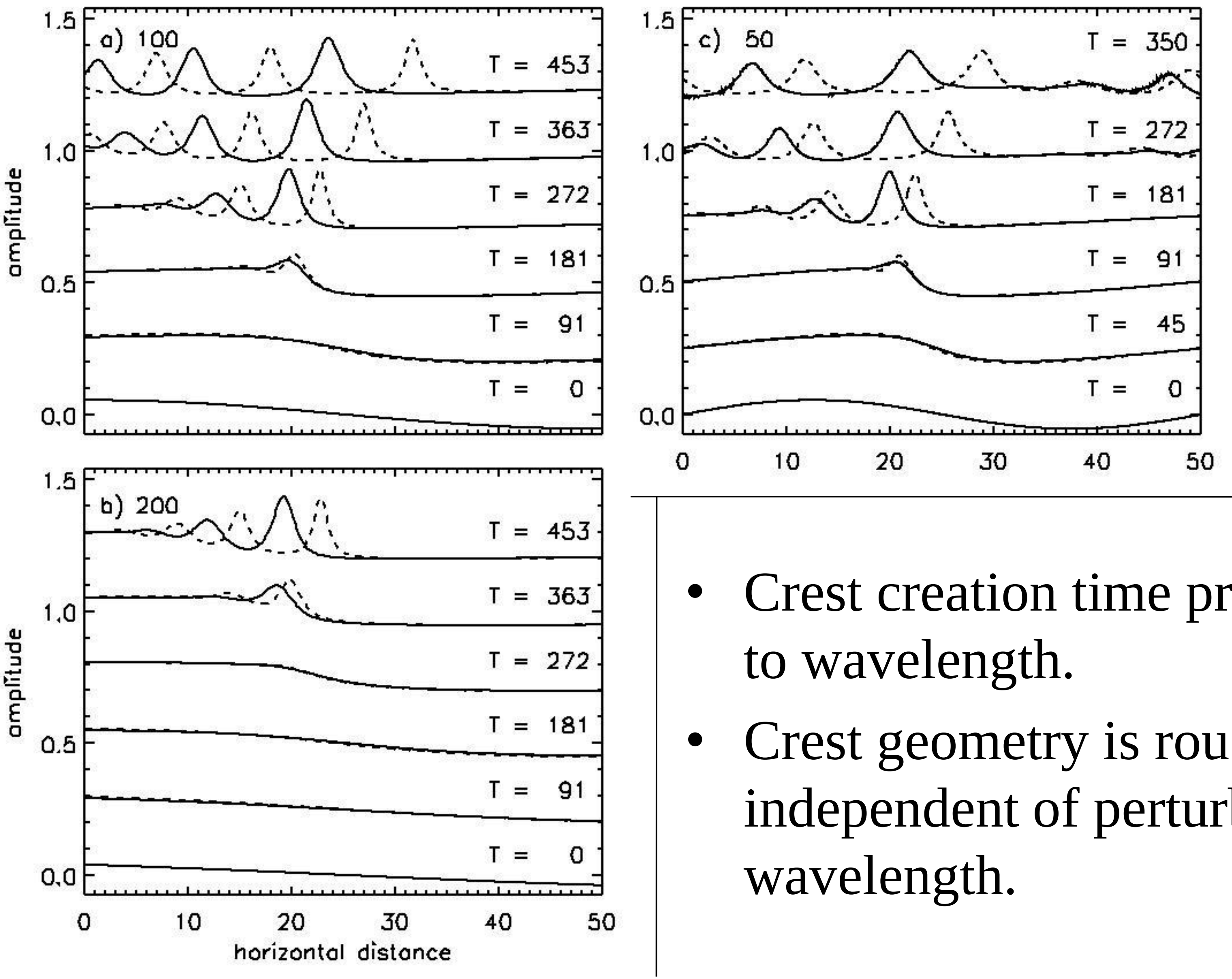




Results : Thermal duct, $\lambda = 100$, $\eta_0 = 0.1$, $\nu = 0$

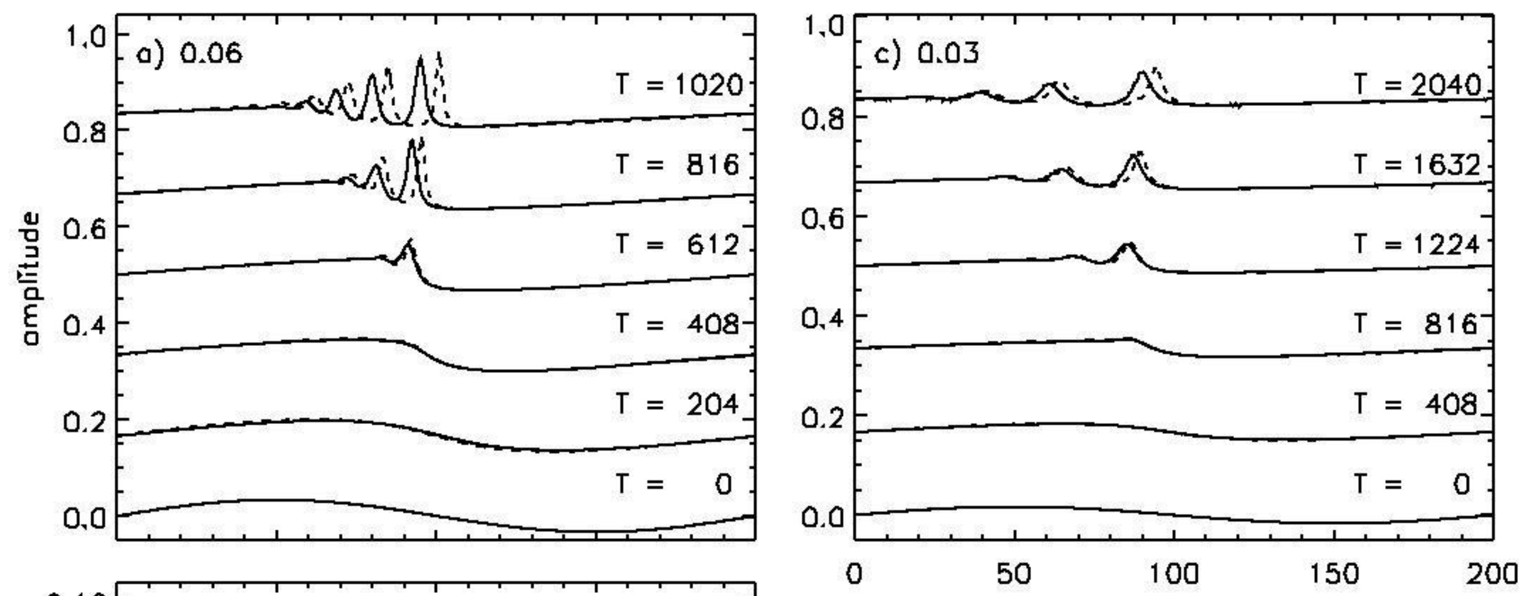


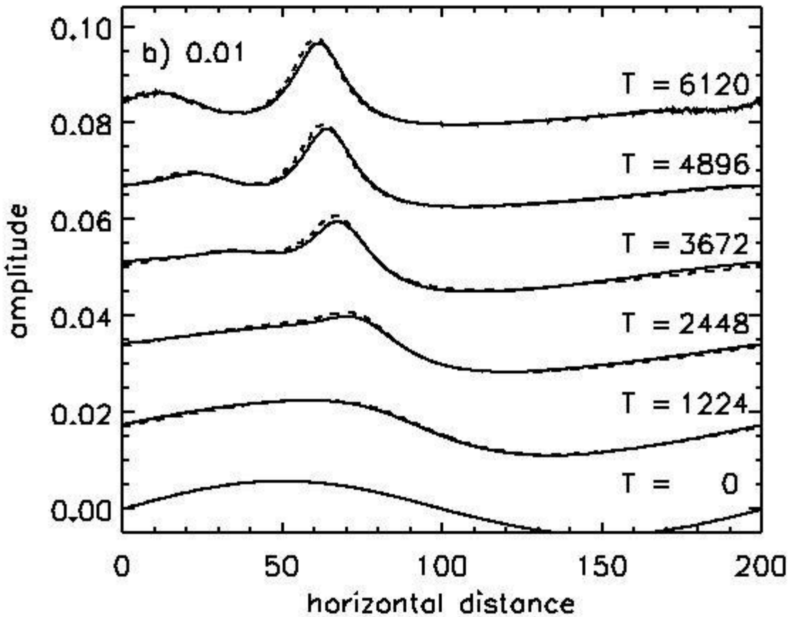
Results : Sine wave, wavelength variation



- Crest creation time proportional to wavelength.
- Crest geometry is roughly independent of perturbation wavelength.

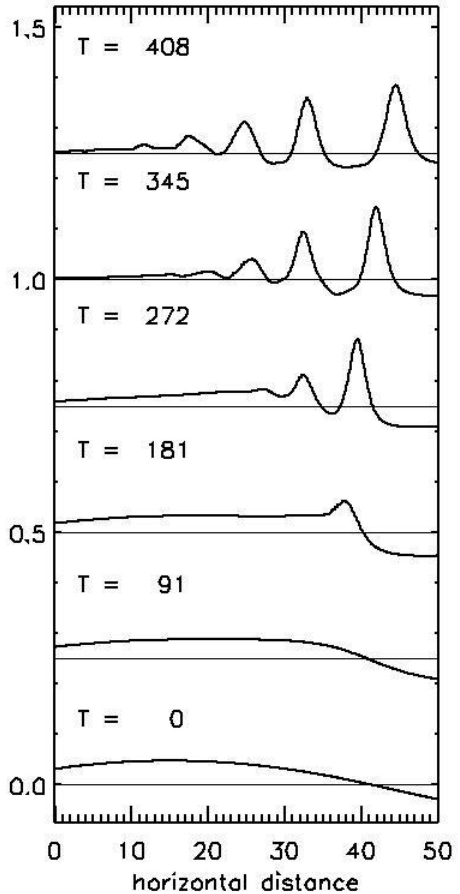
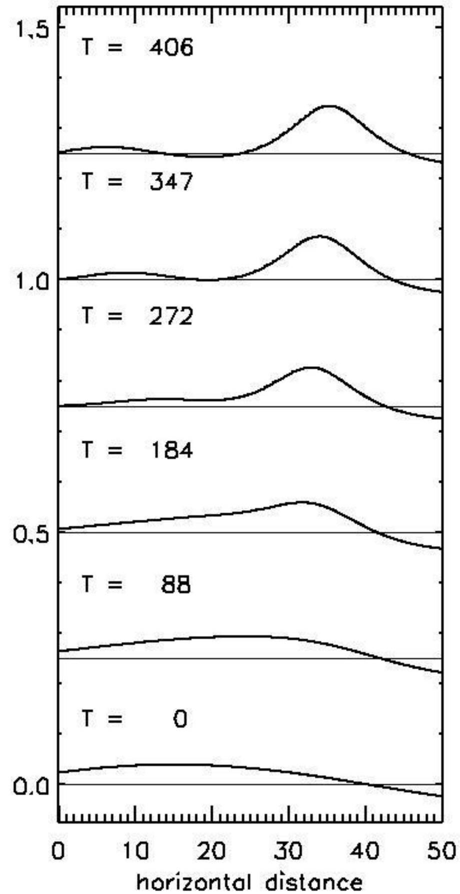
Results : Sine wave, amplitude variation

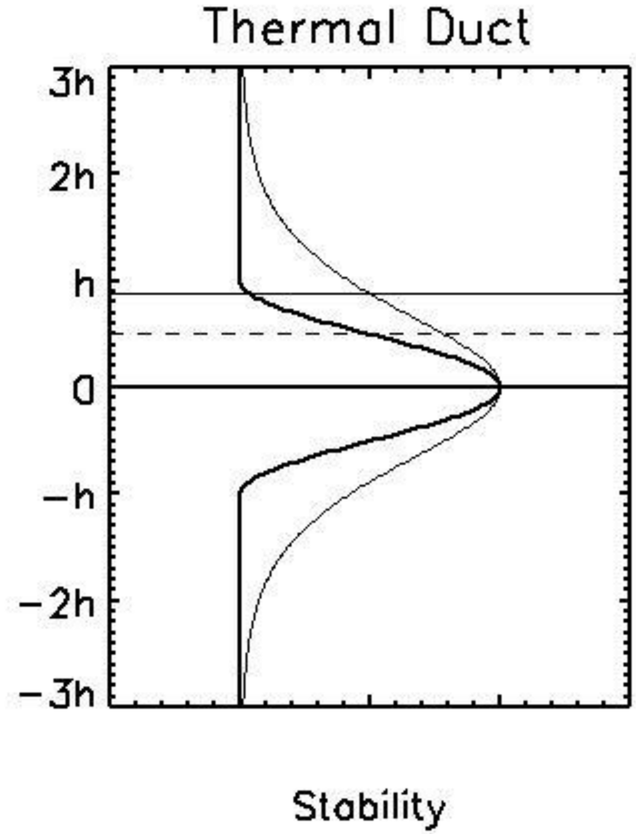




- Crest creation time inversely proportional to amplitude.
- Crest geometry is a function of perturbation amplitude.
- NS/BDO agreement improves for smaller amplitudes.

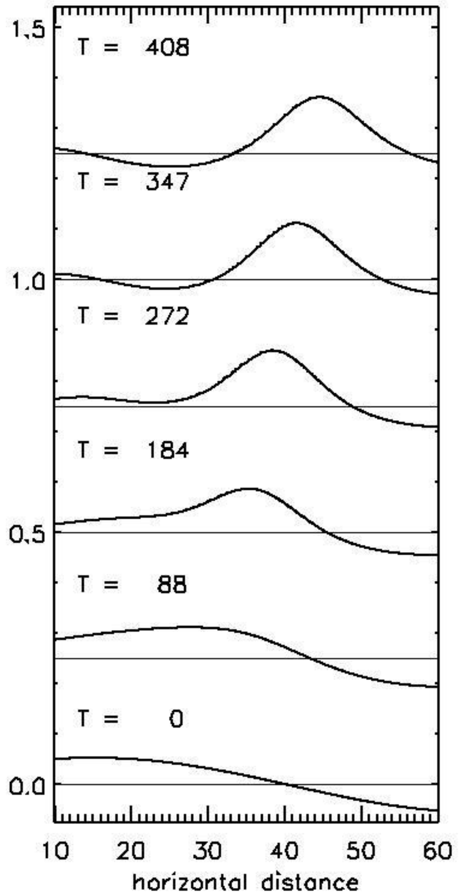
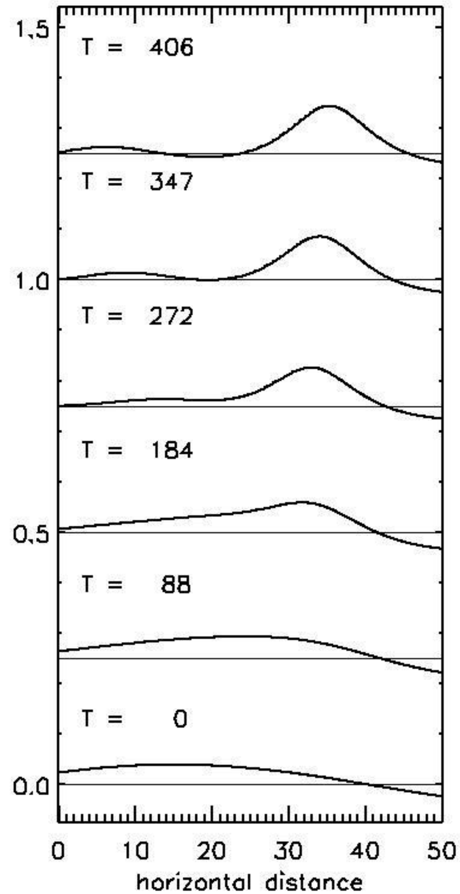
Results : Duct shape

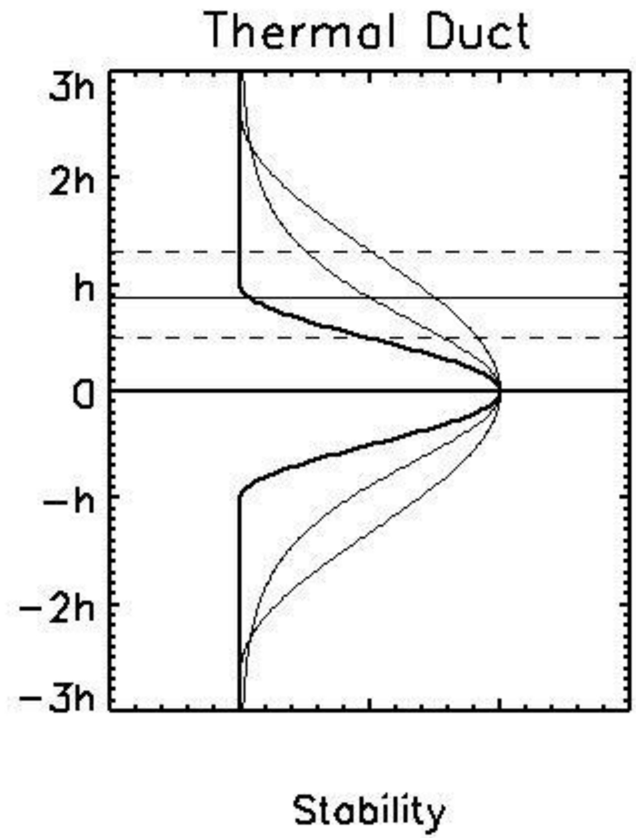
$\sim N_0^2 \cos(\pi z / h)$	$\sim N_0^2 \operatorname{sech}^2 (z/h)$
	
$\alpha \sim 1.03 \quad \delta \sim 0.093$ $c_0 \sim 0.33$	$\alpha \sim 0.84 \quad \delta \sim 0.53$ $c_0 \sim 0.70$



$$a\lambda = \frac{4\delta}{\alpha}$$

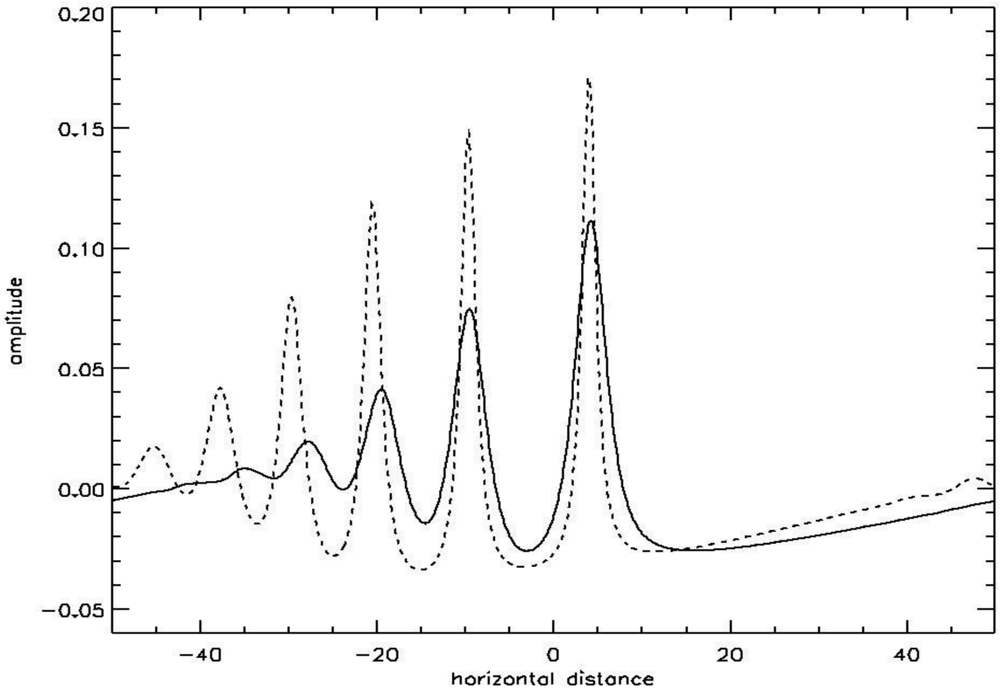
Results : Duct thickness

$\sim N_0^2 \cos(\pi z/h)$	$\sim N_0^2 \operatorname{sech}^2(z/h)$
	
$\alpha \sim 1.03 \quad \delta \sim 0.648$ $c_0 \sim 0.885$	$\alpha \sim 0.84 \quad \delta \sim 0.53$ $c_0 \sim 0.70$



$$a\lambda = \frac{4\delta}{\alpha}$$

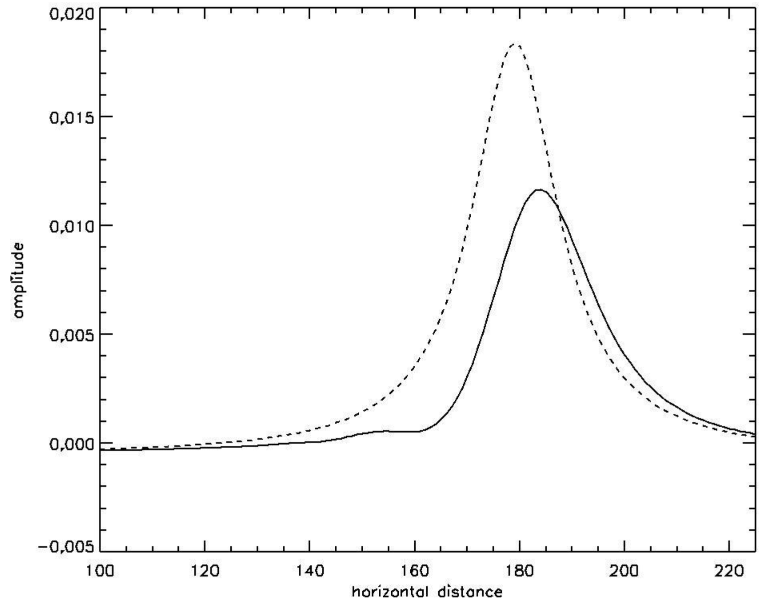
Results: Viscosity = 100 m^2/s



T = 453 ~ 2 hrs, 24 min

$\lambda = 100$

$\eta_0 = 0.1$

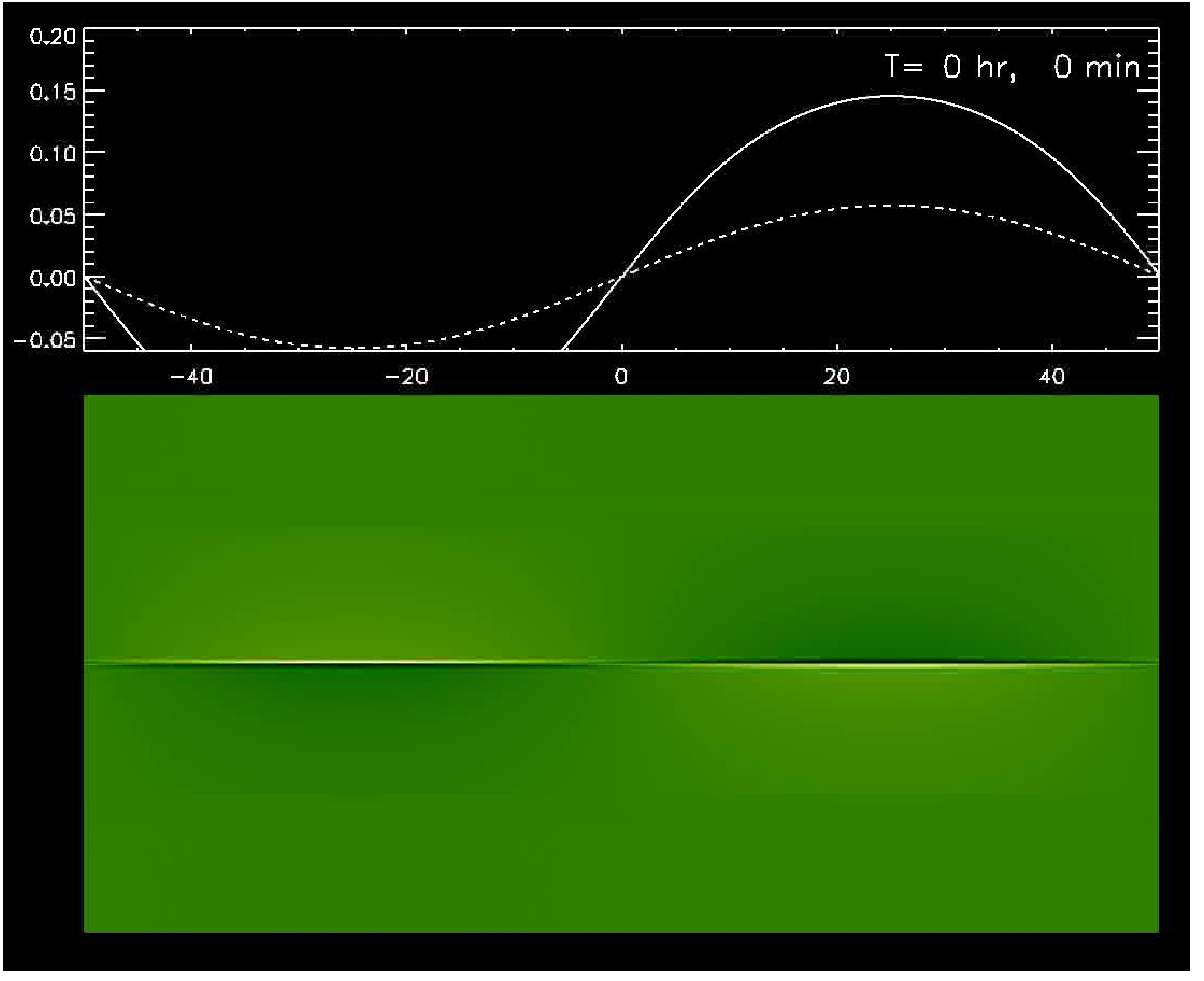


T = 517 ~ 2 hrs, 44 min

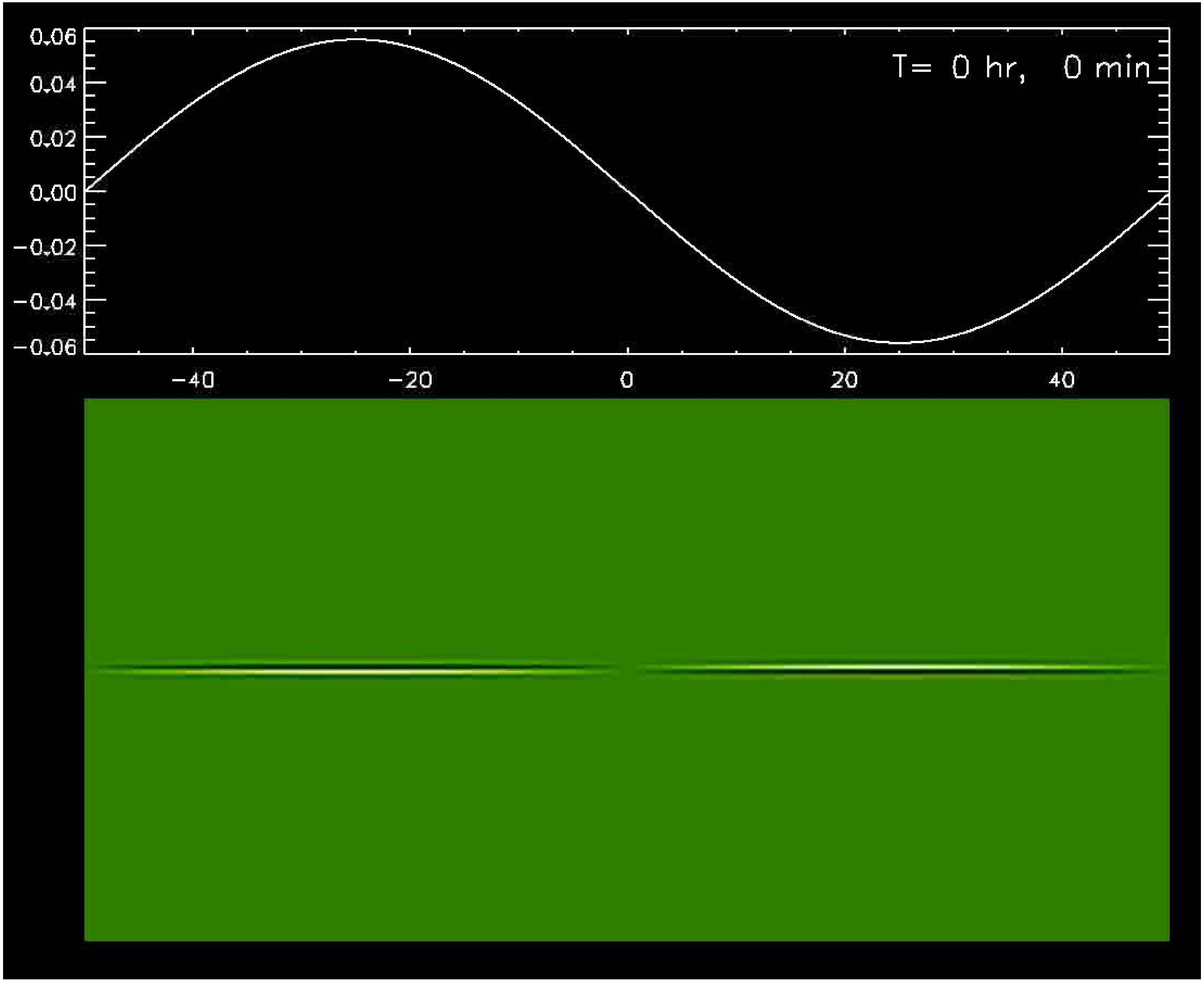
$\lambda = 10$

- Viscosity has the anticipated effect of reducing amplitude
- Viscosity has the unanticipated effect of advancing the leading peaks

Results : Non-zero background stability, ν = 100 m^2/s



Results : Velocity Duct (high viscosity)

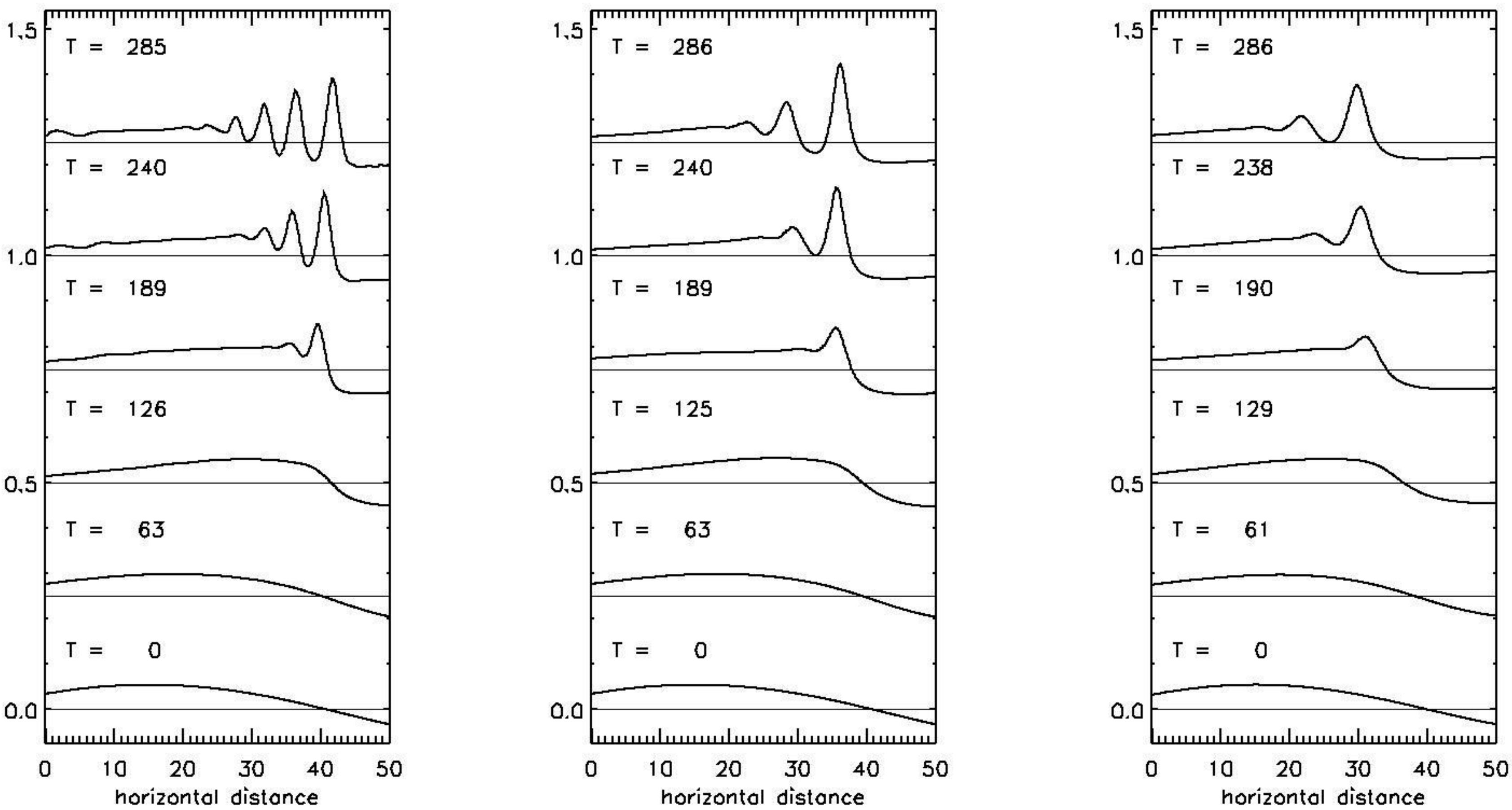


Results : Headwind

Co-located thermal and doppler duct

$$l_s^2 = \frac{N^2(z)}{(U(z)-c)^2} - \frac{\partial_{zz}U(z)}{(u_0-c)}$$

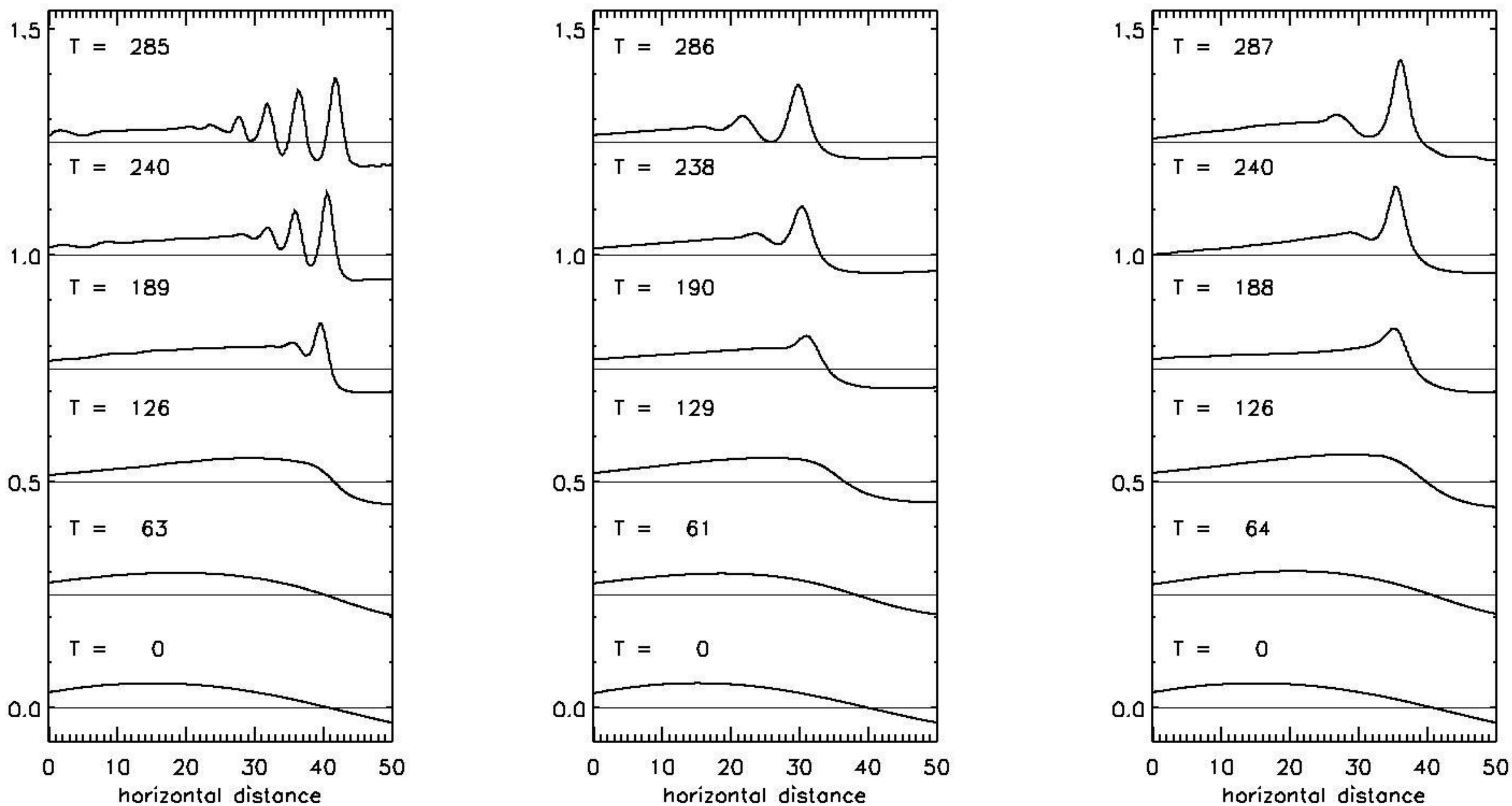
$\sim -U_0 \cos(\pi z/2)$ $\sim -U_0 \cos(\pi z/10)$



Results : Tailwind

Co-located thermal and doppler duct

$$\sim -U_0 \cos(\pi z / 2) \qquad\qquad \sim U_0 \cos(\pi z / 2)$$



Conclusions

- Bore evolution dependence on imposed forcing
- Bore evolution dependence on ducting environment

Future Work

- Ultimately, extension to 3D, breaking bores, turbulence
- Temporally varying ducts
- Add complexity to BDO
- Pose more realistic forcings