Modeling of Gravity Wave and Instability Processes in the Middle Atmosphere

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Outline

1. Motivations for MA Instability Studies
2. Model Formulation
3. Instability due to Wave Breaking
4. Kelvin-Helmholtz Instability
5. Conclusions

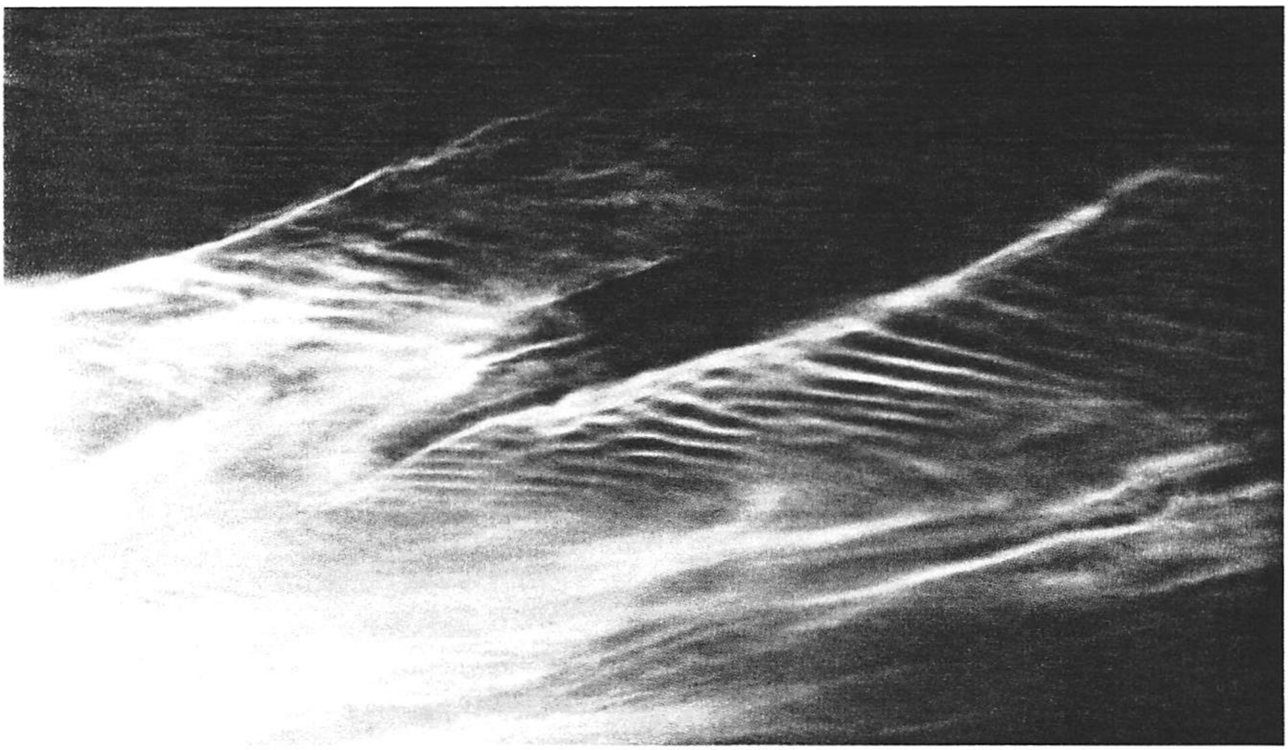
Modeling Motivations

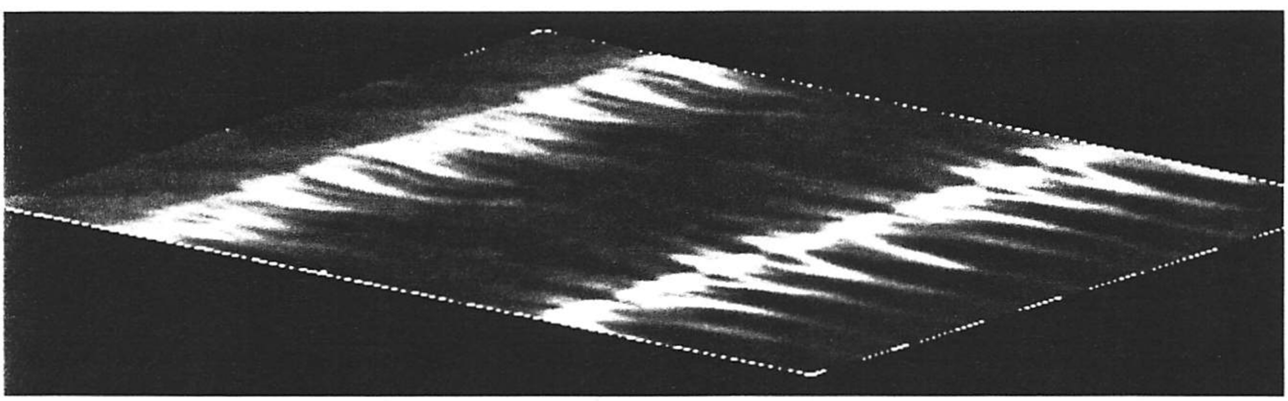
- **Wave transports of energy and momentum are central to our understanding of middle atmosphere dynamics**

- **Wave interaction and instability processes account for wave saturation, spectral character, and constraints on energy and momentum fluxes**

- **Dynamics of transition from laminar to turbulent flow dictates character of turbulence, efficiency of mixing and transports**

Geophysical Research Letters





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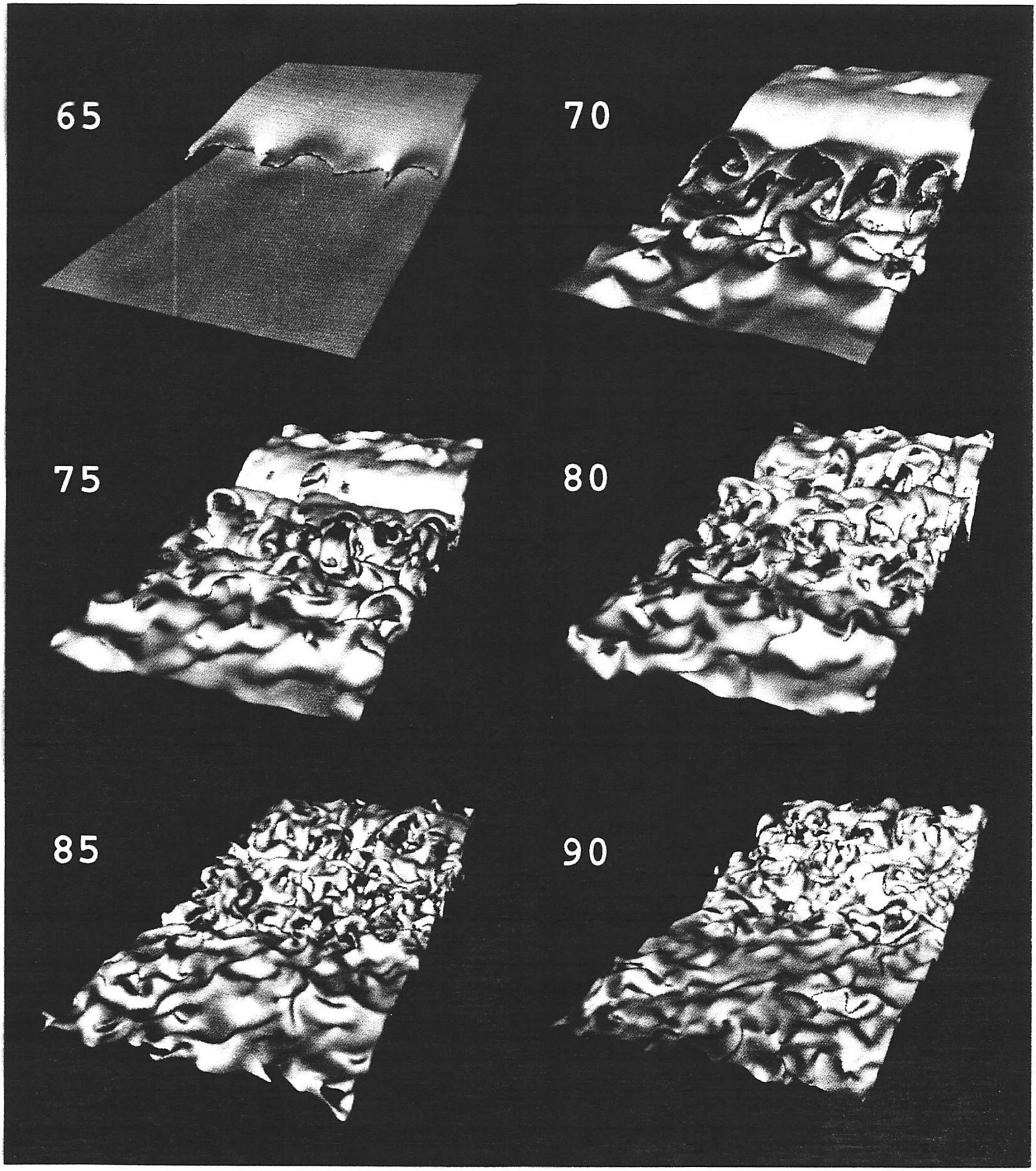
Model Formulation

- **Solves Euler equations with spectral viscosity**
- **Employs spectral collocation techniques**
  - **Fourier in x , y**
  - **Chebyshev in z**
- **Uses domain docomposition for higher resolution, greater efficiency**
  - **wave breaking using two domains**
    - **forcing in low-resolution lower domain (96, 48, 65)**
    - **instability in high-resol. upper domain (192, 96, 129)**
  - **Kelvin-Helmholtz instability using four domains**
    - **Re = 200 to 2000**
- **2D initial evolution, 3D instability evolution following noise insertion at finite amplitude**
- **Boundary and interface conditions**
  - **periodic in x , y**
  - **open in z, using upstream characteristics**

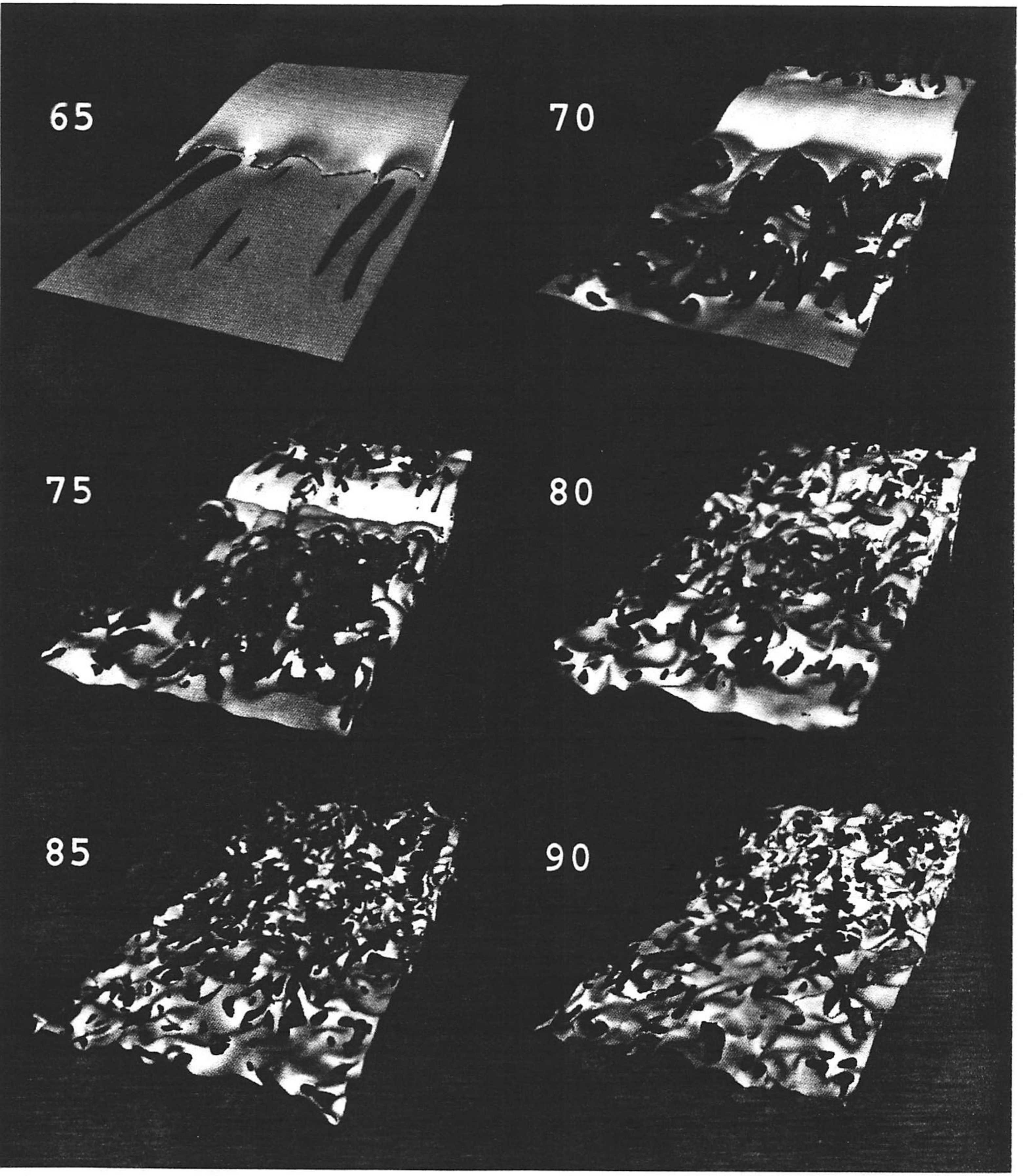
Wave Breaking Simulations

- **high-frequency wave in a shear flow**
  - ~ 30 min period
  - ~ 24 km wavelength
  - ~ 1 km instability depth

- **wave field evolution**
  - initial instability is convective, streamwise
  - secondary instability is dynamical, spanwise and localized (3D KH)
  - evolution is rapid and transient, collapse to turbulence ~ 1 T_b



Wave breaking shown with isosurface of Θ



wave breaking with isosurface of θ
and of positive (red) and negative (blue)
streamwise vorticity

Eddy Kinetic Energy Equation

$$\left(\frac{\partial}{\partial t} + \hat{\mathbf{u}} \cdot \nabla\right) K_e + \frac{\partial}{\partial x}\langle p'u'\rangle + \frac{\partial}{\partial z}\langle p'w'\rangle$$

$$\approx -\hat{\rho}\langle u'u_i'\rangle \frac{\partial}{\partial x}\tilde{u}_i - \hat{\rho}\langle u_i'w'\rangle \frac{\partial}{\partial z}\hat{u}_i + \frac{\hat{\rho}g}{\hat{\theta}}\langle \theta'w'\rangle$$

Vorticity Equation

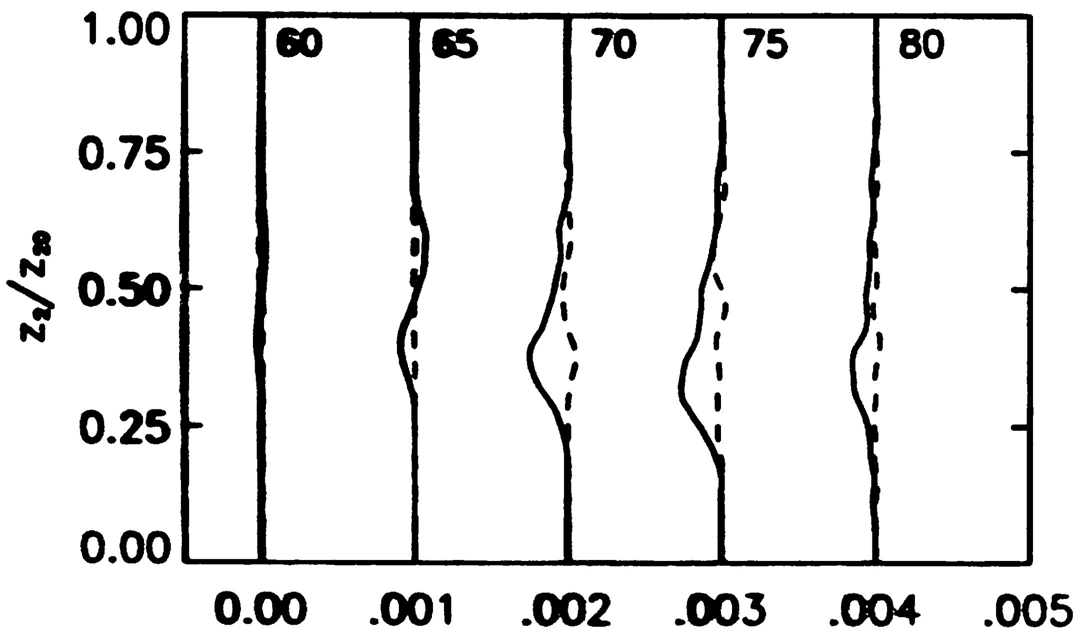
$$\frac{d\omega_i}{dt} \approx \omega_j S_{ij} + \left\{\frac{\nabla\rho}{\rho} \times \frac{\nabla p}{\rho}\right\}_i$$

where

$$S_{ij} = \frac{1}{2}(\partial_i v_j + \partial_j v_i)$$

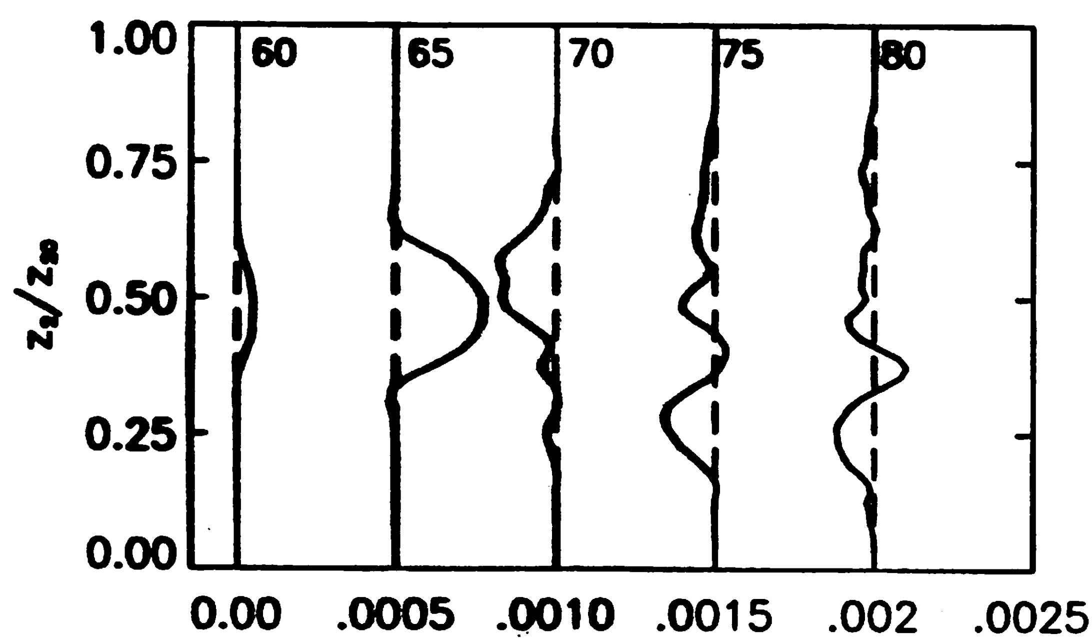
eddy momentum fluxes (domain averaged)

$\overline{u'w'}$ —— $\overline{v'w'}$ - - -



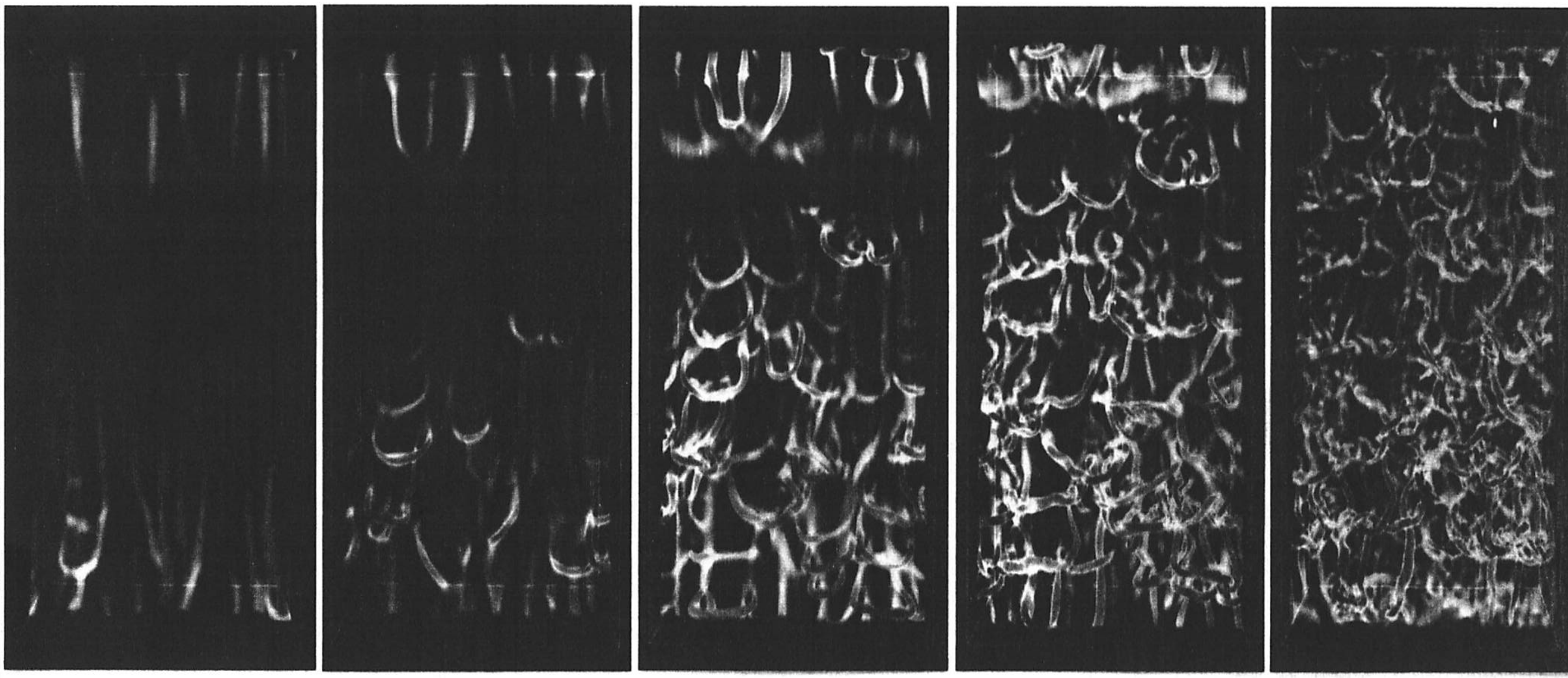
eddy heat fluxes (domain averaged)

$\overline{\theta'w'}$

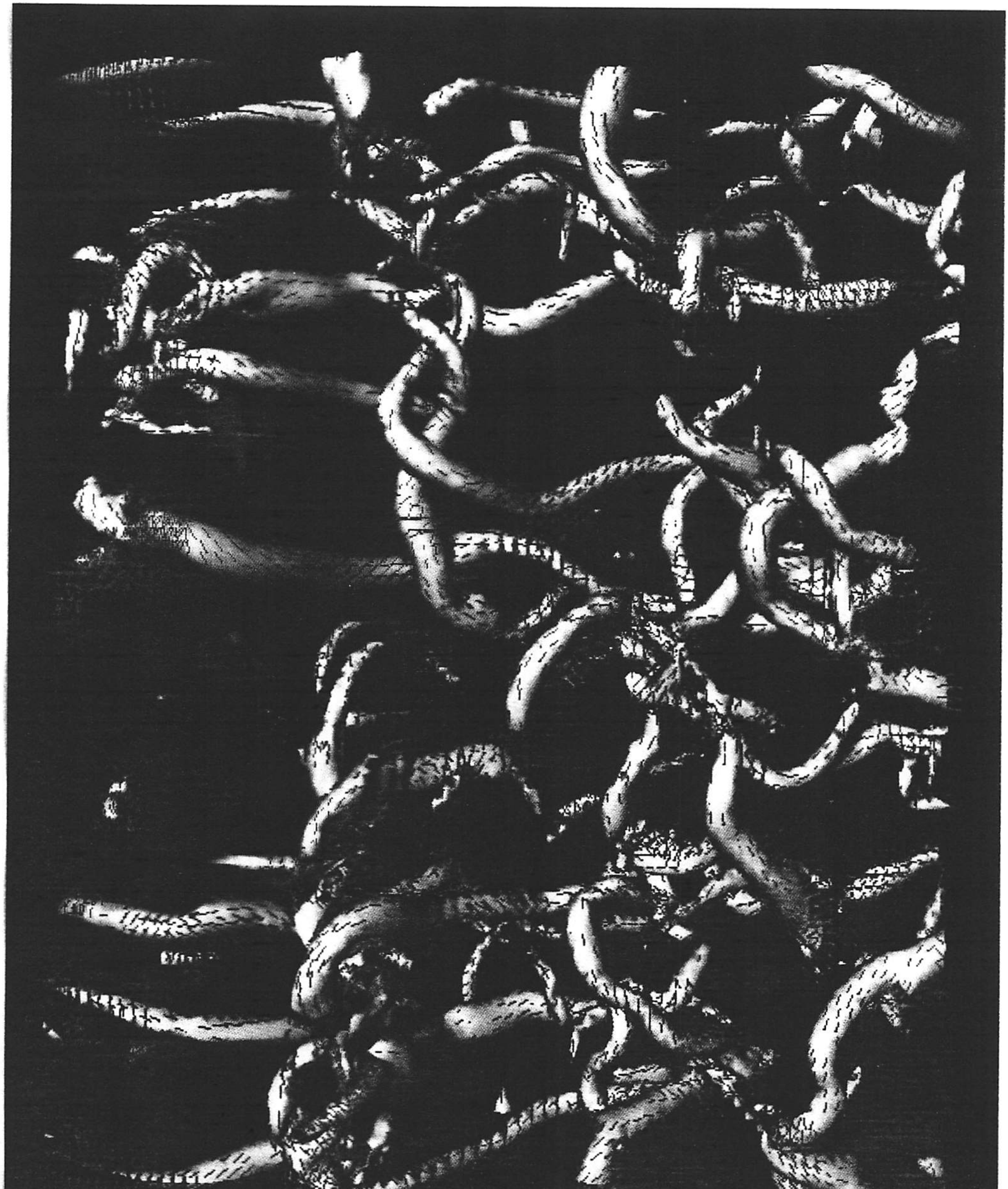


Modeling of Breaking Gravity Wave

- Vortices rendered by $\lambda_2 < 0$ of $S^2 + R^2$, viewed from below



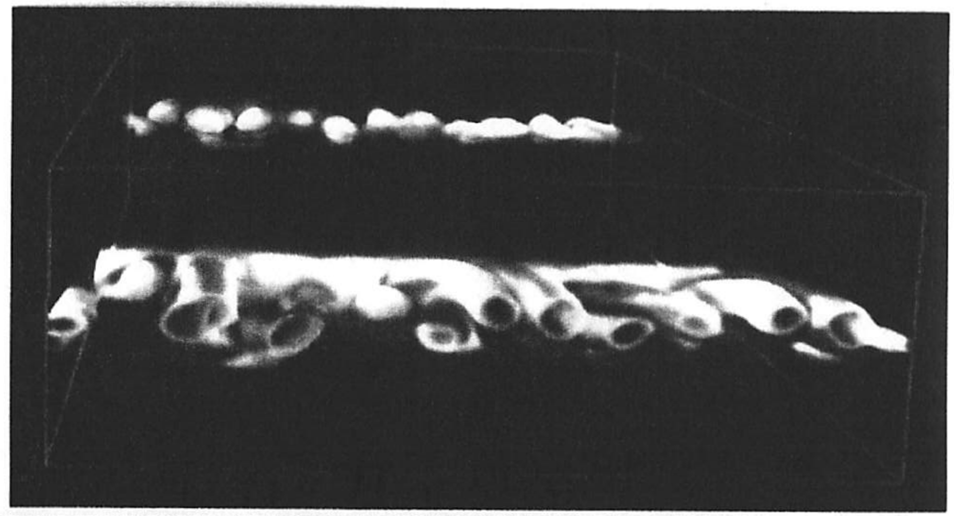
t = 65.1 67.5 70.0 72.5 75.0



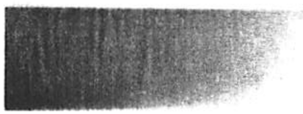
z = 75

x
y

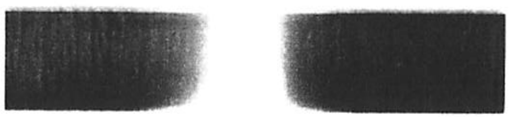
Baroclinic generation of vortices at t=62.5

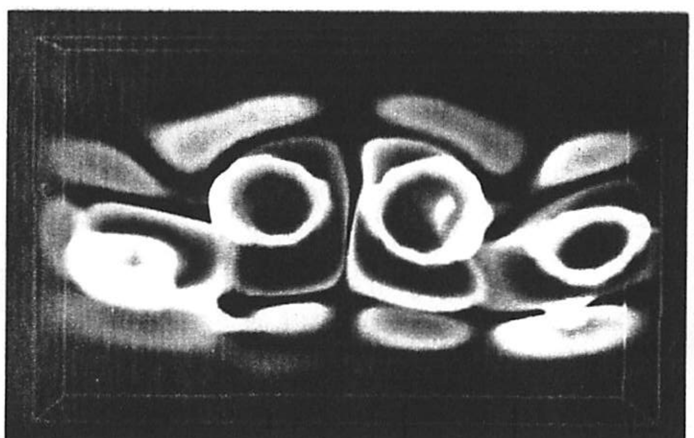


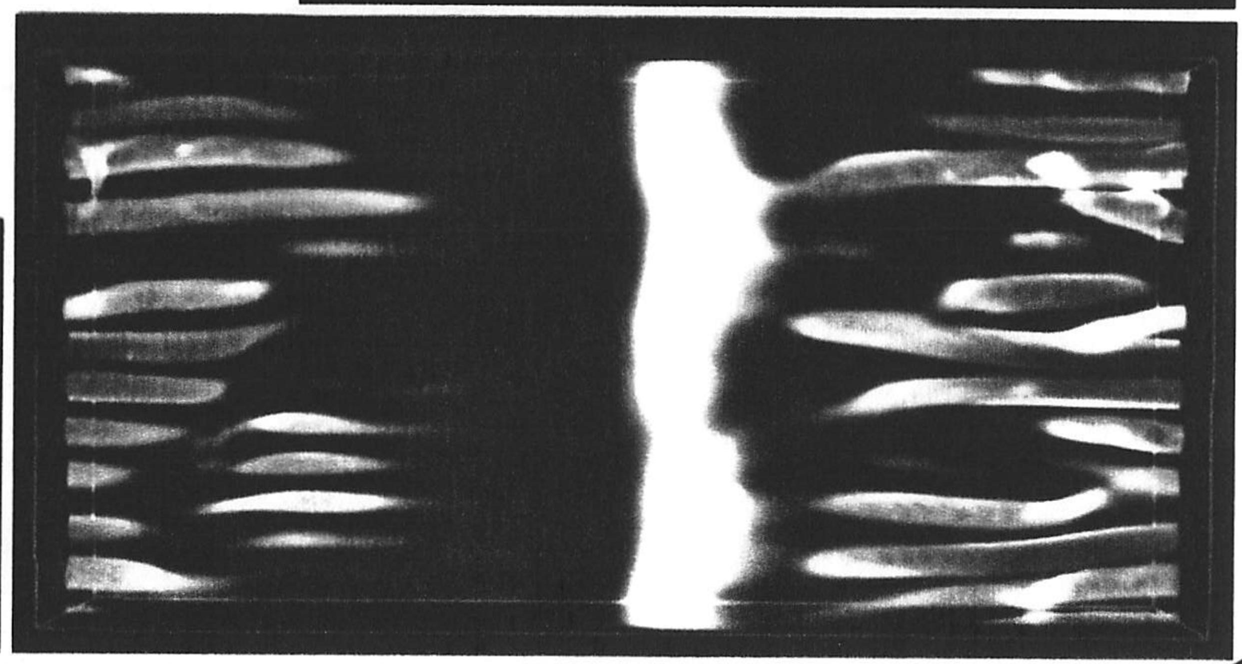
Vortices



Solenoidal sources







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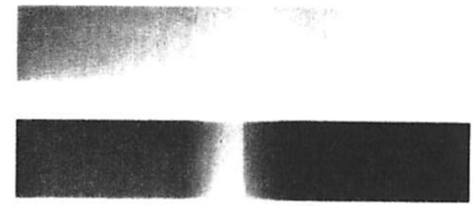
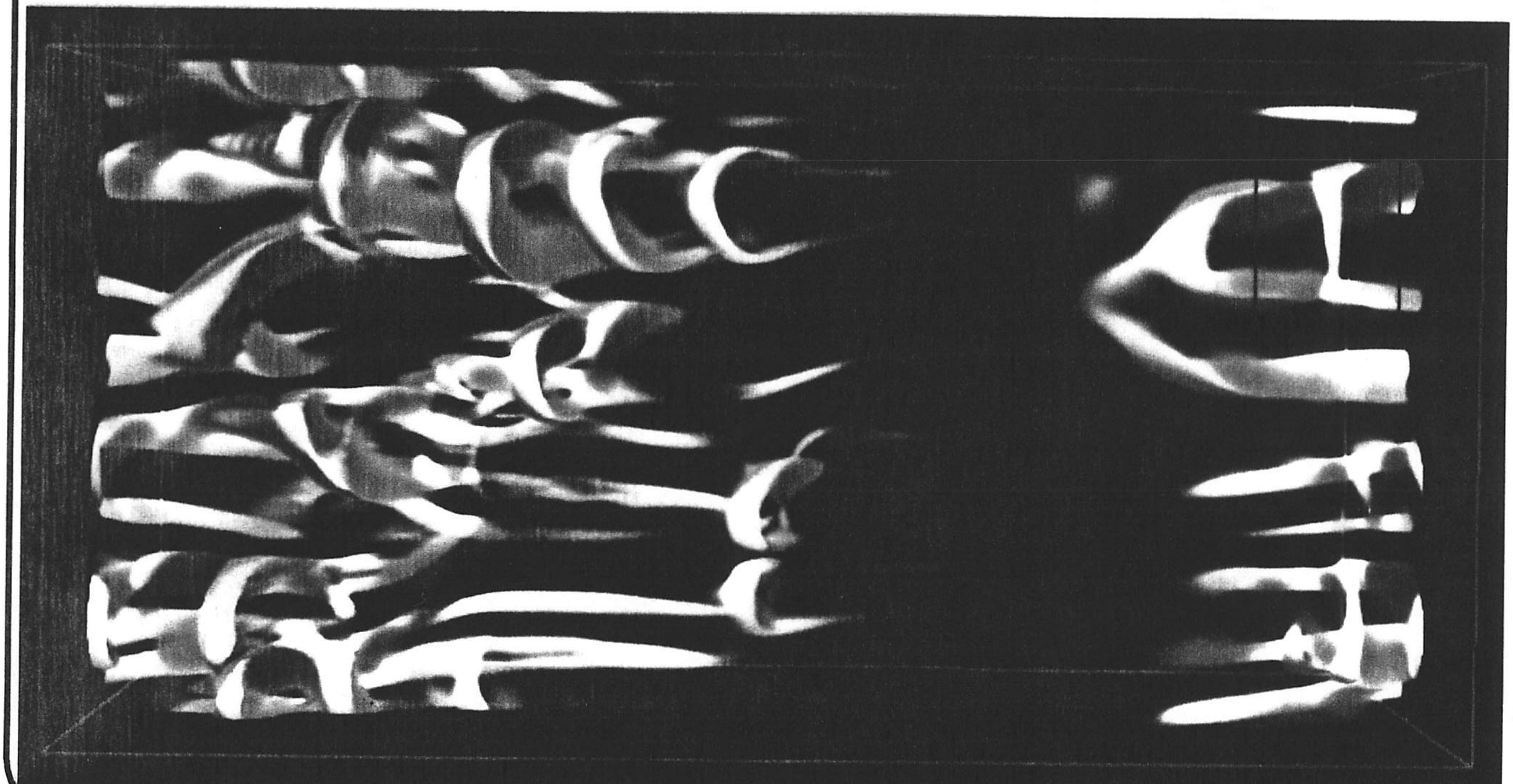
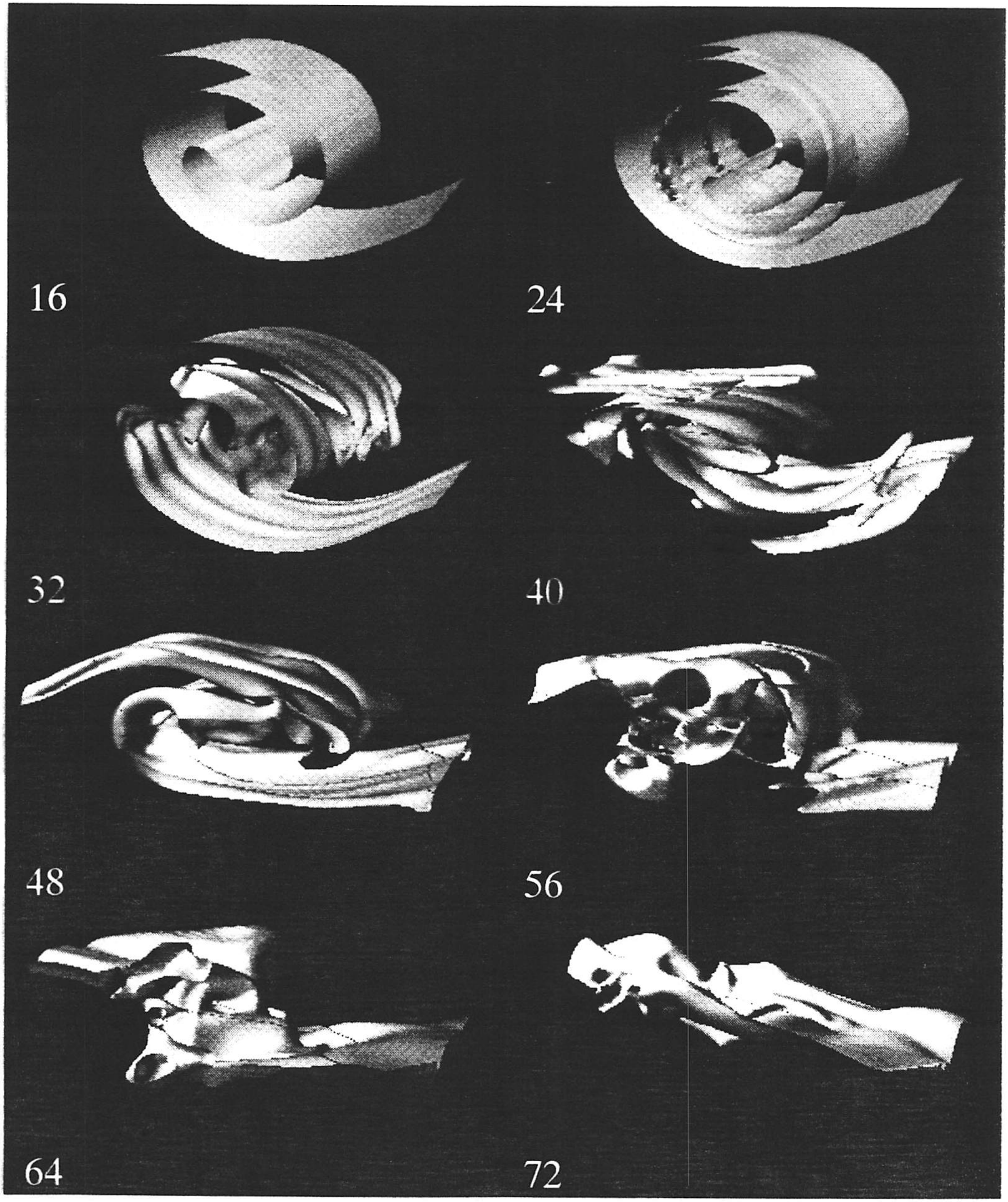
Vortices at t=67.5, strain source of streamwise vorticity $(\omega_j S_{ij})_1$



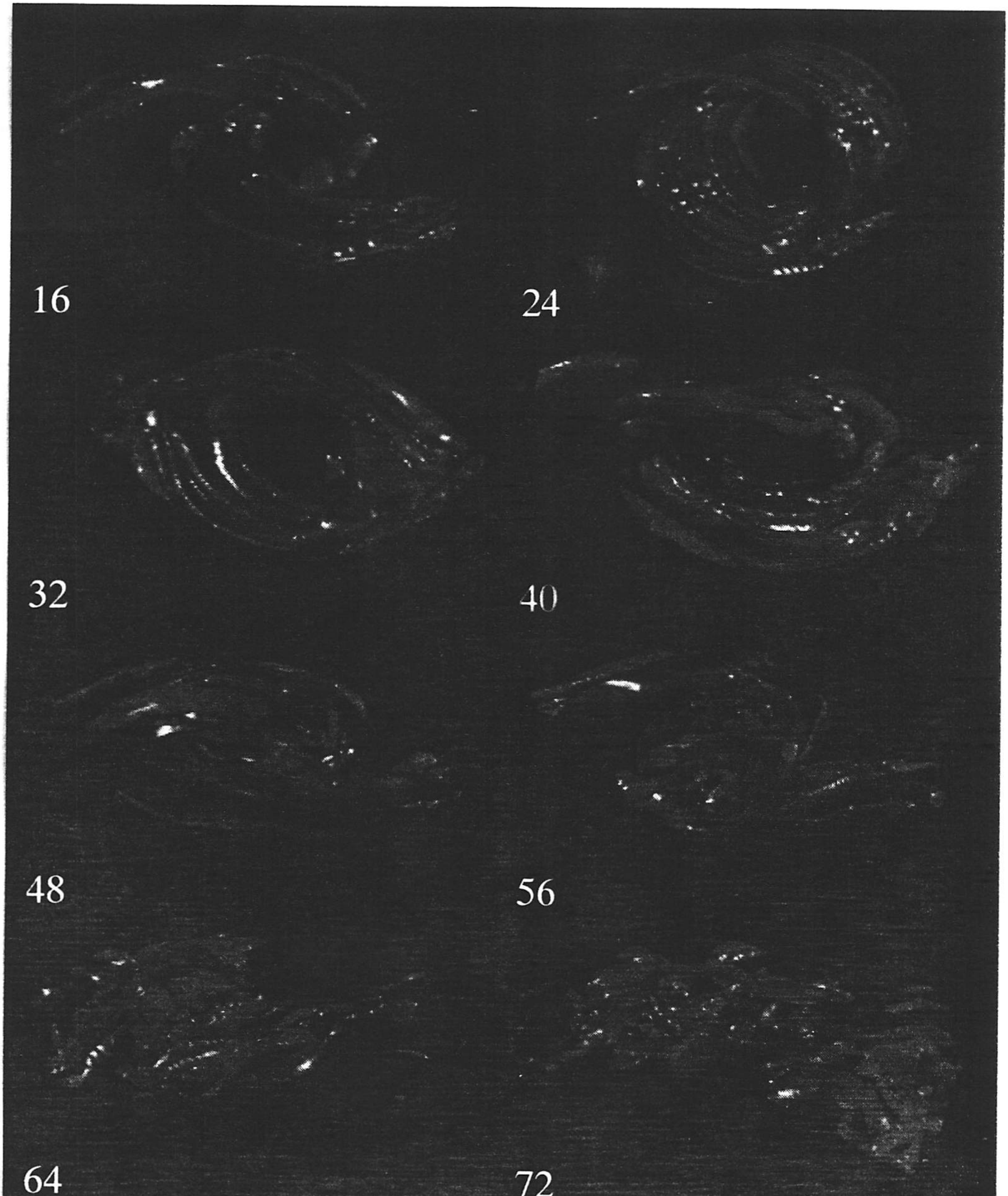


Kelvin-Helmholtz Instability

- **unstable shear flow in uniform stratification**
  - **$U(z) = U_o \tanh(z/h)$, $U_o = 28$ m/s, $h = 300$ m**
  - **wavelength ~ 4 km**
  - **$Ri = N^2/Uz^2 = 0.05$**
  - **Re = 200 to 2000**
- **KH evolutions**
  - **remain 2D, Re < 200**
  - **secondary convective instability, Re > 250**
  - **secondary dynamical instability, Re > 1000**
  - **secondary instabilities**
    - **accelerate KH breakdown, restratification**
    - **mixing and transports are very different in 2D and 3D**

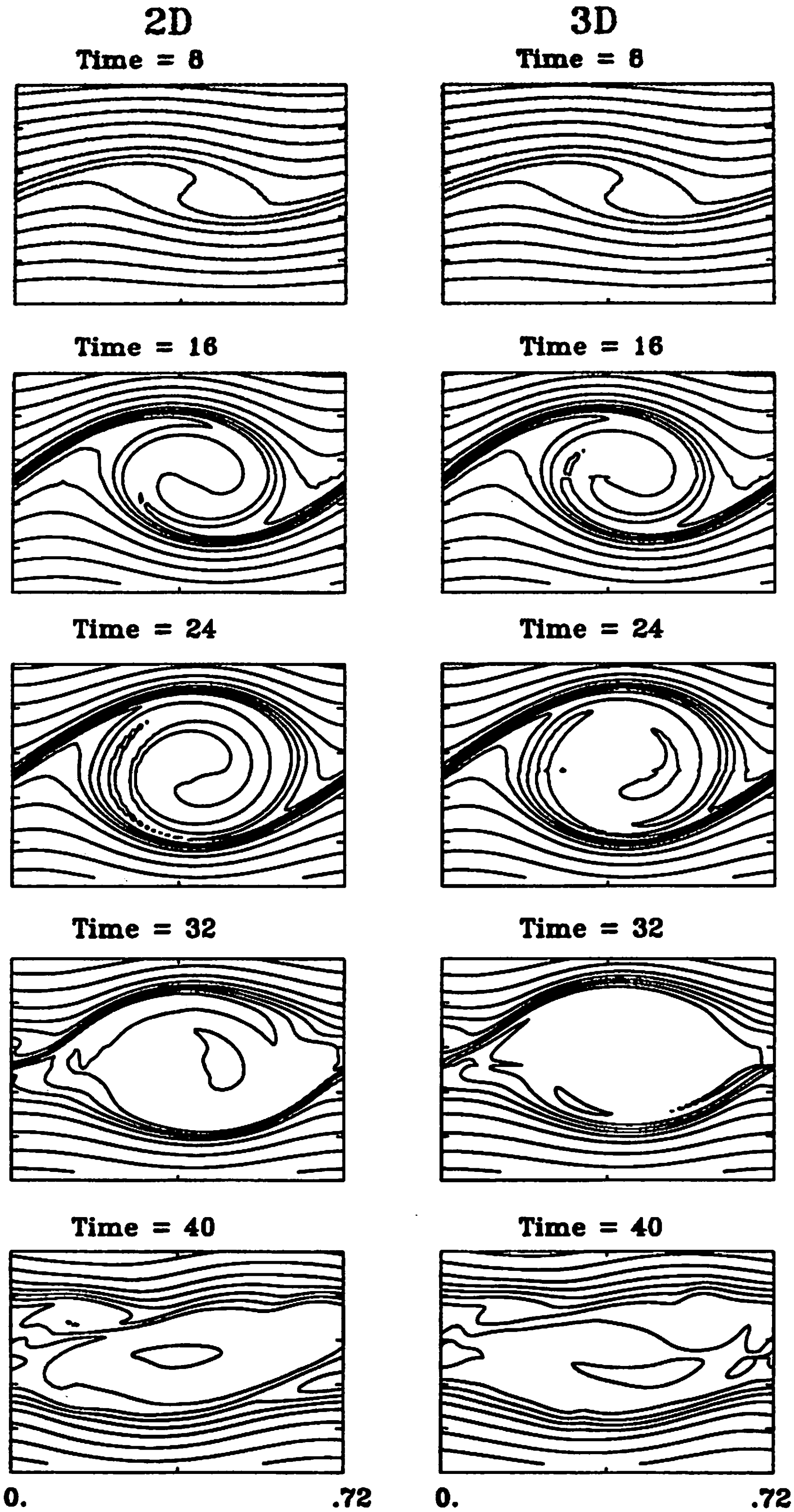


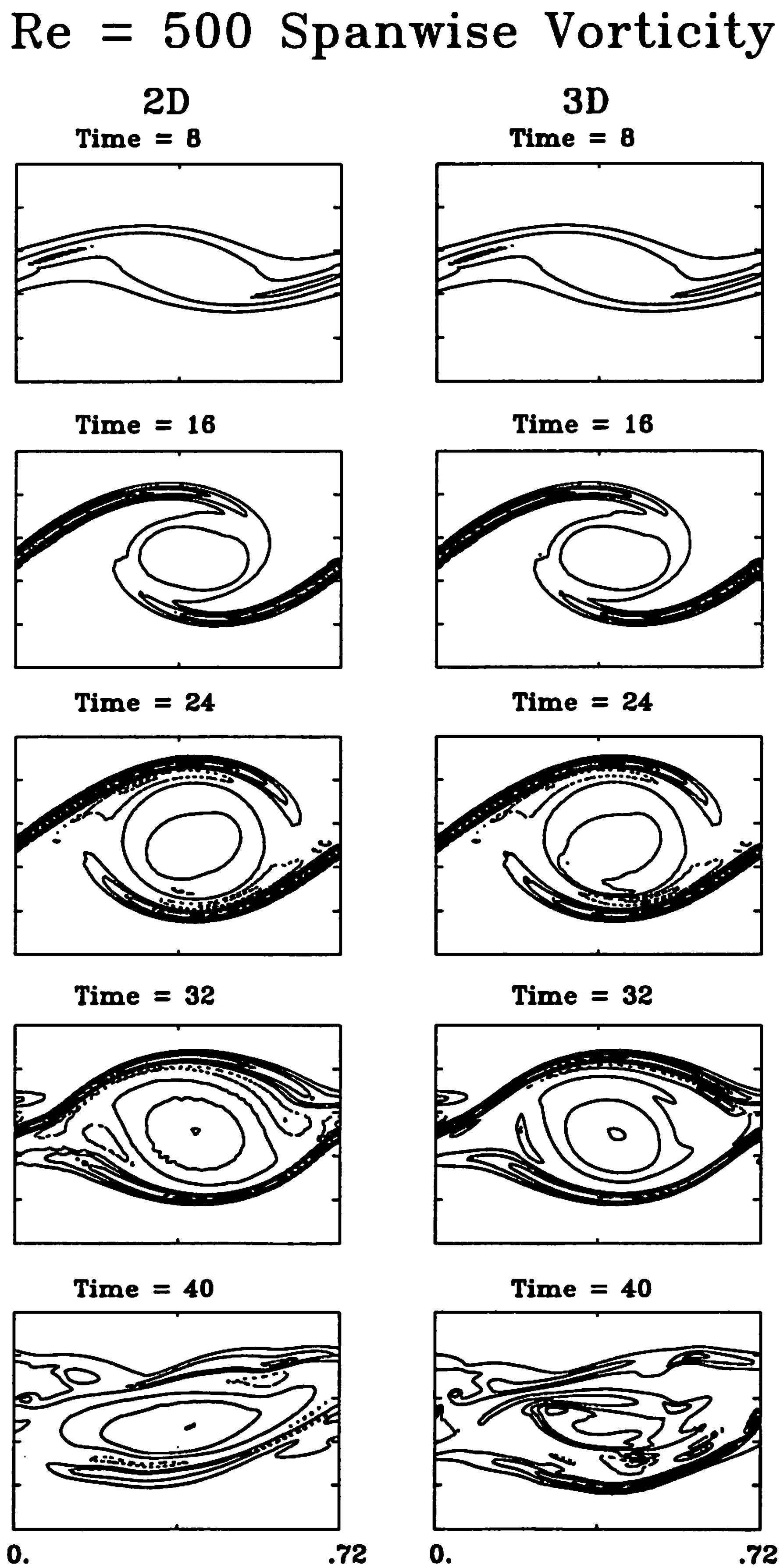
Contour of θ = 1.035 for Re =500



Contours of positive (red) and negative streamwise vorticity for Reynolds number = 500

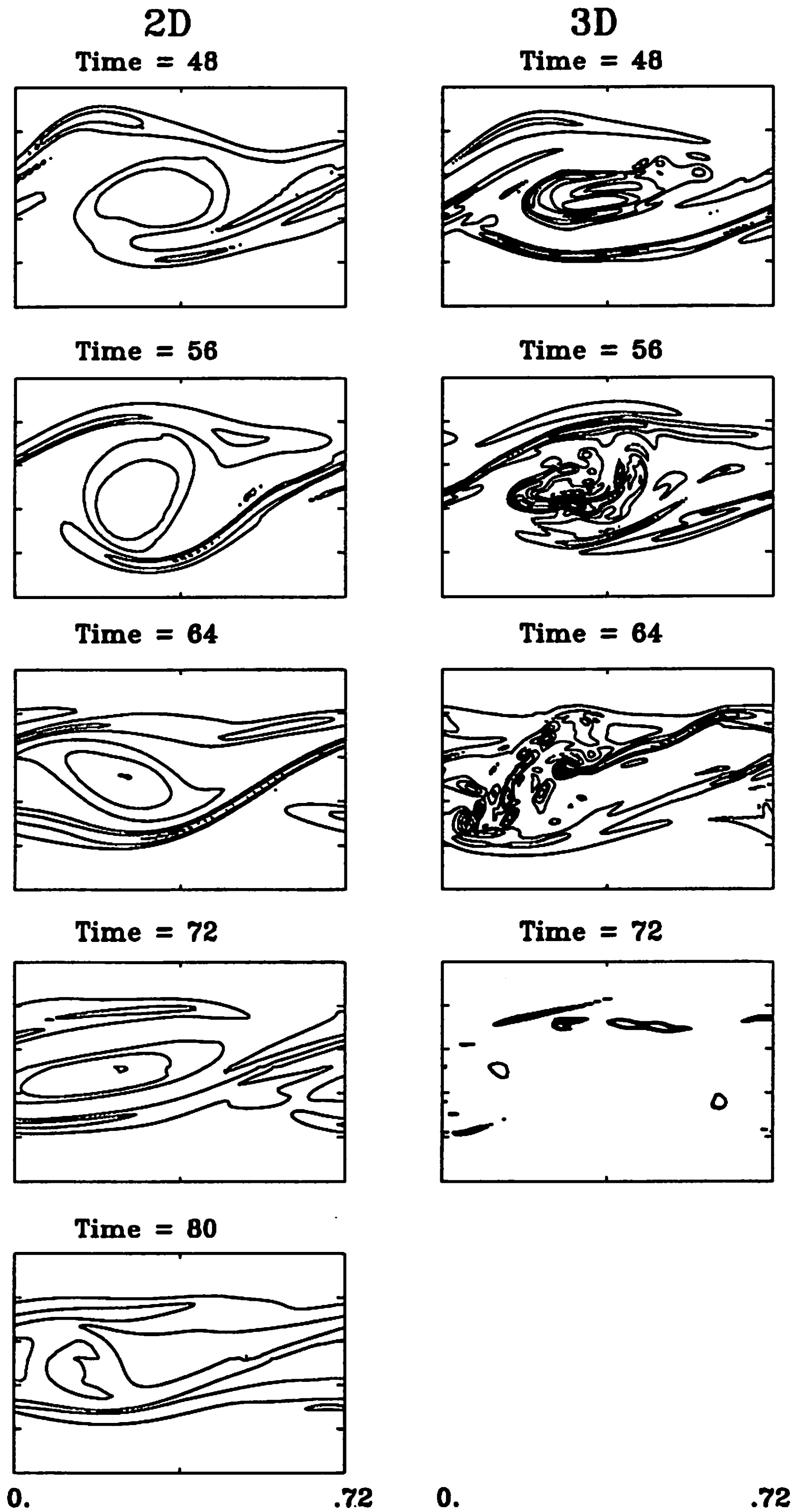
Re = 500 Potential Temperature



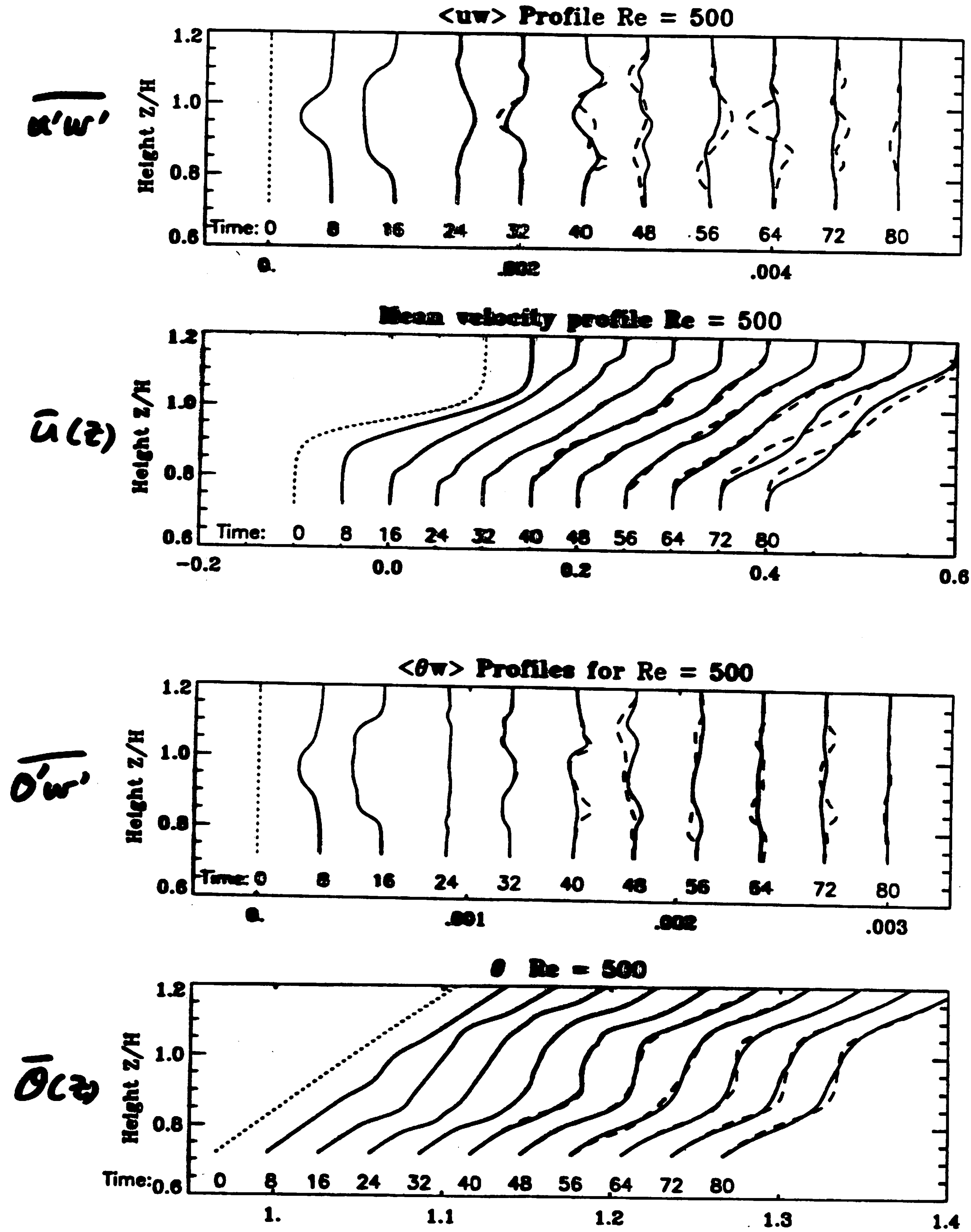


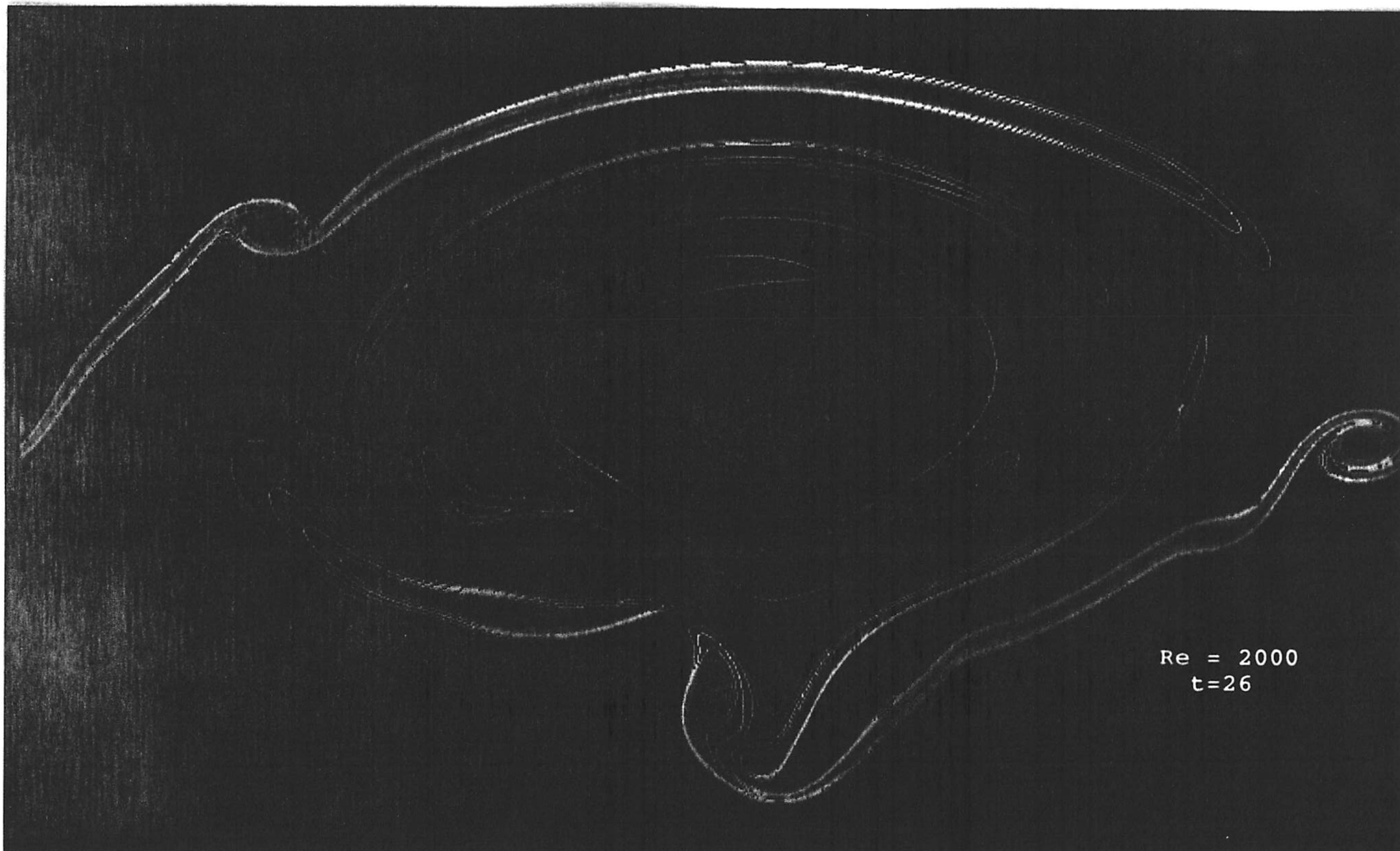
Re = 500 Spanwise Vorticity
2D
3D
Time = 8
Time = 8
Time = 16
Time = 16
Time = 24
Time = 24
Time = 32
Time = 32
Time = 40
Time = 40
0.
.72
0.
.72

Re = 500 Spanwise Vorticity



KH Mean Flow Evolutions
3D —— 2D - - -




Re = 2000
t=26

Conclusions

- **Wave breaking is inherently three dimensional**
  - **primary instability is convective in nature over large range of wave frequencies**
  - **secondary dynamical instability (KH in 3D) arises due to stretching of vortex sheets**
  - **vorticity dynamics drives transition to turbulence**
    - **intertwined vortex tubes**
    - **intense vortex interactions**
    - **vortex fraying, fragmentation => cascade of energy and enstrophy to smaller scales**
- **Kelvin-Helmholtz instability exhibits secondary instability**
  - **convective, streamwise instability, Re > 250**
  - **dynamical, spanwise aligned inst., Re > 1000**
  - **2D and 3D evolutions have very different**
    - **vorticity dynamics**
    - **implications for mixing and transports**