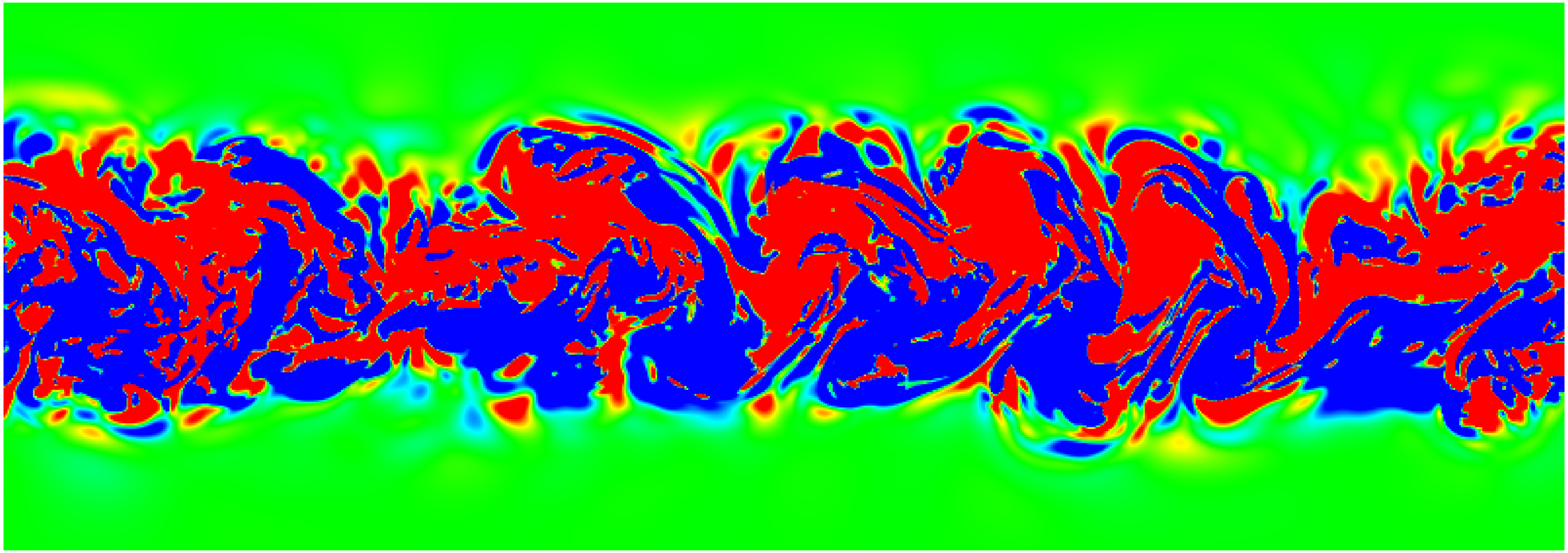

Simulation of a self-propelled wake with small excess momentum in a stratified fluid

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University of California San Diego

Features of Turbulent Wakes in Stratified Fluids

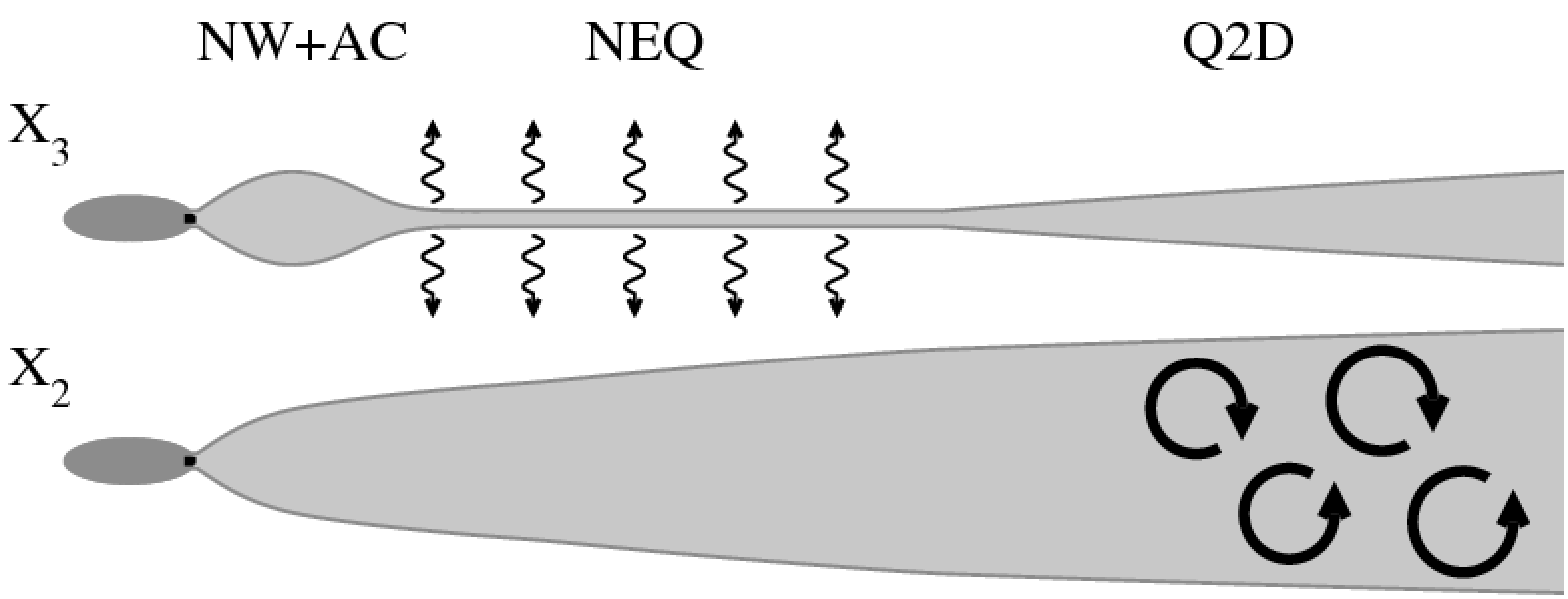
Stratification breaks radial symmetry: vertical motion inhibited

Transfer between kinetic and potential energy

Internal waves radiated

Late time quasi-2D flow

Very different than unstratified wake

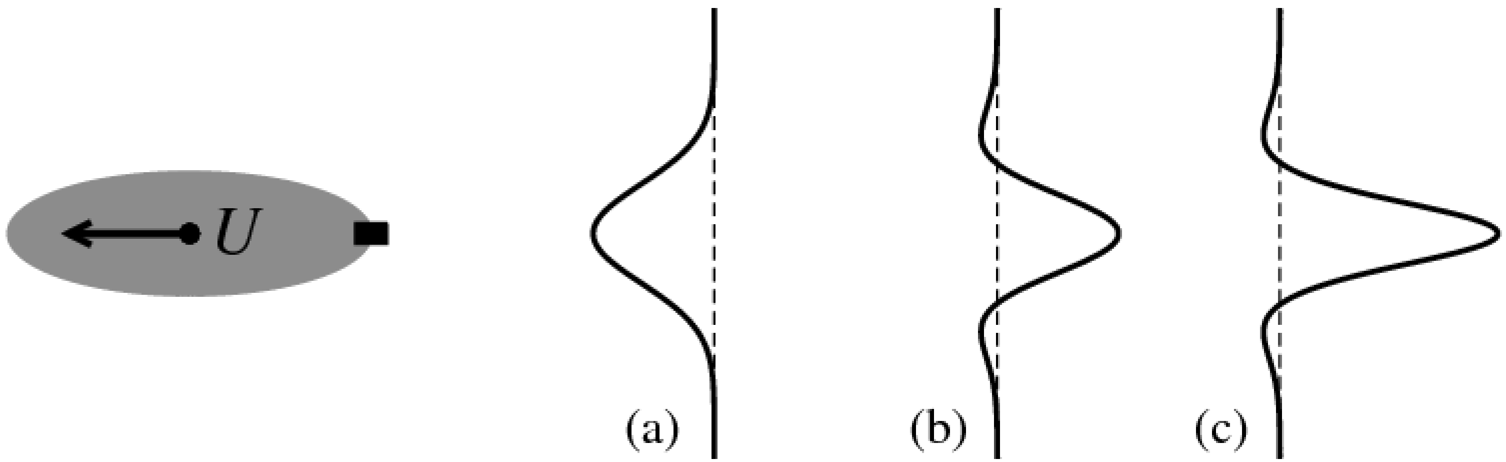


Classes of wakes

Two fundamental classes of wake

Towed: Drag only

Propelled: Thrust and Drag

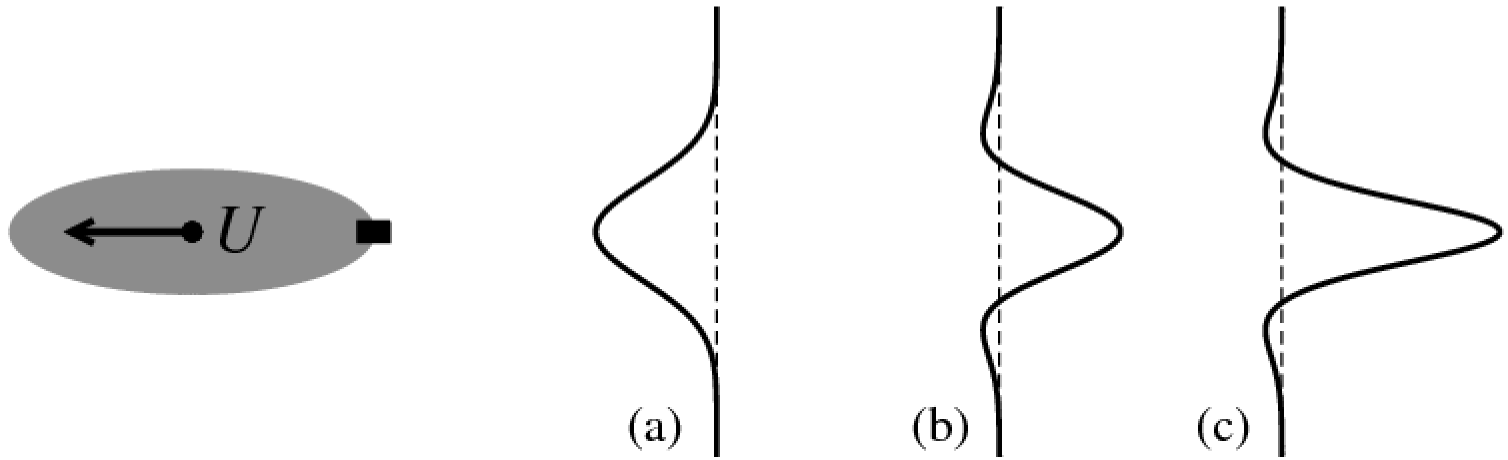


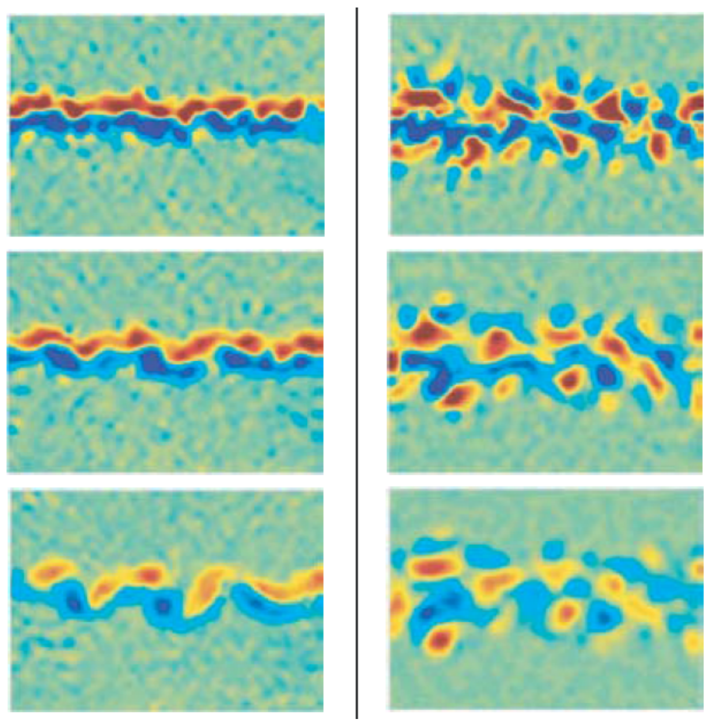
(a) Towed wake, only drag

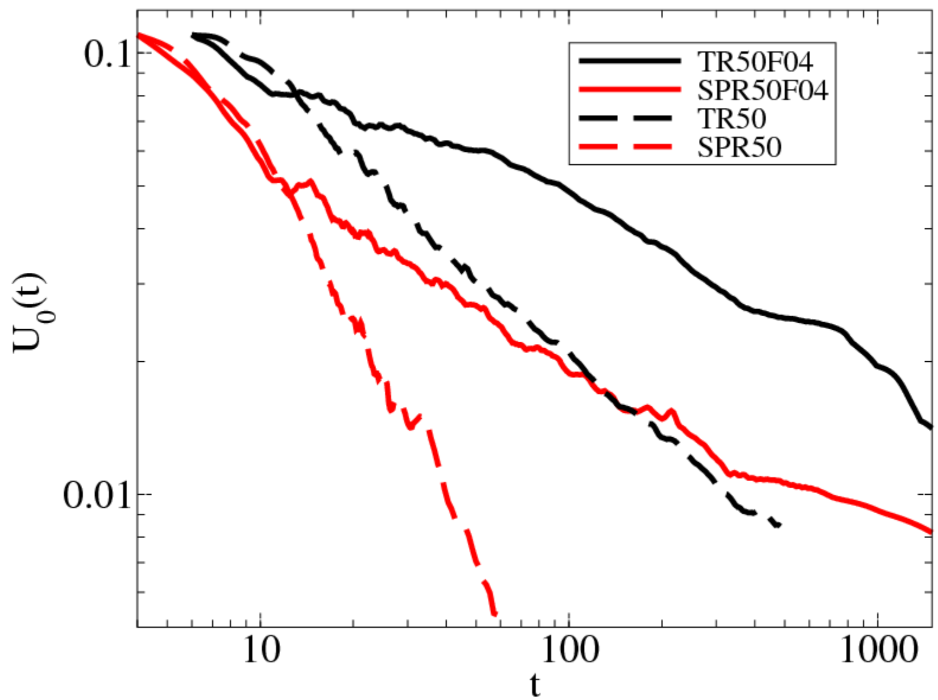
(b) Self-propelled wake, thrust=drag, net momentum=0

(c) Excess momentum wake, thrust > drag

Difference between self-propelled and towed wake







Vorticity data from Meunier and Spedding (2006)
(Left) Momentum wake (right) SP wake

Data from Brucker and Sarkar (2010)

Why this problem?

A self-propelled (SP) wake with zero net momentum is unrealistic

- Unsteady upstream conditions
- Slight imbalances in thrust
- Maneuvers

The self-propelled wake with zero net momentum is qualitatively different from a towed (drag wake)

- Assuming self-similarity, Tennekes and Lumley (1972) determined that an unstratified wake with any excess momentum at late time is dominated by the excess momentum component
- Meunier and Spedding (2006) found qualitatively different results with > 2% excess momentum in the wake vorticity field
- Brucker and Sarkar (2010) found that a self-propelled wake decayed much faster than a towed wake. SP wake has smaller vortical structures.
- Voropayev et al. (1999) and Voropayev and Fernando (2010) show the formation of large coherent structures in the late wake after an accelerating maneuver

Study focus

How is the wake affected by excess momentum?

- Amount of excess momentum
- Shape of excess momentum

Do larger structures form in the late wake with small amounts of excess momentum?

Interested in the effect of excess momentum on

- Defect velocity
- Wake dimensions
- Vorticity dynamics
- Internal wave flux
- Mean and turbulent kinetic energy and associated budgets

Does a small amount of excess momentum qualitatively change the wake evolution?

Problem approach

Use DNS to solve the Boussinesq Navier-Stokes equations in a temporally evolving frame

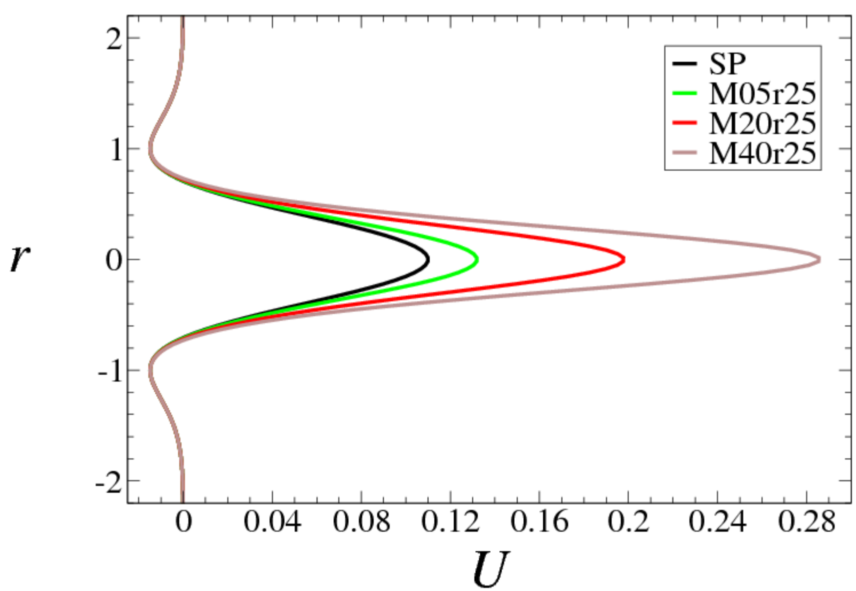
First DNS of a self-propelled wake with excess momentum

Start with a self-propelled profile

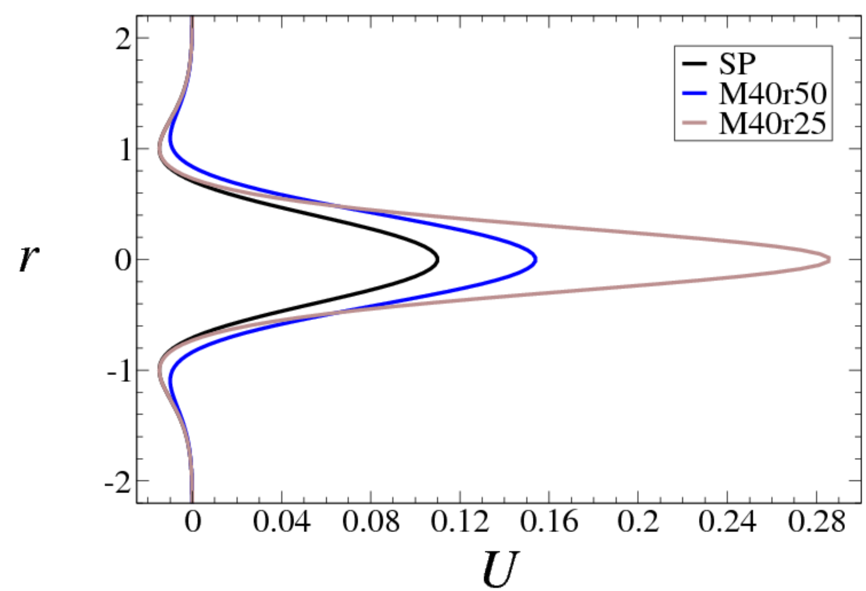
Impulsively add momentum with a Gaussian profile

Linear density stratification

Simulation parameters: Re = 10,000, Fr=3, Pr= 1

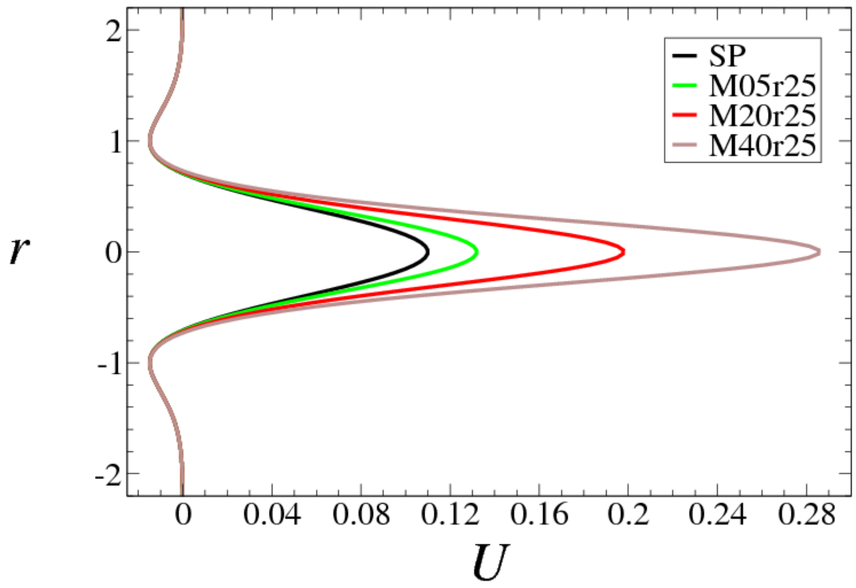


Vary amount of excess momentum



Vary shape of excess momentum

Vary amount of excess momentum

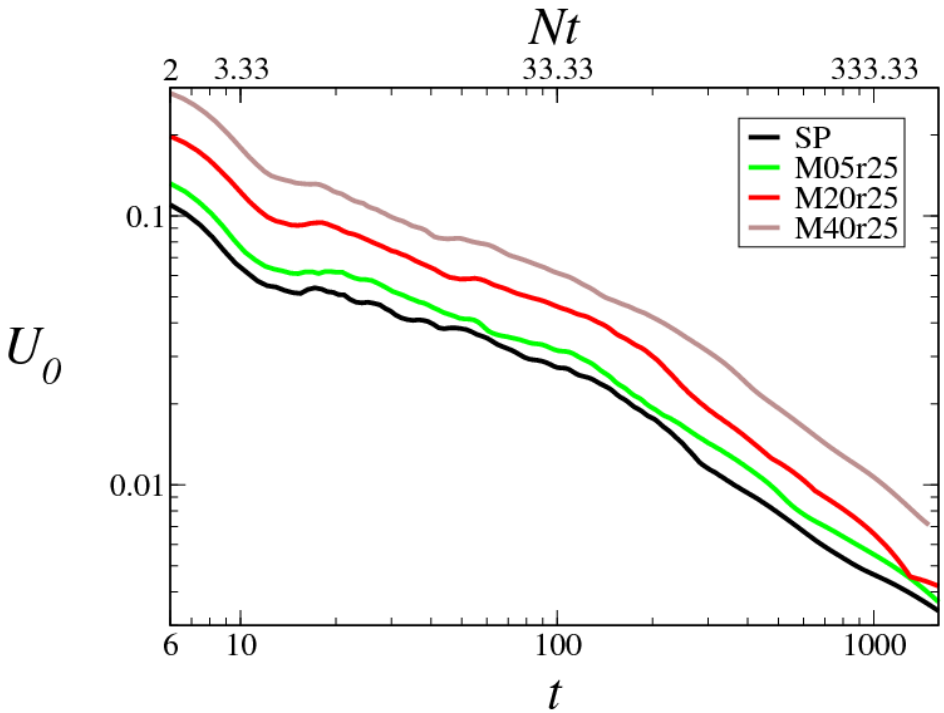


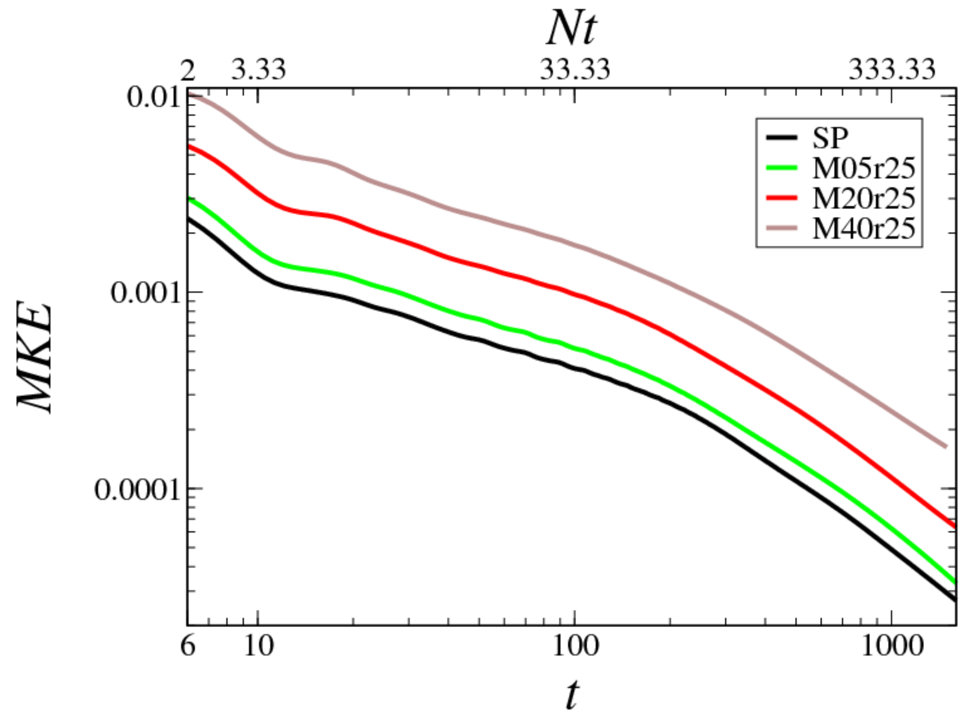
Vary amount of excess momentum

Increasing % M

- Increases defect velocity
- Increased MKE
- Increases velocity gradient

Defect Velocity and MKE



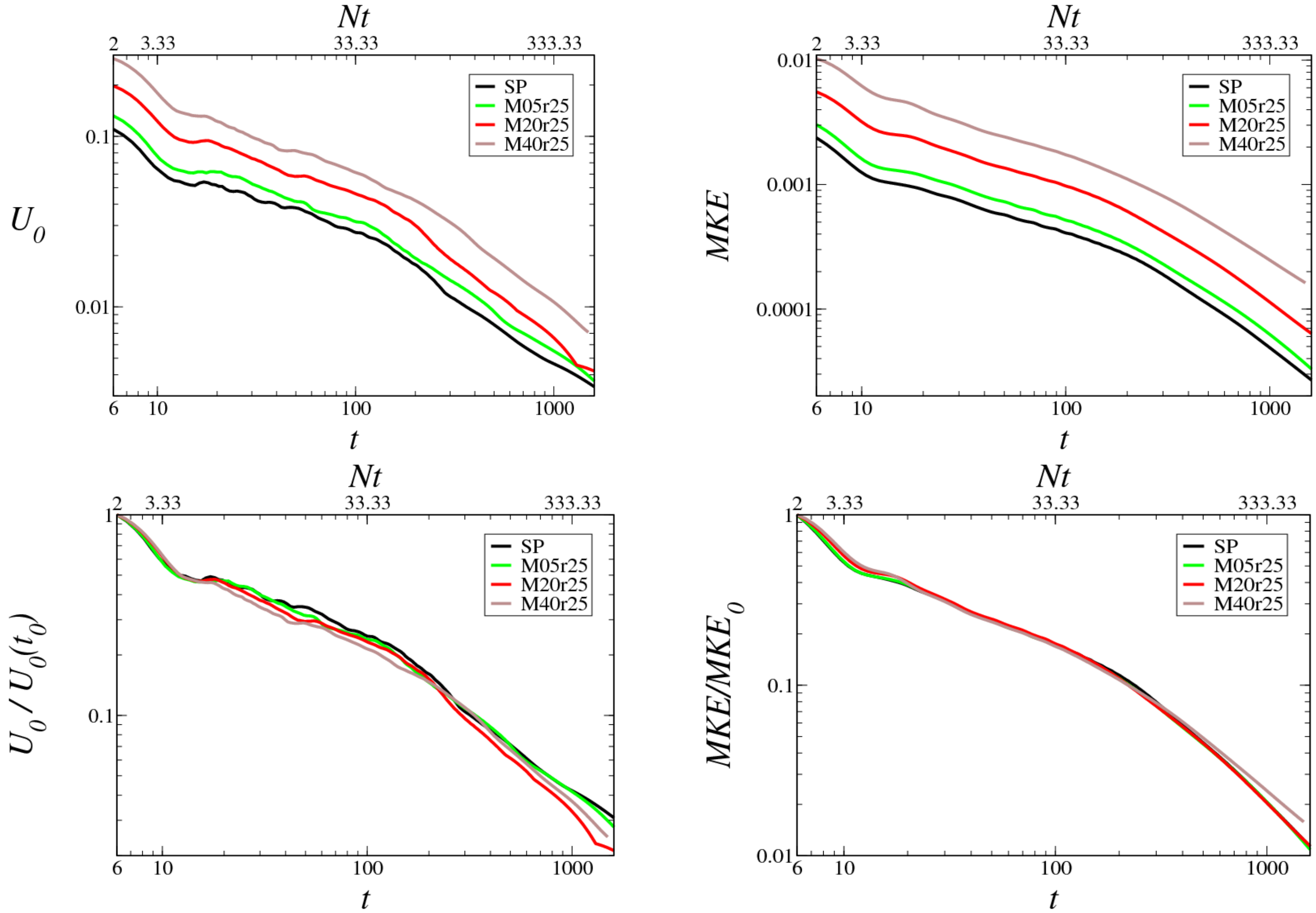


Greater excess momentum gives increased U_0, *MKE*

Good qualitative agreement even in 40% momentum case

Three flow regimes are evident in all cases

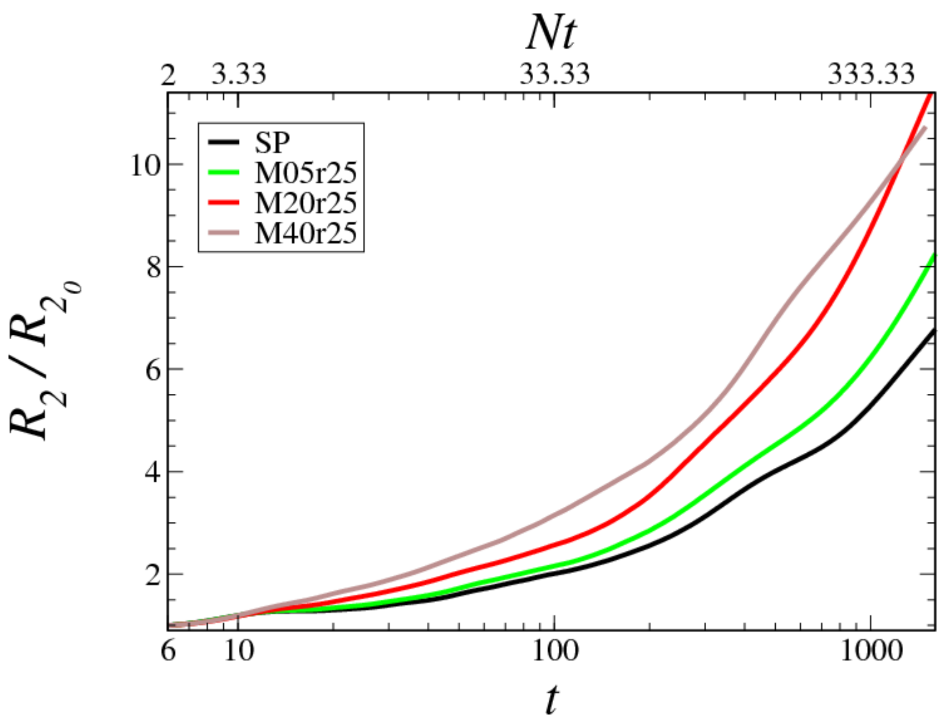
Defect Velocity and MKE

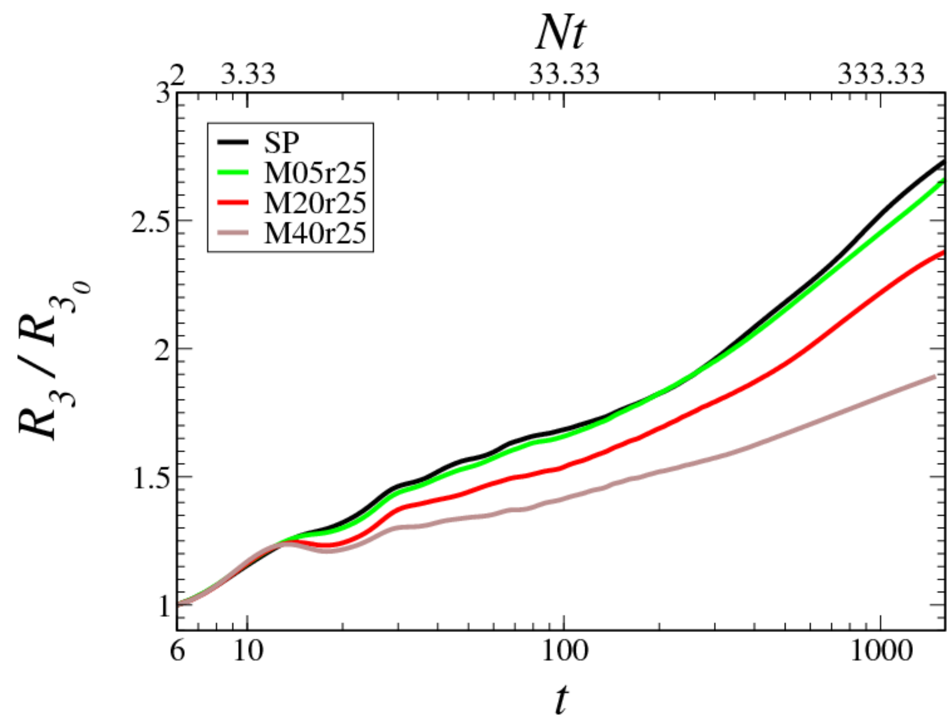


Data collapses when scaled by initial value

Collapse is better or *MKE* than U_0

Wake Dimensions



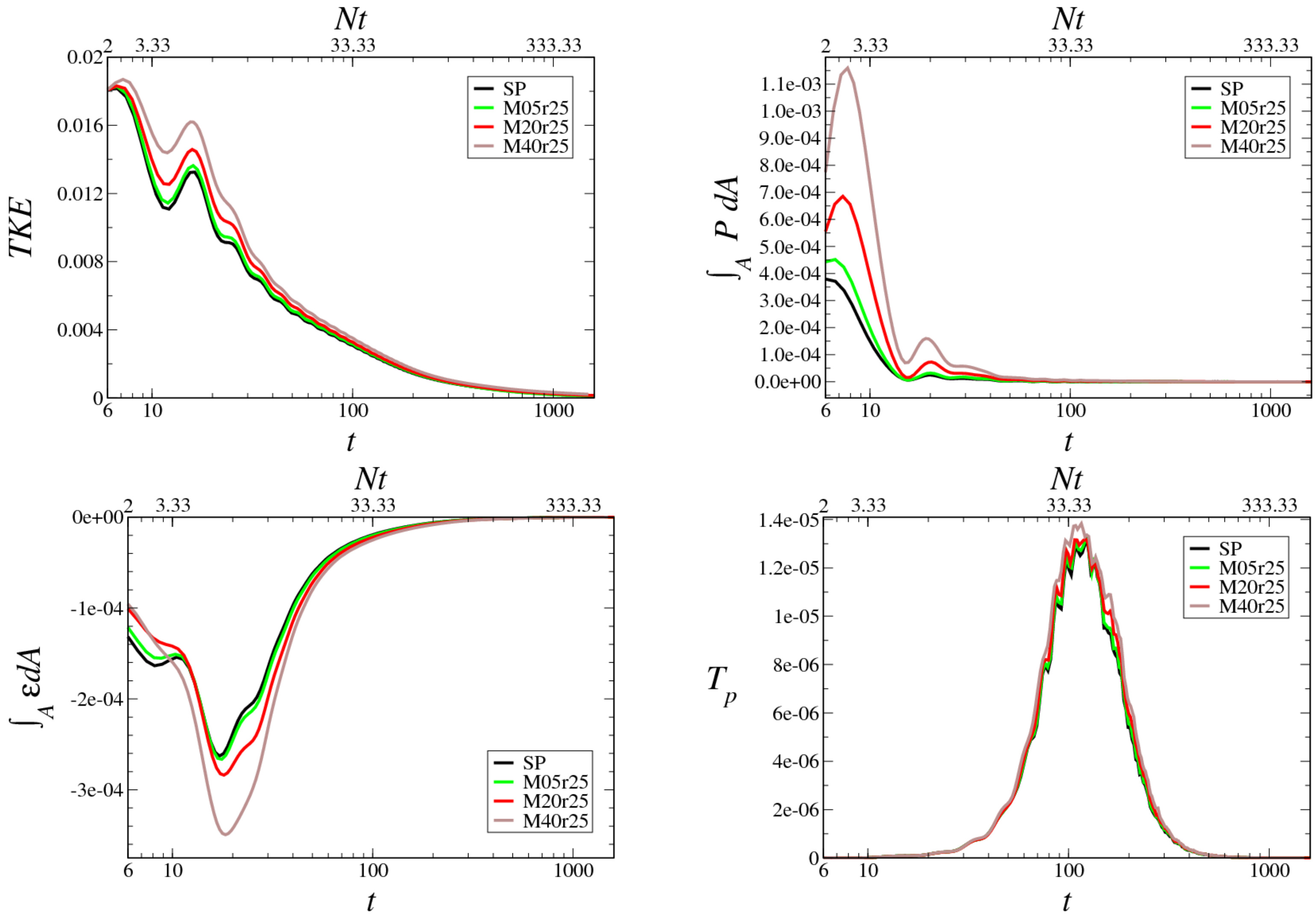


$$R_\alpha^2(t) = F\frac{\int_A (x_\alpha - x_\alpha^c)^2 \langle u_1 \rangle^2 dA}{\int_A \langle u_1 \rangle^2 dA} \qquad x_\alpha^c(t) = \frac{\int_A x_\alpha \langle u_1 \rangle^2 dA}{\int_A \langle u_1 \rangle^2 dA}$$

Excess momentum diffuses horizontally but not vertically

Excess momentum remains close to vertical centerline

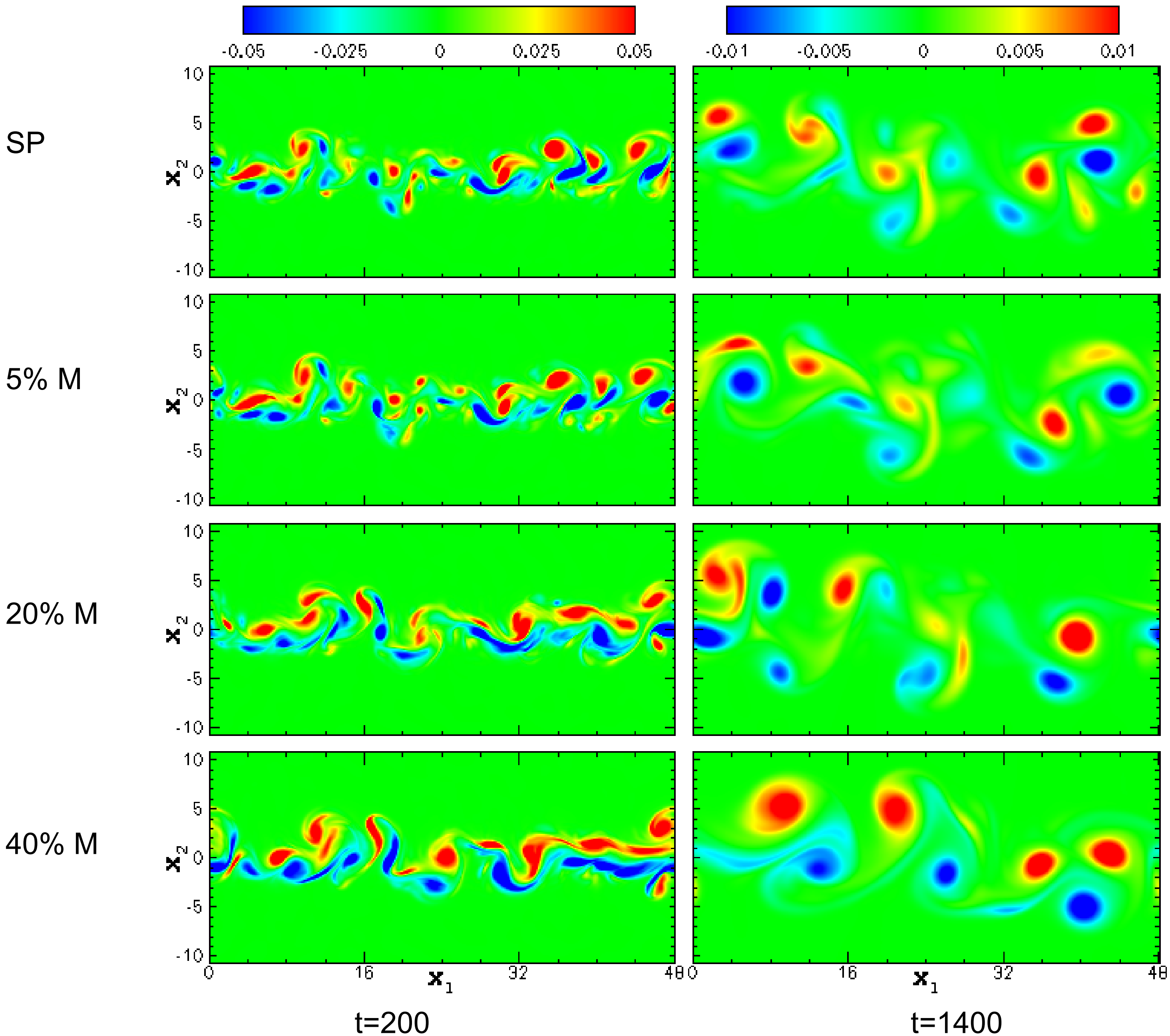
TKE and Wave Flux



Increased %M --> Sharper velocity gradient--> increased production --> increased *TKE* --> increased dissipation

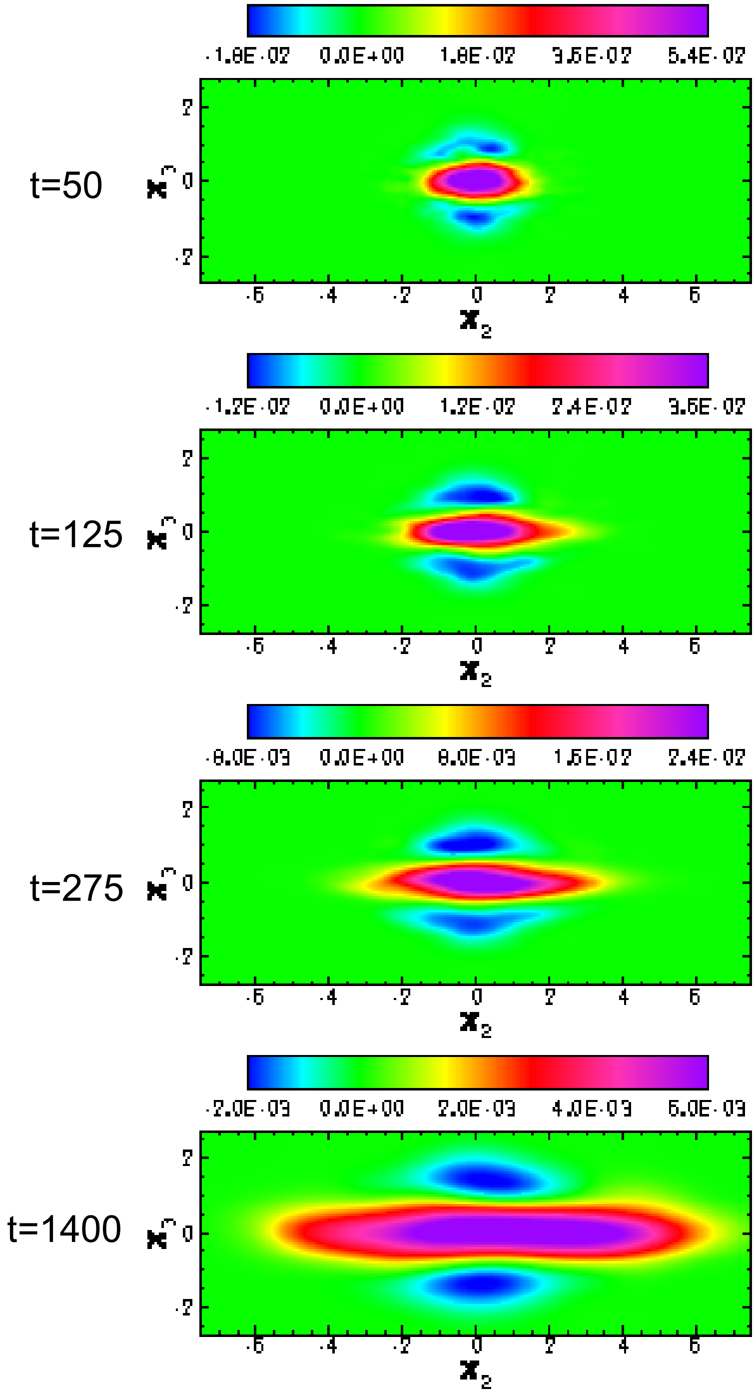
Despite relatively large quantitative differences, qualitative agreement is generally quite good

Wake Vorticity Field ω_3 at $x_3=0$



Larger structures formed with more excess momentum

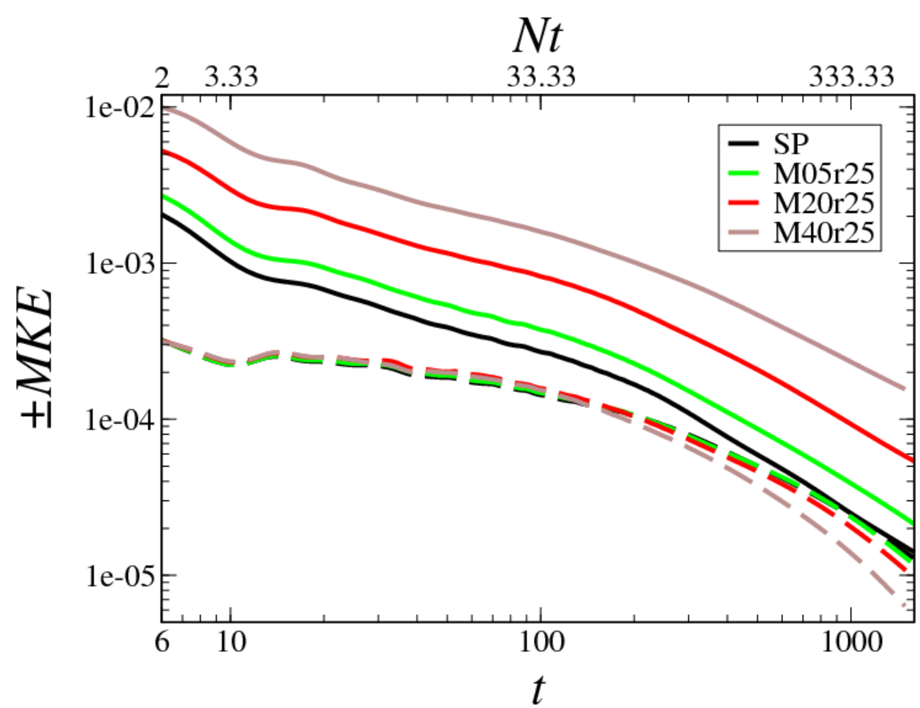
Streamwise velocity structure and decay



r_M=0.25, 40% M

Buoyancy preserves 3 lobe structure in late wake

Velocity decoupled



Solid line max(+U_1). Dashed line max(-U_1).

Small differences in drag lobe evolution with %M

Conclusions

Narrower shape and/or increased amount of excess momentum gives

- Larger defect velocity, MKE, sharper velocity gradient
- Increased production, TKE, and dissipation
- Small differences in internal wave flux

Buoyancy traps excess momentum near the vertical centerline

- Three lobed structure preserved in the vertical direction

Increasing excess momentum leads to larger structures

A small amount of excess momentum does not qualitatively change behavior

Numerical Method

Fully explicit finite volume staggered grid method

Second ordered centered differences for spatial terms

3rd order low storage RK3 time advancement

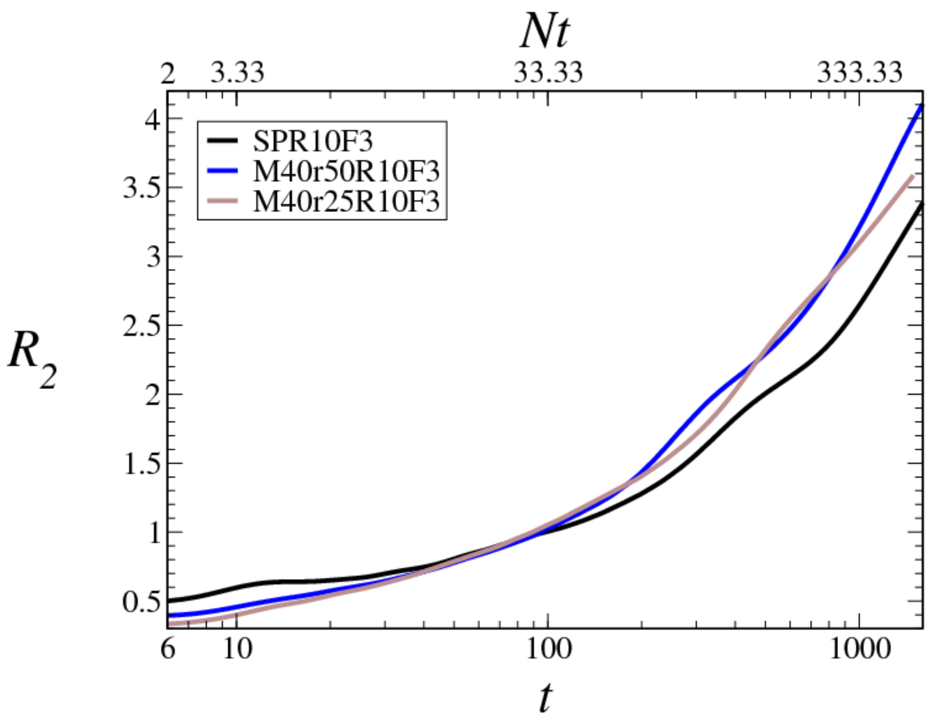
Parallel multigrid pressure solver

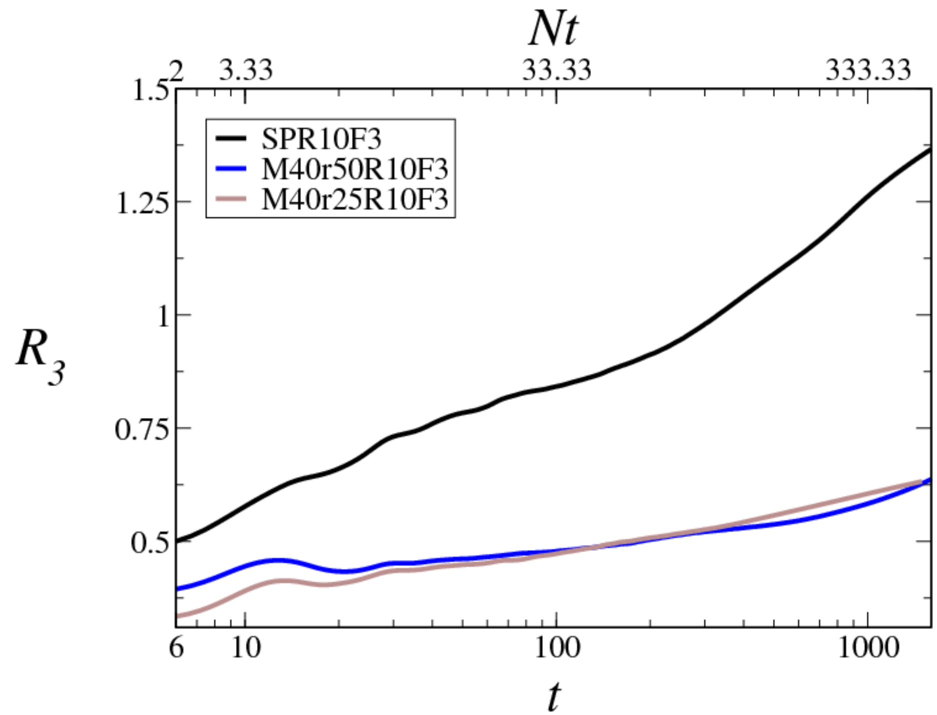
3-D domain decomposition using MPICH II

Sponge region at physical boundaries; streamwise periodicity

ICs: Idealized mean profile, broadband velocity fluctuations, no density fluctuations, adjustment period used to let correlations develop

Wake Dimensions

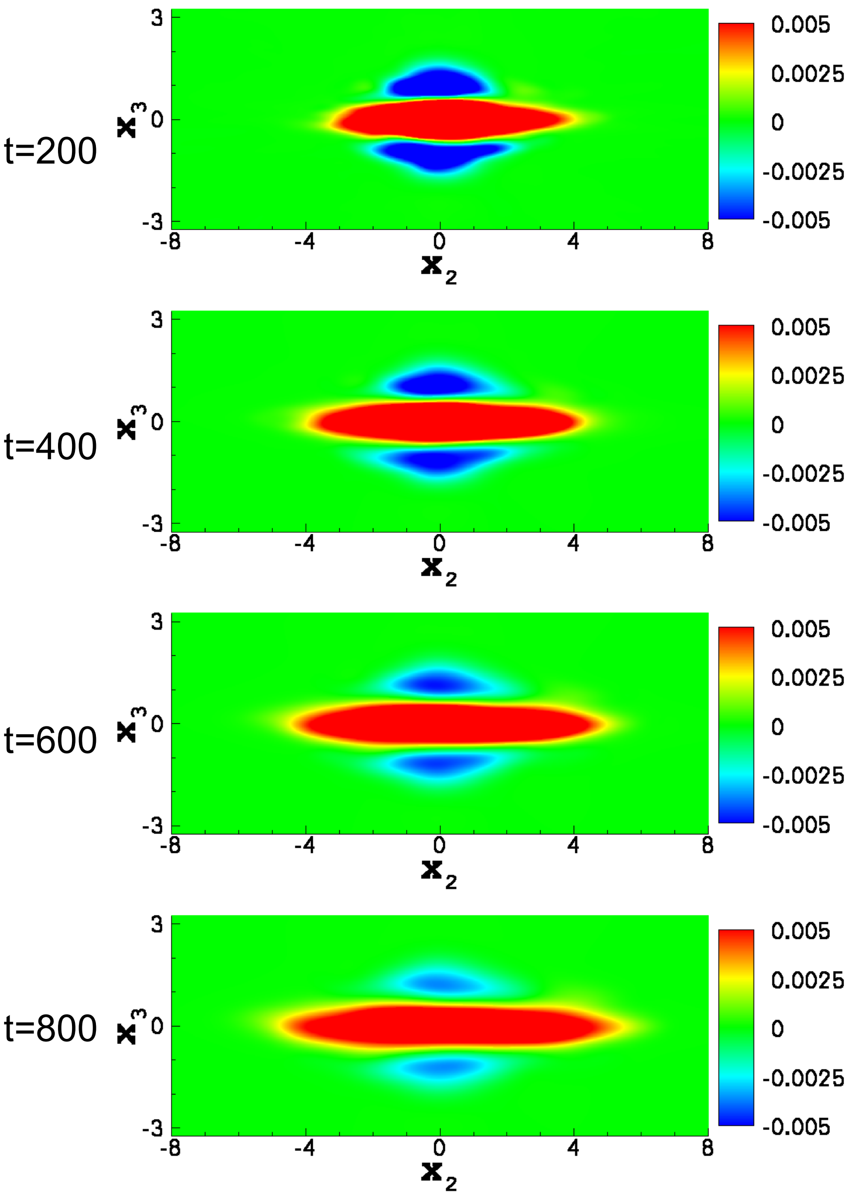




Excess momentum diffuses horizontally but not vertically

excess momentum remains close to vertical centerline

Streamwise velocity structure and decay



r_M=0.25, 40% M

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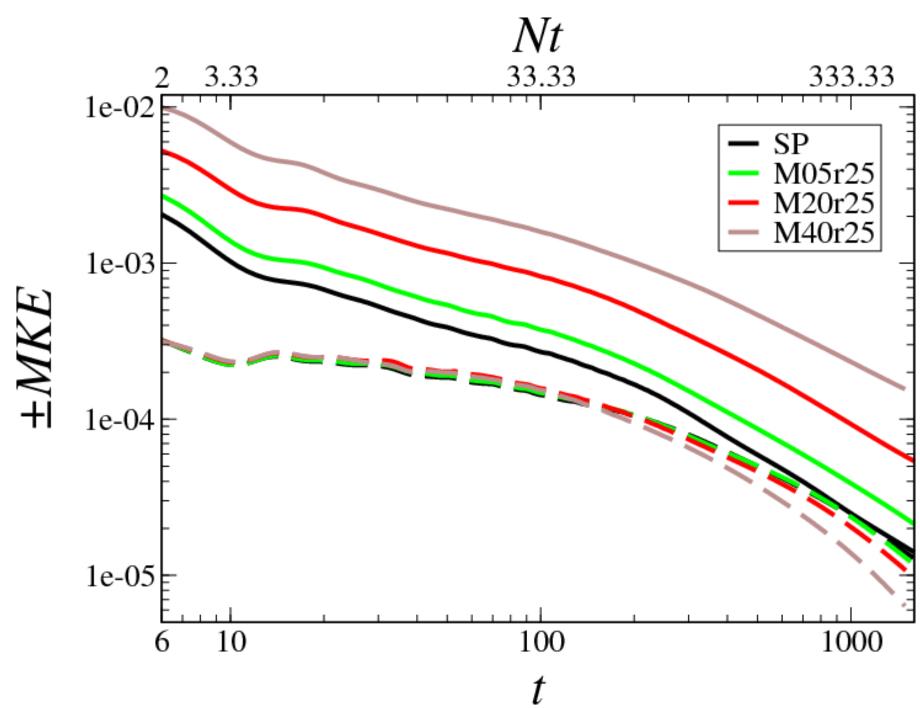


Solid line max(+U_1). Dashed line max(-U_1).

Small differences in drag lobe evolution with %M

Motivation

Wake studies usually consider two cases:

- Towed steady velocity
- Self-propelled steady velocity

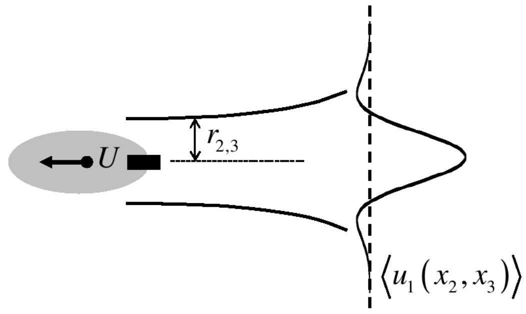
Neither case is realistic

- Unsteady upstream conditions
- Slight imbalances in thrust
- Maneuvers

Large eddies observed experimentally when submersible accelerates

Re=1274, Fr=26
Voropayev et al. Physics of Fluids, 1999

Difference between self-propelled and towed wake



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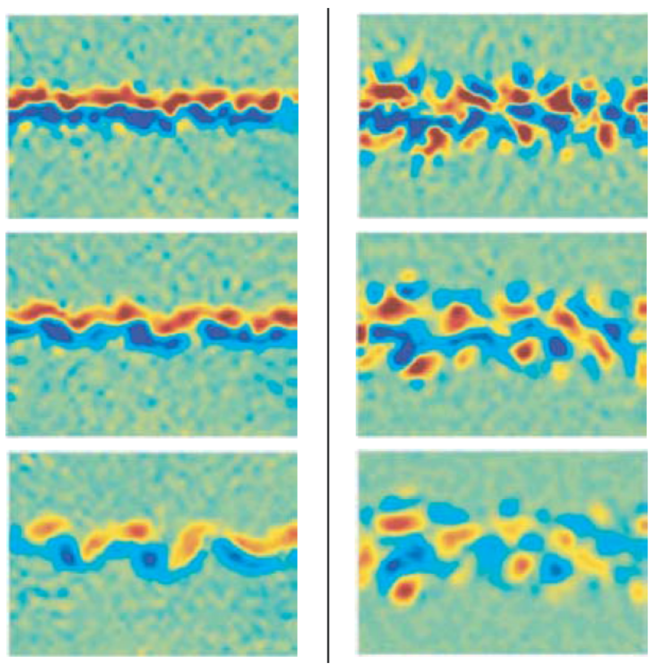
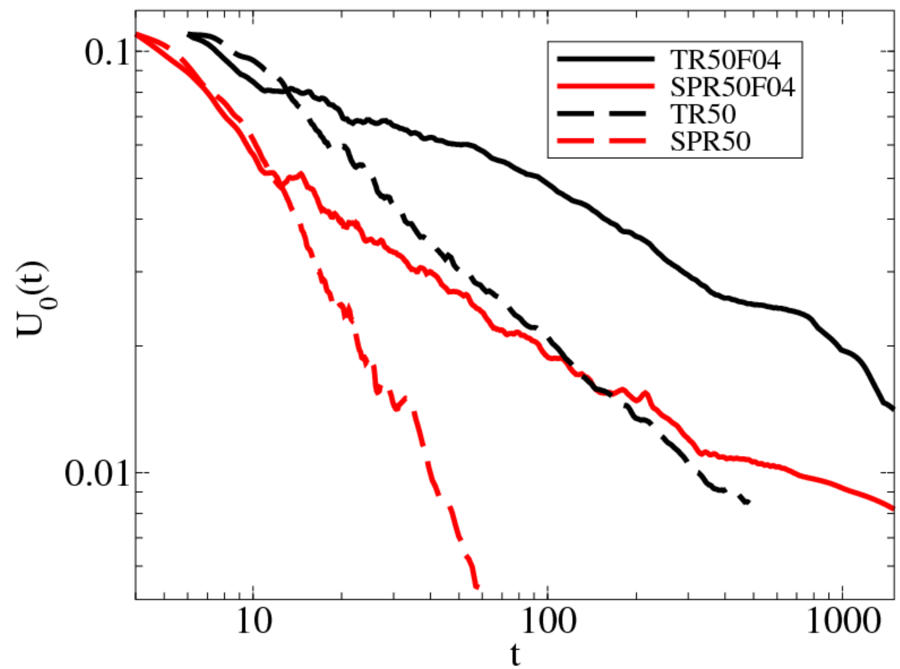


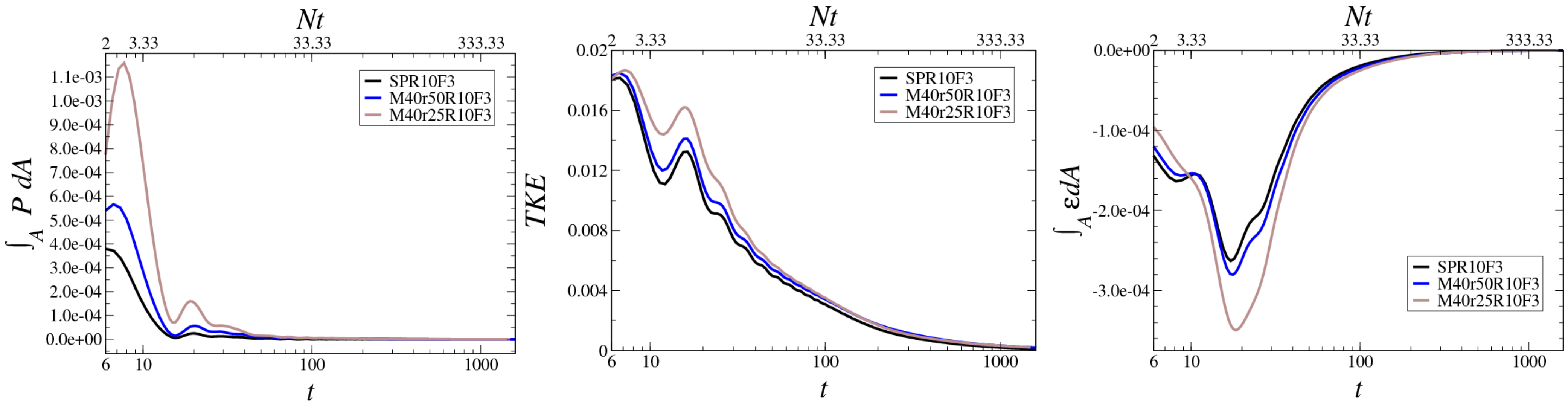
Vorticity data from Meunier and Spedding (2010)



Data from Brucker and Sarkar (2010)

Very different than unstratified wake

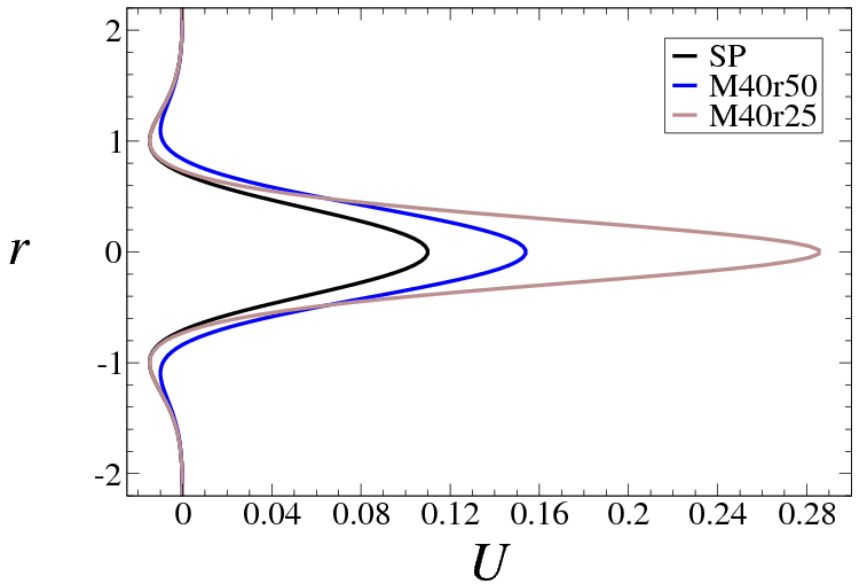
TKE and Wave Flux



Increased %M --> Sharper velocity gradient--> increased production --> increased *TKE* --> increased dissipation

Despite relatively large quantitative differences, qualitative agreement is generally quite good

Vary shape of excess momentum



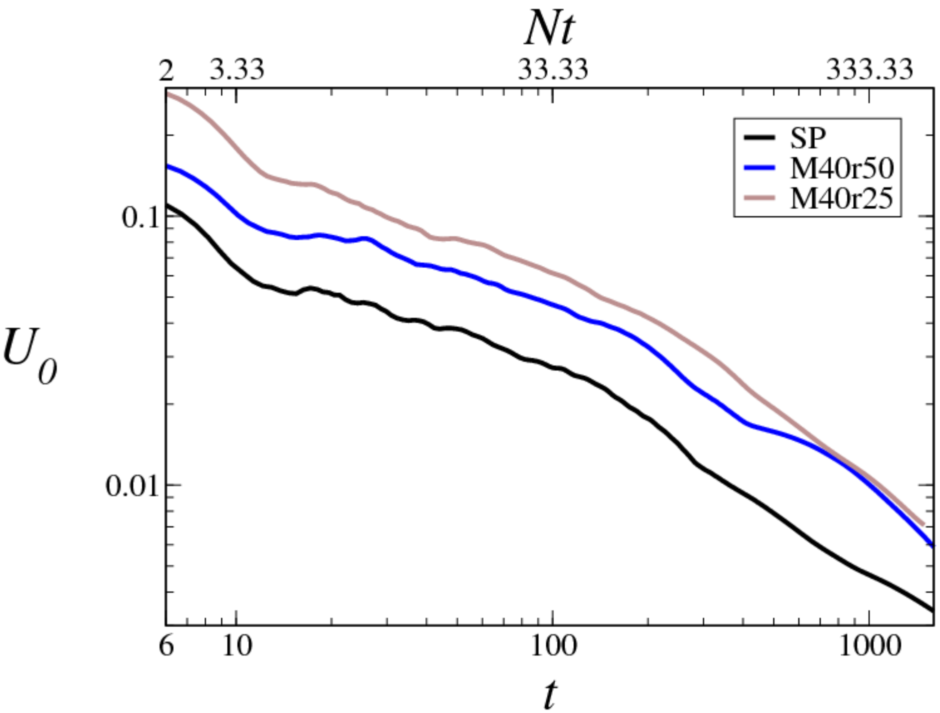
Vary amount of excess momentum

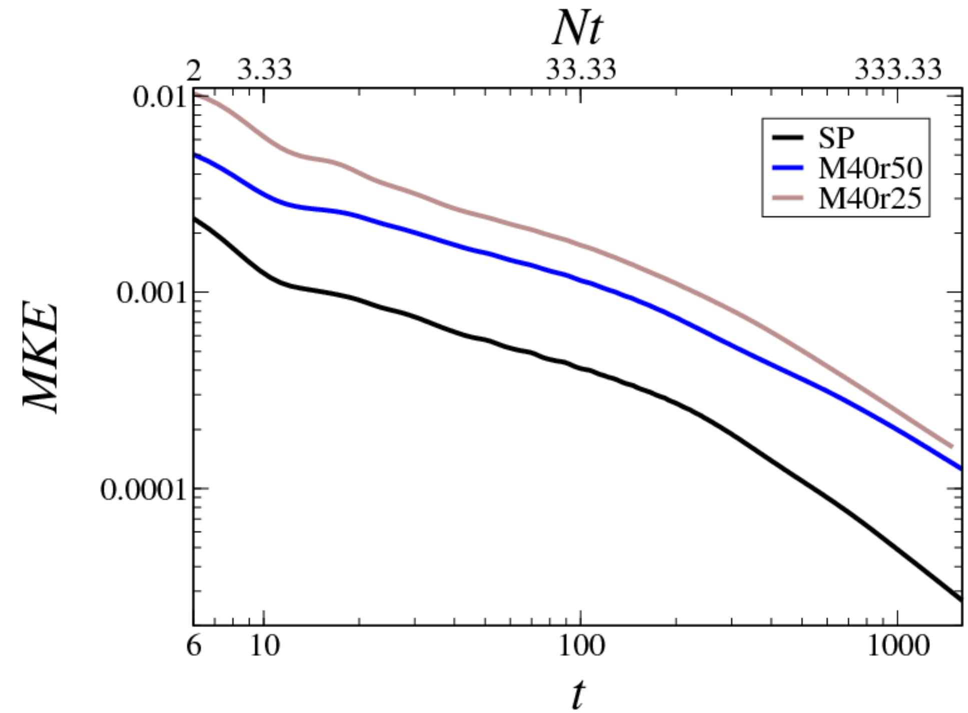
Reducing radial extent of %M

- Increases defect velocity
- Increased MKE
- Increases velocity gradient

- r25 case does not disturb drag lobes
- r50 case does

Defect Velocity and MKE

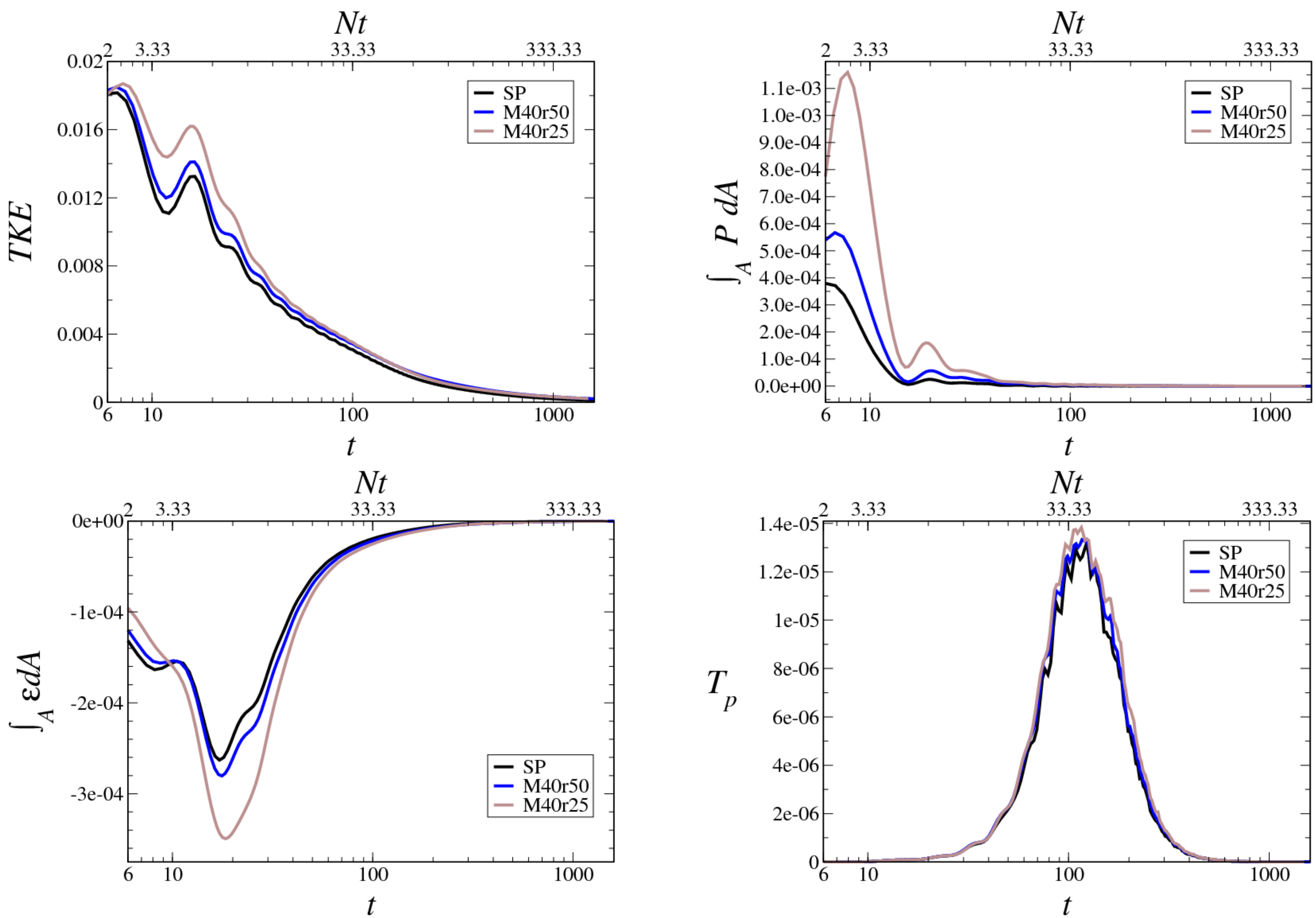




Narrower radial extent of excess momentum --> increased U_0, *MKE*

Wake evolution follows similar trends compared to SP case for both cases

TKE and Wave Flux



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