Novel uses of DNS with turbulent separation for RANS models

Gary Coleman*, Chris Rumsey* and Philippe Spalart**

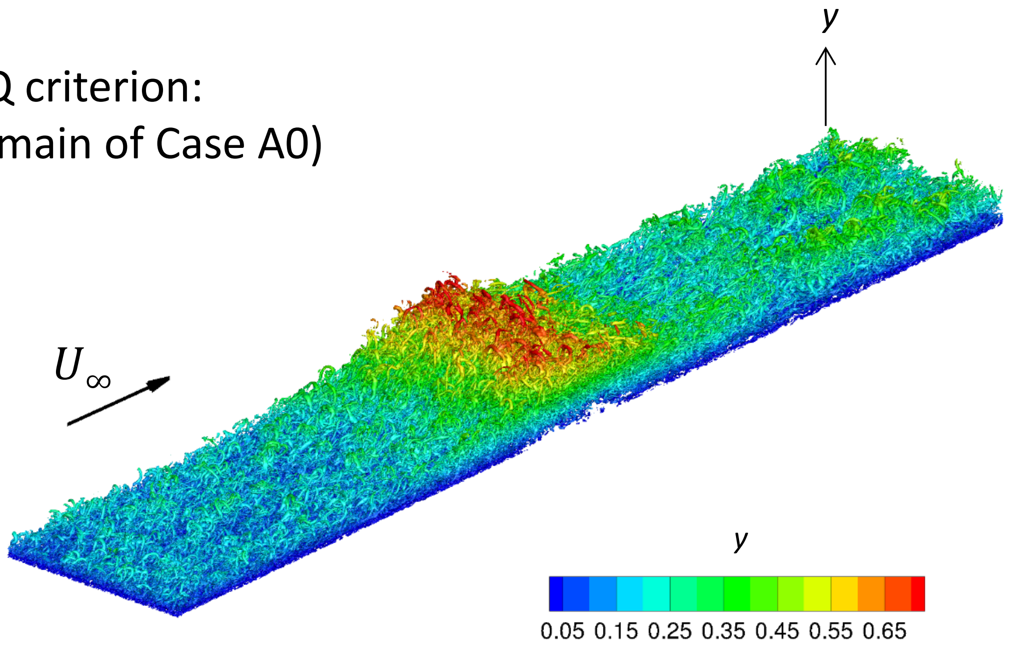
**NASA Langley Research Center*
***Boeing Commercial Airplanes*

Outline

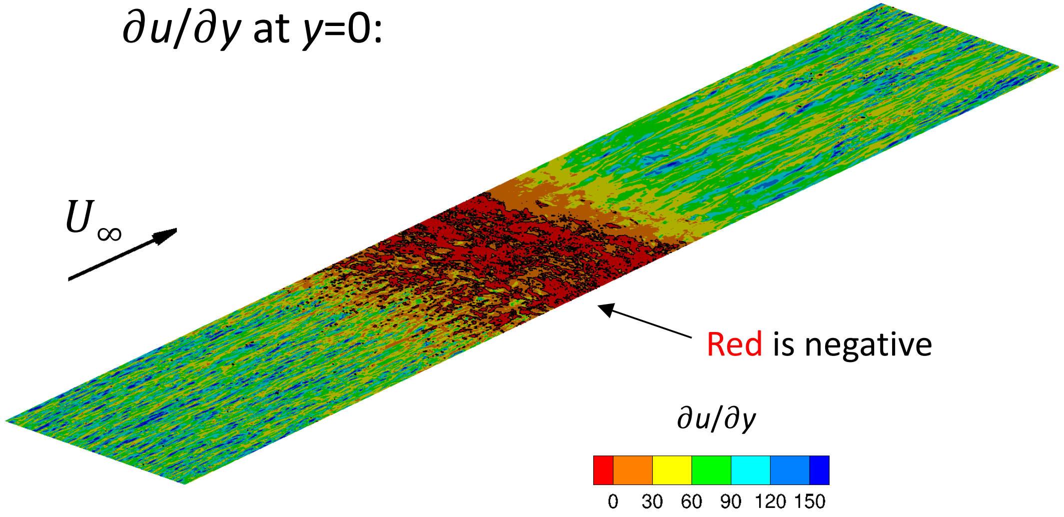
- Flow: *spatial separation bubbles*
  - Extending Spalart & Coleman 97 (Eur J. Mech. B/Fluids 16(2):169-189)
  - Five cases: with/without sweep, sudden/gradual pressure gradient (PG), 2X Reynolds number; larger domain
- Strategy – use DNS data for…
  - “Conventional” uses – Test turbulence theory and RANS modeling…
    - Concepts (Stratford scaling at $C_f = 0$ stations)
    - Predictions (SA, SST, RSM, …) of separation/reattachment locations
  - “Novel” uses – Diagnose *Effective eddy viscosity* for...
    - Full Reynolds-stress tensor
      - RANS model counterparts (check correlation to separation predictions)
      - Frozen-field solutions (check constitutive relationships)
    - Only wall-parallel components, for *cases with sweep*
      - Explore idea of a different eddy viscosity in the *x-z* plane than in the *y* direction
- Summary/Open questions

Flow – Visualization: DNS of PG-induced flat-plate separation bubbles

Q criterion:
(subdomain of Case A0)



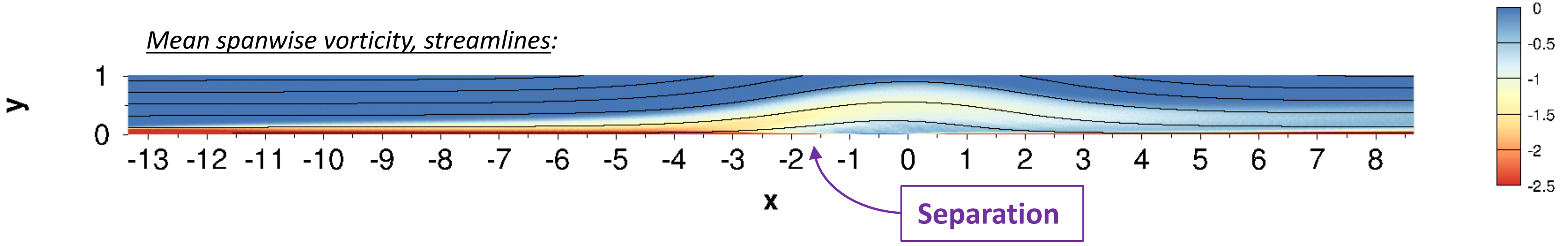
$\partial u/\partial y$ at y=0:

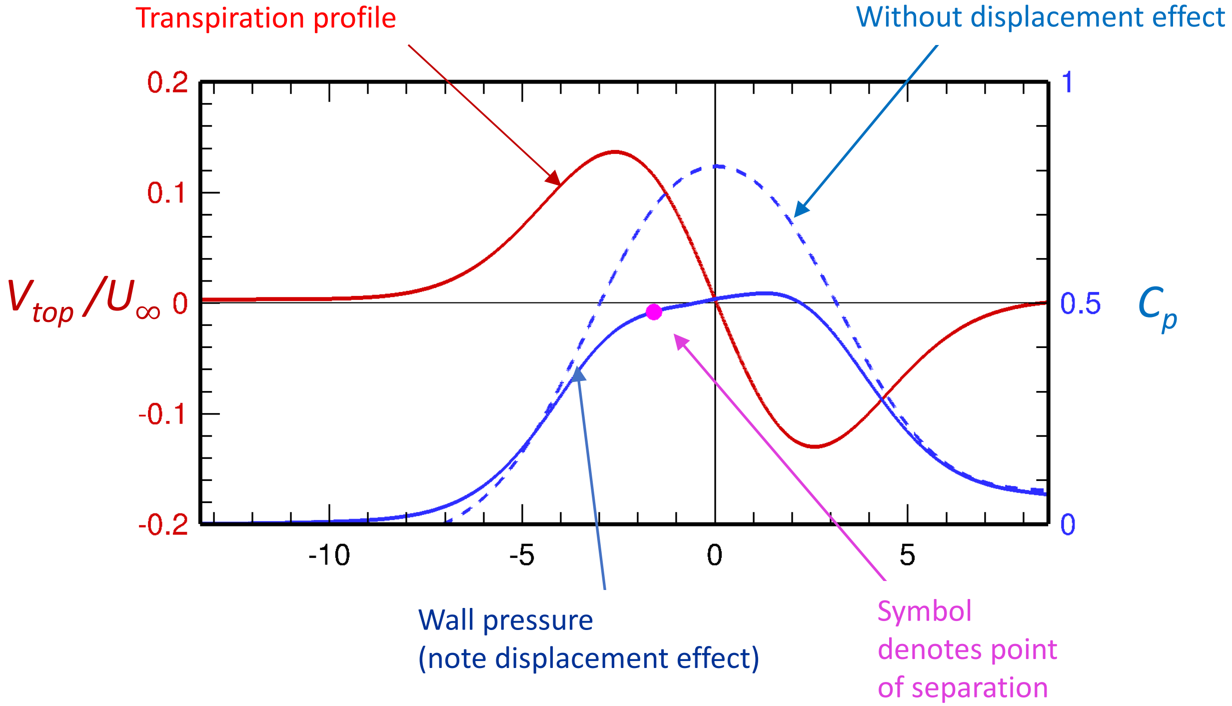


Flow – Mean: DNS of PG-induced flat-plate separation bubbles…

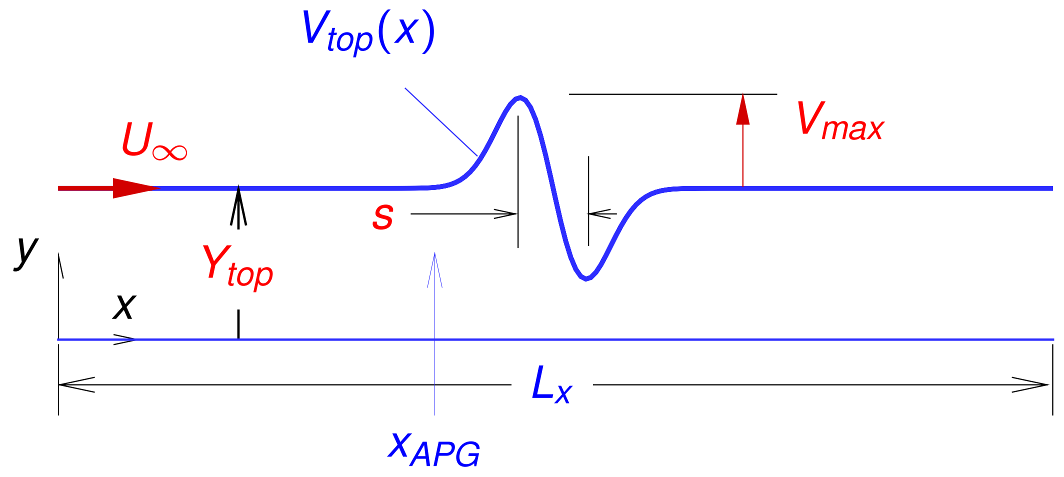
Case C0 (gradual APG, Re=80000):

Mean spanwise vorticity, streamlines:





Cases

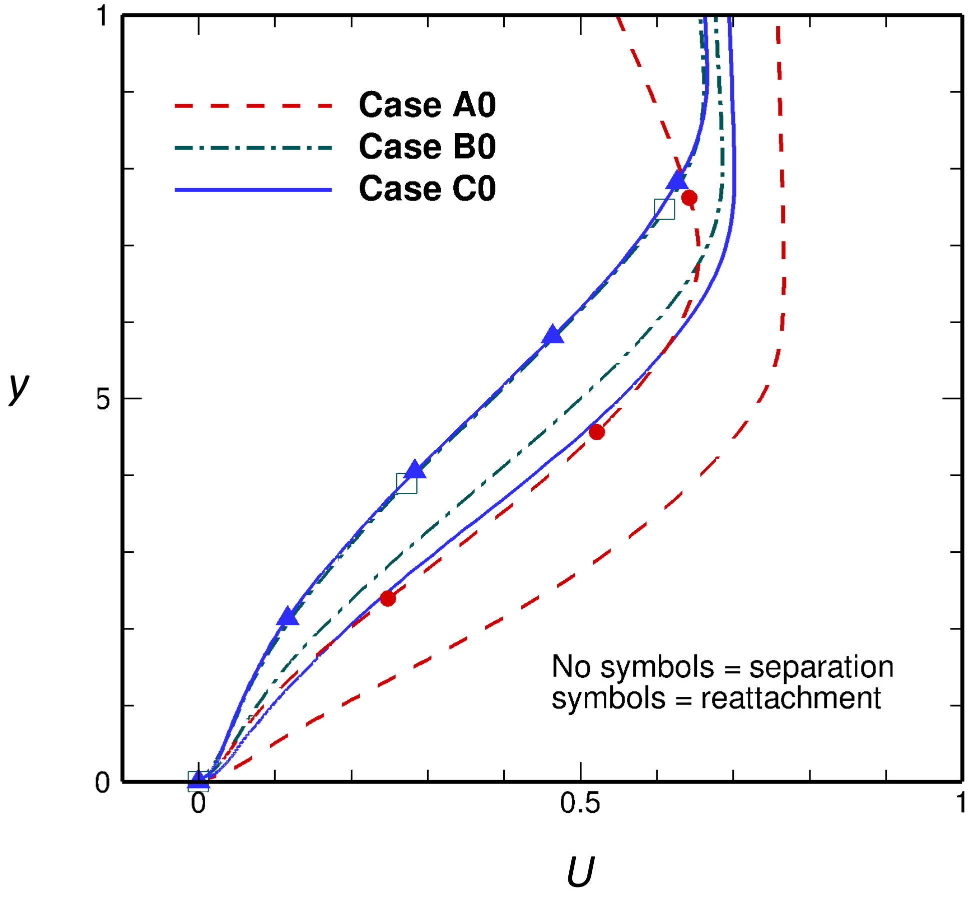


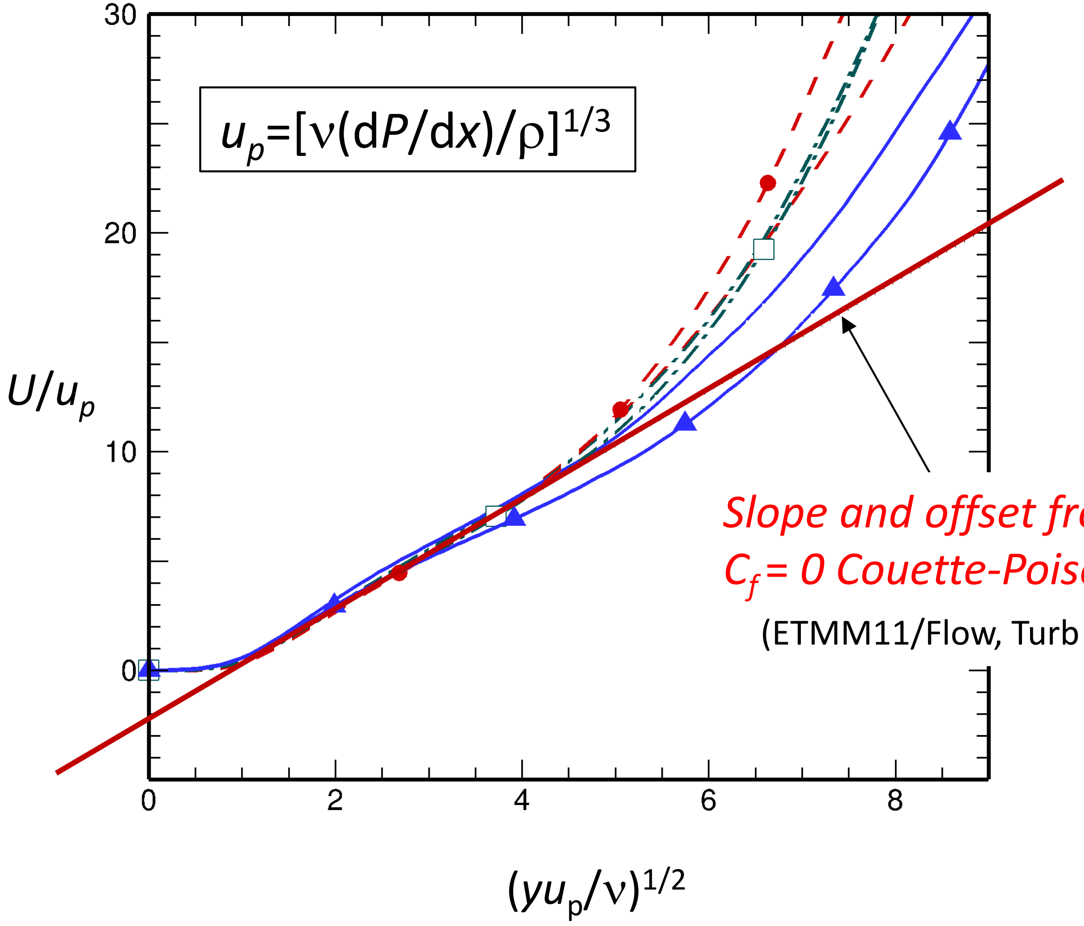
Case	$\arctan\left(\frac{W_\infty}{U_\infty}\right)$	s/Y_{top}	V_{max}/U_∞	$R_\theta\vert_{x_{APG}}$	$N_x \cdot N_y \cdot N_z$
SC97	0°	1.7	0.435	550	0.03×10^9
A0	0°	1.7	0.40	1400	0.98×10^9
B0	0°	5.2	0.13	980	0.98×10^9
C0	0°	5.2	0.13	2200	4.72×10^9
A35	35°	1.7	0.40	1350	1.97×10^9
B35	35°	5.2	0.13	835	1.97×10^9

SC97: $L_x/Y_{top} = 10$, $L_z/Y_{top} = 1.4$

New cases: $L_x/Y_{top} = 26$, $L_z/Y_{top} = 4.0$

”Conventional” strategy – Part 1 of 2: Test theoretical concepts:
Stratford zero-stress velocity scaling ($U \sim \sqrt{y}$)
Profiles at separation and reattachment (all three unswept cases)

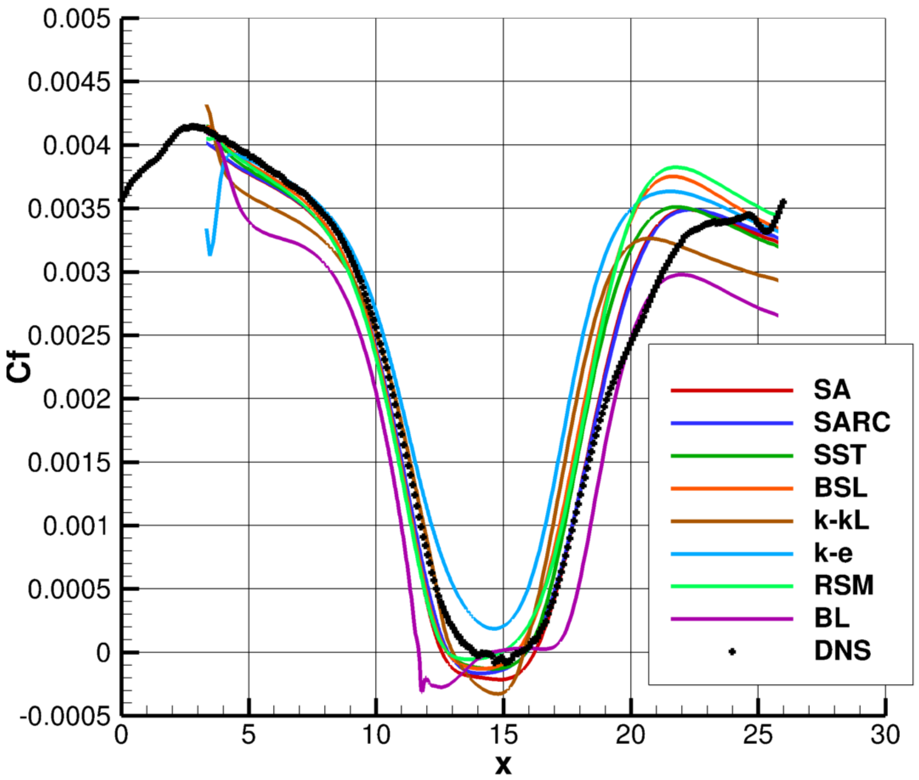


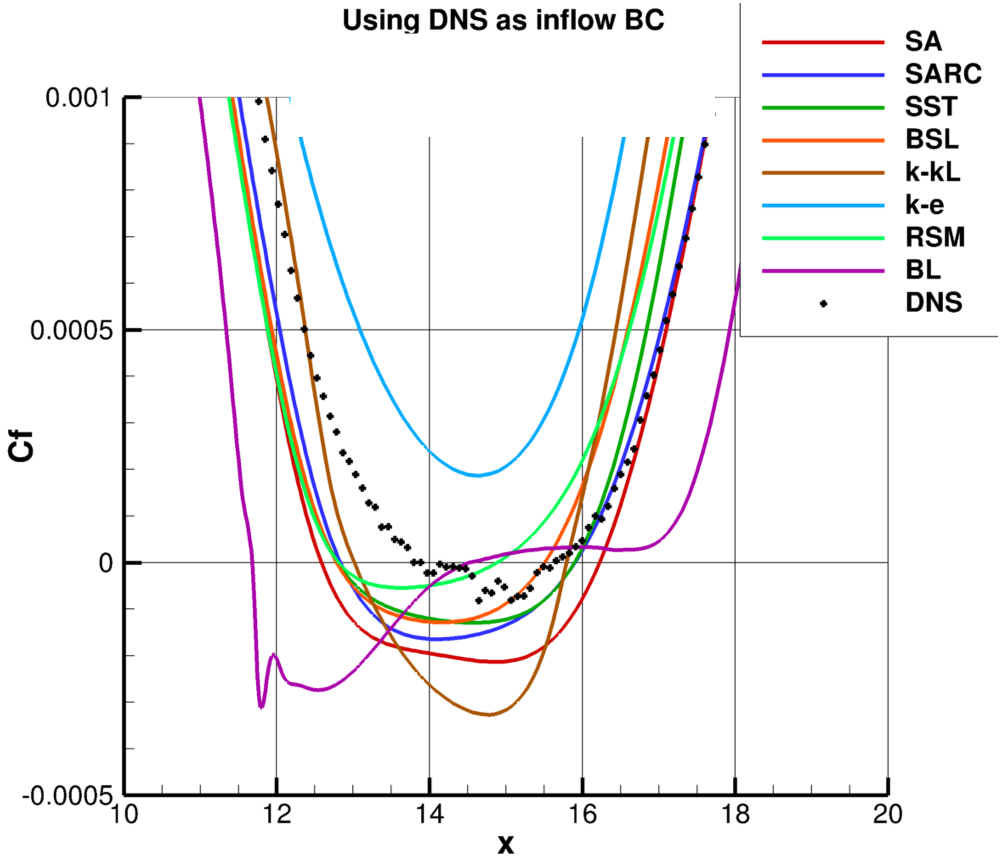


Slope and offset from earlier C_f = 0 Couette-Poiseuille DNS
(ETMM11/Flow, Turb & Comb 2017)

Implication: *Prolonged C_f = 0 region* ***NOT*** *required!*

”Conventional” strategy – Part 2 of 2: Test CFD RANS predictions:
Skin friction profiles/separation & reattachment locations





Solutions via CFL3D, using DNS as inflow BC

Findings:

BL: ***sep too early***
k-e (Abid): ***no sep***
} *As expected, found elsewhere*

SA/SST/RSM/etc: ***somewhat too early and too deep***, and ***together*** (why?)…

(Recovery difficult in its own right)

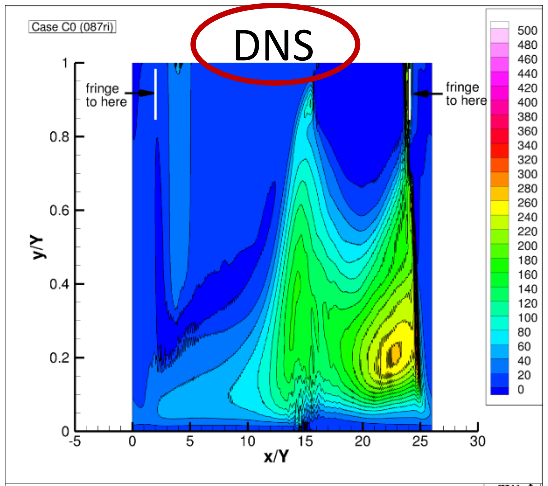
”Novel” strategy - Effective eddy viscosity

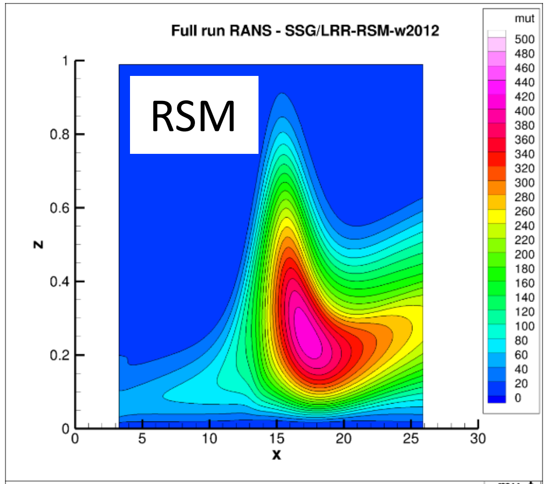
$$\nu_{t,eff} \equiv \frac{\mathcal{P}_{TKE}}{2\mathcal{S}^2} = \frac{-\overline{u_i'u_j'}\,S_{ij}}{2S_{k\ell}S_{k\ell}}, \text{ where } S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right).$$

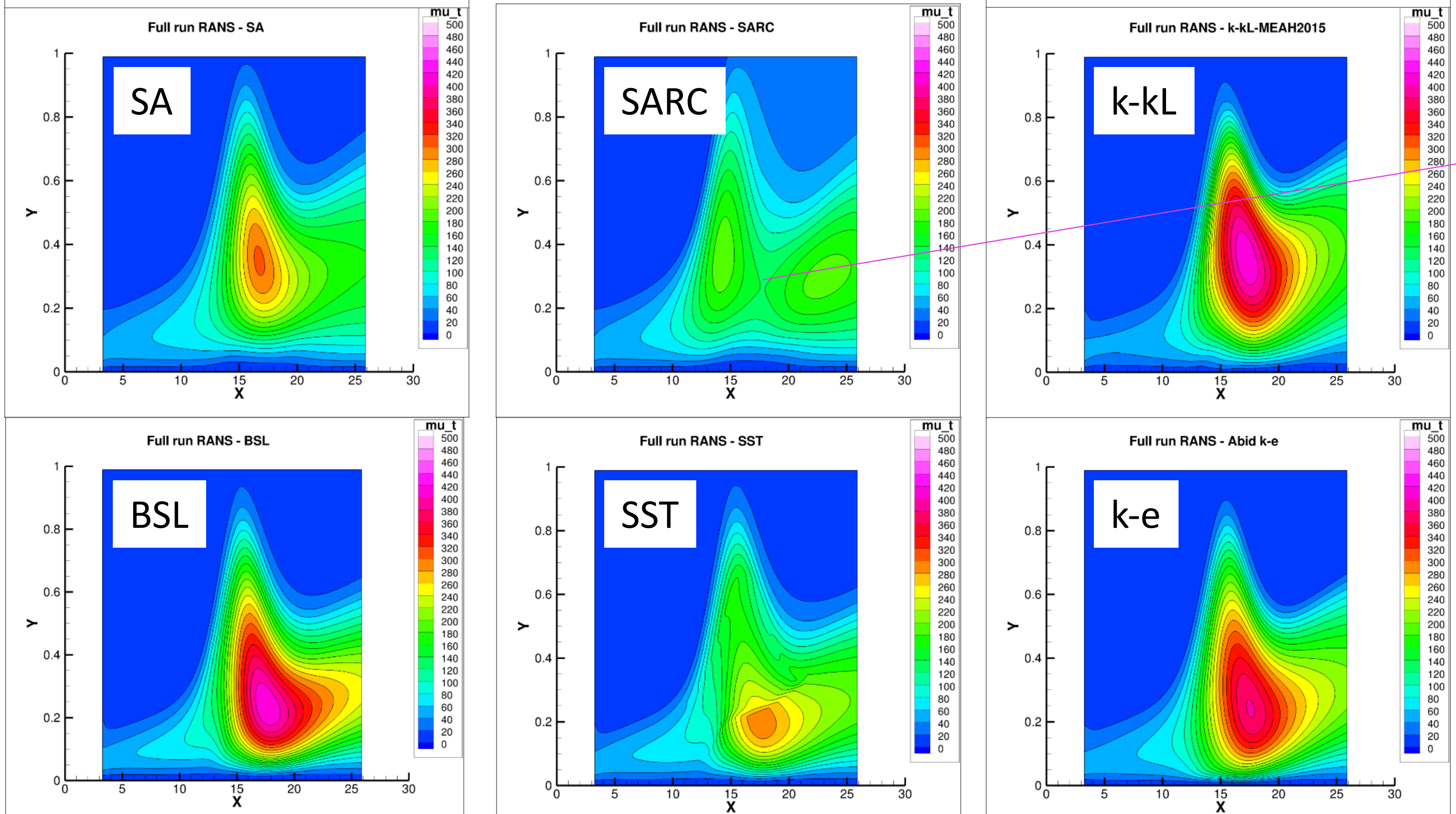
- Follows from Boussinesq approximation and assumed dependence of eddy viscosity on TKE production (to give correct mean-to-turbulence energy transfer)
- Corresponds to least-squares fit of Reynolds stress tensor by scalar eddy viscosity
- Available from DNS, convenient RANS-model diagnostic – *tool for Machine Learning?*
    - Full RANS-model solutions (highlight critical regions)
    - Models solved in “frozen” DNS fields (check constitutive relationship)

RANS eddy viscosity

Using full RANS solutions



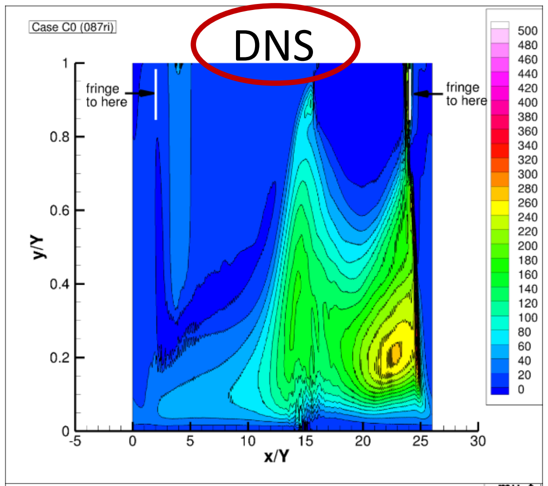


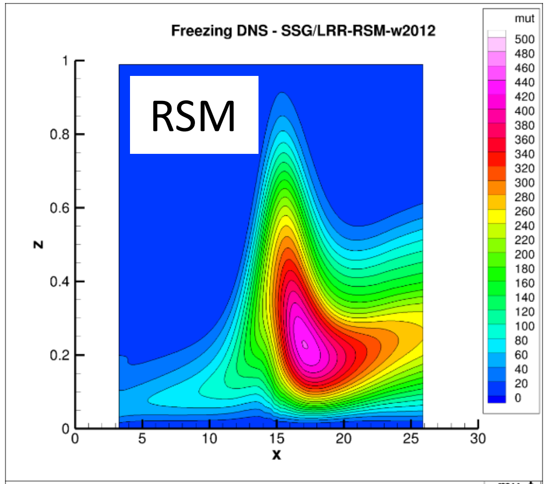


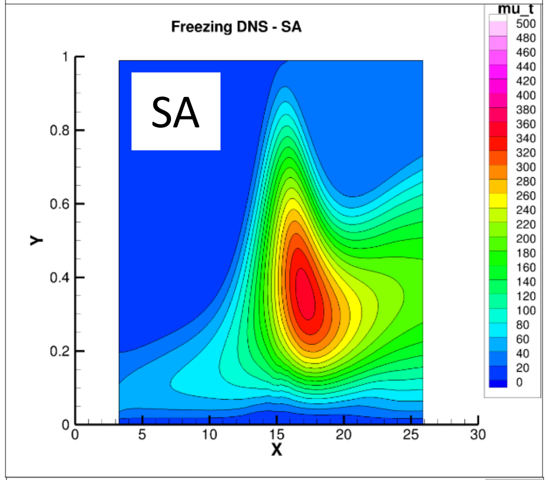
Note similarity to DNS – although little difference between SARC's and SA's $C_f(x)$ predictions (?!🤔...)

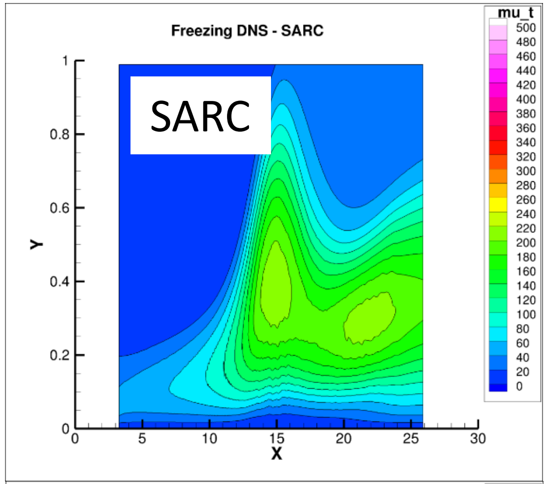
RANS eddy viscosity

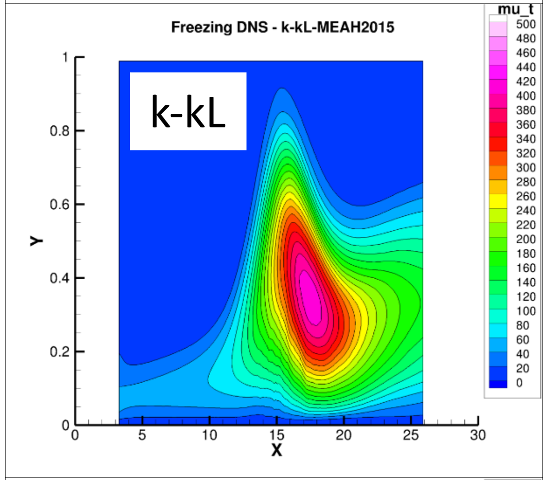
Using frozen DNS mean field

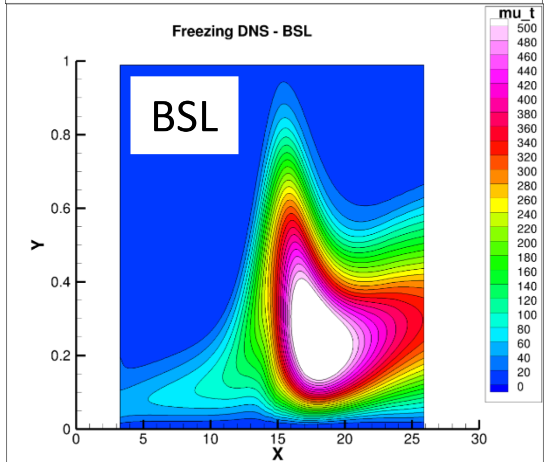


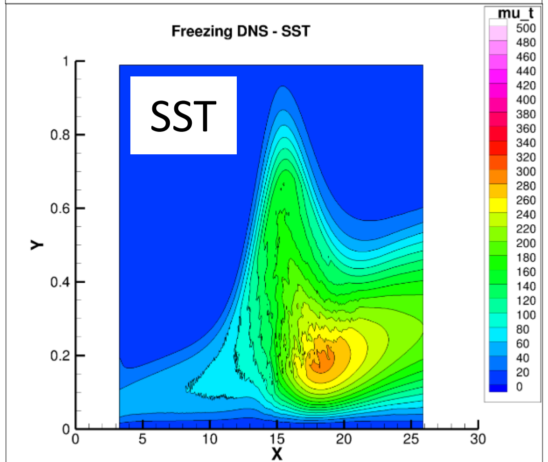


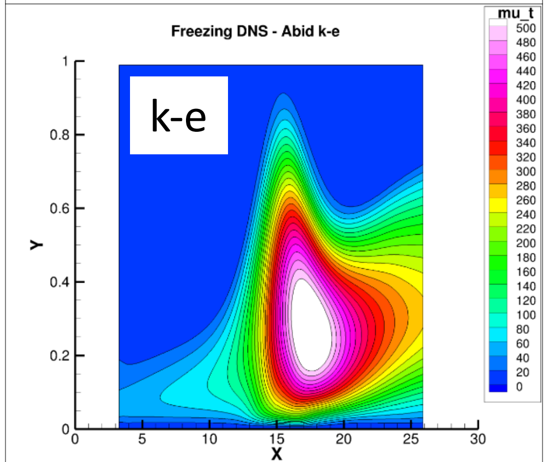












Effective eddy viscosity (cont'd)…

Comment: Effective eddy viscosity tends to be higher for frozen-field solutions than for normal/coupled RANS solutions. *Why?...*

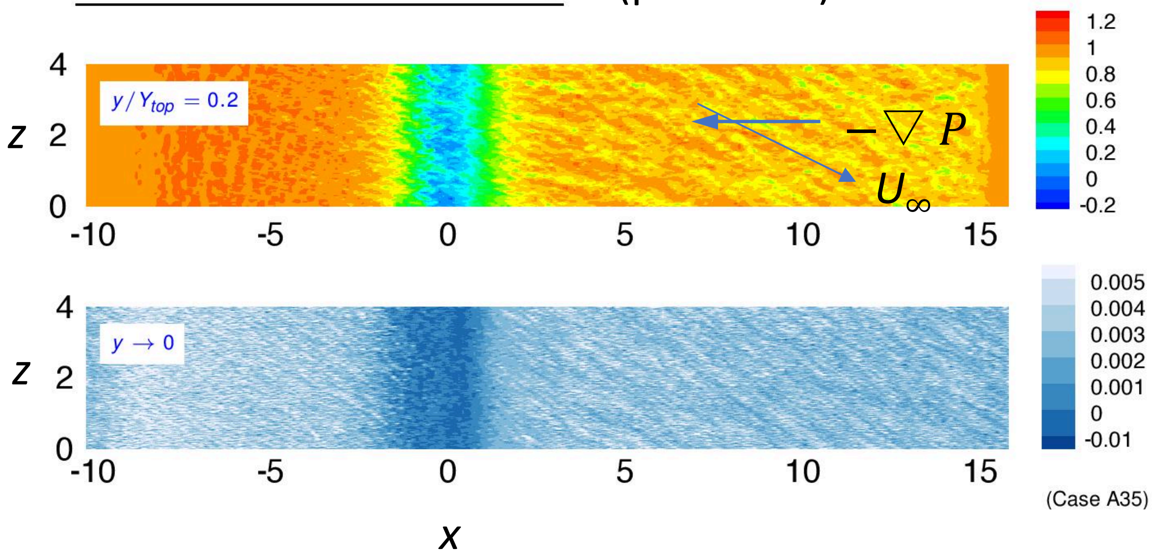
Question: Why did such large differences in eddy viscosity in models produce relatively little difference in $C_f(x)$ predictions? *Near-inviscid behavior in APG region? Common model structure? TBD…*

Effective Eddy Viscosity in Different Directions

- *In the effective eddy viscosity shown earlier, the wall-normal terms dominate: $-\overline{u'v'}$ and S_{12}*
  - *The RANS models are made to favor the wall-normal diffusion*
- *We can define a "lateral" eddy viscosity, possibly quite different from the wall-normal eddy viscosity…*
  - *…And probably larger! Evidence from wall jets, and turbulent wedges in a laminar BL*
- *The first idea is to apply the formula, but only to the strain and stresses in the x-z plane*
  - *Recall that in the past, eddy viscosity in a single direction has been defined, e.g., $-\overline{u'v'}$* / (dU/dy)
- *2D flows don't have an "interesting" strain S_{11} in the x direction…*
- *But the **swept APG flow** has a meaningful strain field in the x-z plane, allowing a non-trivial "$\nu_{t,xz}$" to be defined*

Consider APG-induced separation with **sweep**…

Instantaneous *x*-wise velocity: (plan view)



…and examine

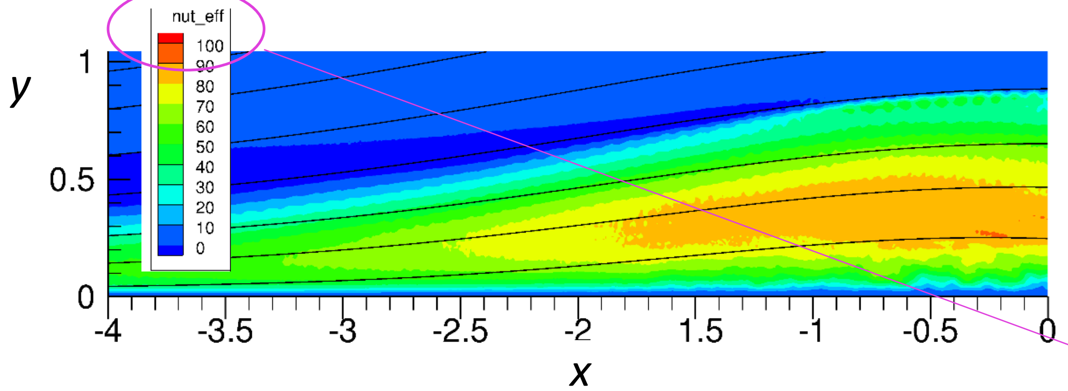
$$\nu_{t,eff} \equiv \frac{\mathcal{P}_{TKE}}{2\mathcal{S}^2} = \frac{-\overline{u_i' u_j'}\, S_{ij}}{2 S_{k\ell} S_{k\ell}}.$$

for *i* = 1,3 ***only***…

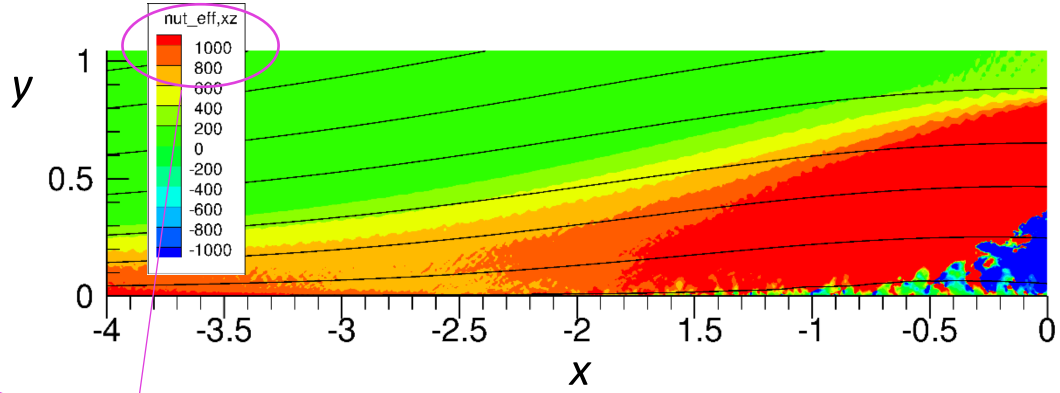
Effective eddy viscosity in wall-parallel plane: i = 1,3 only…

$$\nu_{t,eff} \equiv \frac{\mathcal{P}_{TKE}}{2\mathcal{S}^2} = \frac{-\overline{u_i' u_j'}\, S_{ij}}{2 S_{k\ell} S_{k\ell}}$$

APG region: eff eddy viscosity, all components



APG region: lateral eff eddy viscosity, i = 1,3 only



(!)

- *Very different behavior of effective wall-parallel eddy viscosity may lead to new modeling ideas*
  - *This eddy viscosity is indeed much larger*
  - *And has strong negative excursion at separation*
- *We would have a constitutive relation that incorporates the wall-normal vector*
- *Role for/input to Machine Learning?*

Summary/Open questions

- DNS of spatial separation used to address modeling issues, in conventional and new ways
  - New family of cases, with much "bigger data" than in 1997
- Effective-eddy-viscosity "target" from DNS highlights:
  - model limitations
  - wide variations in eddy viscosity between models (only around separation)
- Correlation between model's separation prediction and eddy-viscosity fields not strong – is it a feature of flow or model?
- Proposed "wall-parallel eddy viscosity" exhibits unexpected behavior
  - Very preliminary concept
- Paper(s) in preparation, data to be made available soon