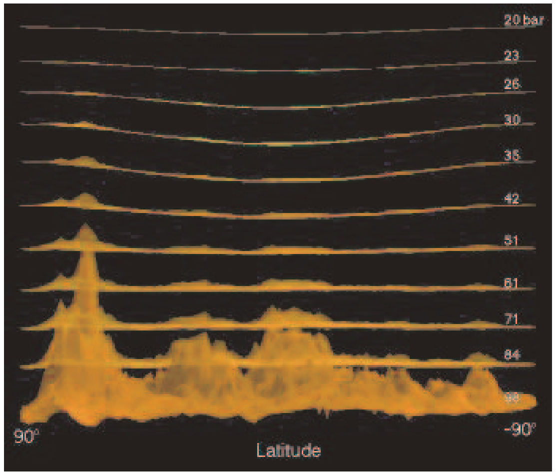
Validation Studies of Detached Eddy Simulation in a Planetary General Circulation Model

R. P. LeBeau, University of Kentucky
T.E. Dowling, University of Louisville

Atmospheric turbulence is a critical in many meteorological phenomena, from the planetary boundary layer (PBL) on Earth to eddy viscosity mixing parameterizations used in atmospheric chemistry. For turbulence effects away from planetary surfaces, a favored technique for modeling turbulence in atmospheric models is Large Eddy Simulation (LES). For the PBL, there is a plethora of numerical models designed to capture the dynamics often through highly parameterized models that rely on data measurements of the atmosphere. As PBL data is not readily available for most planets besides Earth, recalibrating such models for new environments like Venus, Titan, or Triton is a challenge.

The objectives of this project are to reduce the dependence of the PBL model on in situ data so that it is more readily cross-applicable to many planetary systems and to create a unified model that provides turbulence closure from the PBL to the upper atmosphere. Our approach is to draw on recent advances in engineering turbulence research by employing the detached-eddy simulation (DES) concept [Spalart *et al.,* 1997]. Our attraction to DES is threefold: it is able to reproduce benchmark and practical engineering turbulent flows with a high degree of success, it readily fits into eddy viscosity closure models, and it transits smoothly from a Reynolds-Averaged Navier-Stokes (RANS) model in the PBL to a LES model aloft.

Presented results focus on the incorporation of the DES approach into the multi-planet EPIC atmospheric model [Dowling *et al*., 2004] and efforts to validate the model, including reconfiguring EPIC to simulate benchmark engineering flows. This allows for a more precise assessment of the model capabilities than typically more qualitative comparisons against geophysical data.



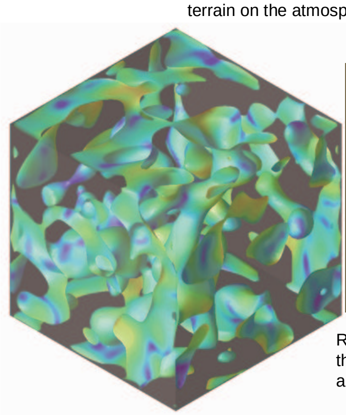
The terrain-following hybrid θ-σ coordinate of the EPIC model applied to Venusian topography. At the surface, the vertical coordinate is purely pressure-based (σ); far away from the surface the coordinate is potential temperature (θ). In between, the two coordinates are blended. To gain the full benefits of this coordinate system requires a planetary boundary layer that can properly simulate the effects of the terrain on the atmosphere.

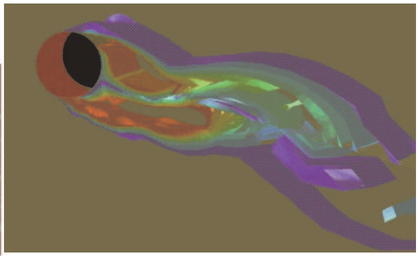
Detached Eddy Simulation

Detached Eddy Simulation (DES) is a hybrid turbulence model developed by Spalart and associates [Spalart *et al*., 1997]. The critical feature of DES is the modification of the traditional "length scale" l within a Reynolds-Averaged Navier-Stokes (RANS) turbulence model as follows:

$$l_{DES} = \min(l_{RANS}, C_{DES}\Delta)$$

where Δ is a measurement of the local grid spacing such as $\Delta = \max(\delta x, \delta y, \delta z)$ and C_{DES} is a parameter that depends on the choice of model. Typically, the length scale for RANS models increases as one moves away from the surface. Thus, near the surface $l_{DES} = l_{RANS} << C_{DES}\Delta$ and the RANS model behaves normally. Away from the surface, $l_{DES} = C_{DES}\Delta << l_{RANS}$, and the RANS formulation becomes a sub-grid-scale model for LES-like (Large Eddy Simulation) turbulence. Below are shown the mathematical details of the DES formulation adapted to two popular RANS models, the one-equation Spalart Allmaras (SA) model [Spalart and Allmaras, 1992] and the two-equation Menter's SST (M-SST) model [Menter, 1994]. The DES approach has been successfully applied to numerous benchmark and application engineering flows. Examples include channel flow [Nitikin *et al.,* 2000], flow over a sphere [Constatinescu and Squires, 2002], flow over a cylinder [Travin *et al.,* 1999; Strelets, 2001], and flow over fighter aircraft [Forsythe *et al.,* 2002].





Results of two standard simulations using DES with the CFD code LESTool. Above is turbulent flow over a cylinder; left is homogeneous turbulence.

DES: Spalart-Allmaras

$$\frac{D\tilde{\nu}}{Dt} = c_{b1}\tilde{S}\tilde{\nu} + \frac{1}{\sigma}\left[\nabla.((\nu+\tilde{\nu})\nabla\tilde{\nu}) + c_{b2}(\nabla\tilde{\nu})^2\right] - c_{w1} f_w \left[\frac{\tilde{\nu}}{d}\right]^2$$

Turbulent Viscosity: $\nu_t = \tilde{\nu} f_{v1}$

Length Scale: $d = \min(d_w, C_{DES}\Delta)$

Distance to Surface: d_w

Local grid spacing: $\Delta = \max(\delta_x, \delta_y, \delta_z)$

Total viscosity: $K_m = (\nu_t + \nu)$

Constants: $c_{b1} = 0.1355$

$c_{b2} = 0.622$

$\sigma = 2/3$

Functions: $\tilde{S} = S + \frac{\tilde{\nu}}{(\kappa d)^2} f_{v2}$

$$f_{v1} = \frac{\chi^3}{\chi^3 + c_{v1}^3}; \chi = \frac{\tilde{\nu}}{\nu}$$

$$f_{v2} = 1 - \frac{\chi}{1+\chi f_{v1}}$$

Auxiliary functions: $c_{w1} = \frac{c_{b1}}{\kappa^2} + \frac{1+c_{b2}}{\sigma}$

$$f_w = g\left(\frac{1+c_{w3}^6}{g^6 + c_{w3}^6}\right)^{1/6}$$

DES: Menter SST

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \frac{\tau_{ij}}{\rho}\frac{\partial U_i}{\partial x_j} + \frac{\partial}{\partial x_j}\left[(\nu + \sigma_k \nu_t)\frac{\partial k}{\partial x_j}\right] - \beta^* \omega k$$

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \frac{\gamma}{\rho \nu_t}\tau_{ij}\frac{\partial U_i}{\partial x_j} - \beta\omega^2 + \frac{\partial}{\partial x_j}\left[(\nu + \sigma_\omega \nu_t)\frac{\partial \varepsilon}{\partial x_j}\right]$$

$$+ 2(1-F_1)\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}$$

$$\nu_t = \frac{a_1 k}{\max(a_1\omega; \Omega F_2)}$$

where, k - turbulent kinetic energy

ω - specific dissipation rate

ν_t – turbulent viscosity

Ω - local vorticity

$a_1 - 0.31;$

$F_2 = 1$, for boundary layer flows

$= 0$, for free shear flows

For all constants, $\phi = F_1\phi_{k-\omega} + (1-F_1)\phi_{k-\varepsilon}$

$$\arg_1 = \min\left[\max\left(\frac{\sqrt{k}}{0.09\omega y}; \frac{500\nu}{y^2\omega}\right); \frac{4\rho_{\omega 2}k}{CD_{k\omega}y^2}\right]$$

$$CD_{k-\omega} = \max\left[\frac{2\rho\sigma_{\omega 2}}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}; 10^{-20}\right]$$

$$l_{k-\omega} = k^{1/2}/(\beta^*\omega); \tilde{l} = \min(l_{k-\omega}, C_{DES}\Delta)$$

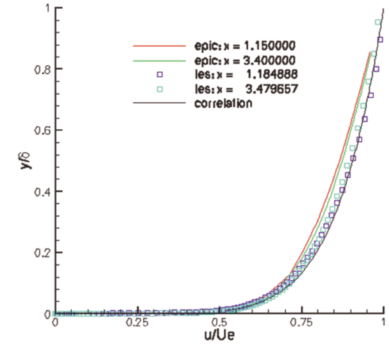
$$\beta^* = 0.09; \sigma_{\omega 1} = 0.5; \sigma_{\omega 2} = 0.856$$

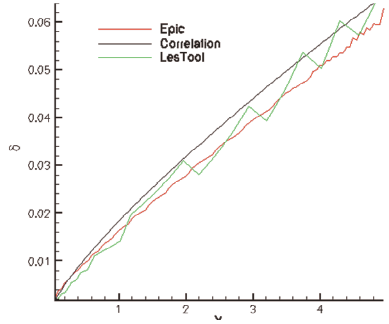
DES in the EPIC Atmospheric Model

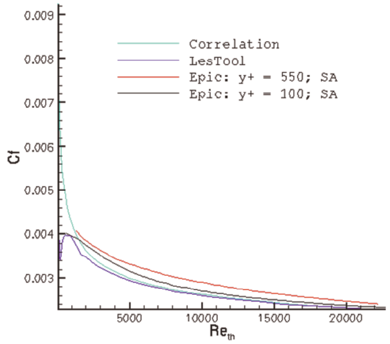
Several modifications to the standard DES models are required to incorporate them into the EPIC GCM. These include:

- changing the vertical gradients from altitude (z) to the hybrid potential temperature-pressure (θ–σ) coordinate used in EPIC
- determining sufficiently accurate surface boundary conditions
- adjusting for the shallow nature of atmospheres in which the horizontal scales are much longer than the vertical scales
- including the buoyancy effect on turbulence generation

The latter two points are not critical for simulating the engineering benchmark cases, but come into play for atmospheric geophysical flows. The current approach to the boundary is based on a log-law profile. Variations of this profile can account for surface roughness, a convenient means to include subgrid terrain effects.







The three plots above show sample results from validation tests for turbulent flat plate flow. EPIC results using the SA-DES model and the law-of-the-wall boundary are compared against the standard correlations based on the Karman-Schoenherr correlation combined with a n = 1/7 power-law profile and against the computational results from LESTool in which the initial grid spacing was within the viscous sublayer ($y^+ < 1$). For the normalized velocity profile (y/δ vs. u/U_e) and the downstream growth of the boundary layer (δ vs. x), the initial grid spacing is $y^+ = 100$ in EPIC; for the coefficient of friction plot (C_f vs. Re_θ), two different values of initial y^+ are shown. Please note that calculation of the LESTool values for δ are relatively crude, leading to the jagged appearance.

Acknowledgements

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