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HYBRID LARGE EDDY SIMULATION/REYNOLDS AVERAGED NAVIER-STOKES FORMULATION FOR NUMERICAL WEATHER PREDICITON

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Presentation Outline

1. Motivation for the Proposed Approach
2. Review of the Statistical Approaches for Describing Optical Turbulence
3. Proposed treatment of Optical turbulence
4. Comparison with experiment
5. Suggestions for improving Numerical Weather Prediction Codes
6. Concluding Remarks

Motivation

1.About five years go, we started an effort at North Carolina State University to improve predictions of Atmospheric Optical Turbulence (AOT)

2.AOT refers to turbulence in the atmosphere that causes fluctuations in the refractive index of air.

3.Primary sources of high altitude AOT are gravity waves and jet streams

4.Gravity waves arise from a number of sources including topography, convection and wind shear

5.Turbulence layers resulting from these gravity waves have thicknesses of the order of tens of meters and stretch many kilometers in the horizontal direction

Motivation Cont'd

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6. Weather prediction codes, such as MMS, are used to currently provide velocity, temperature, relative humidity, etc. for calculating the index of refraction structure function. Typical grids in such codes are in the range 4-30 Km in the horizontal direction and 0.3 – 1Km in the vertical direction with some further refinement in the planetary boundary layer

7. As is seen from the above, mesoscale codes present a number of problems:

   a. Resolution is not adequate to resolve sufficiently gravity waves and optical turbulence

   b. Mesoscale turbulence parameterization is suited for Large Eddy Simulation (LES) . However, mesoscale model resolution are not resolving LES scales

8. Parameterization used to calculate Cn^2 is based on rather old turbulence models

Review of Statistical Approaches

1. For wavelength near the visible range, C_n is given by

$$C_n^2 = \left(76 \times 10^{-8} \frac{P}{\theta T} \right)^2 C_\theta^2 \qquad (1)$$

where P is the pressure in Pascals, T and θ are the temperature and potential temperature in Kelvin

2. $$C_\theta^2 = a^2 \in_\theta / \in^{1/3}, \qquad a^2 \simeq 2.8 \qquad (2)$$

where C_θ is the dissipation rate of the variance of potential temperature, and $\in$ is the dissipation rate of the variance of velocity or turbulent kinetic energy (TKE)

3.Assuming a Richardson number of zero, setting production equal to dissipation, assuming turbulent eddy viscosity to be equal to turbulent diffusivity (i.e., Prandtl number of one), and using mixing length theory, the following expression for C_θ^2 is obtained

$$C_\theta^2 = 2.8 L_0^{4/3} \left(\frac{\partial \theta}{\partial z} \right)^2 \qquad (3)$$

where L_0 is the outer length scale and z is the vertical direction.

Current statistical models calculate L_0 in terms of one or more of the following: z, $\partial T/\partial z$, $\partial u/\partial z$ using available experimental data.

Proposed Approach

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1.In order to address resolution issues, a grid adaptation approach is employed. My colleague Dr. Scott McRae has already discussed this topic

2.Instead of using mixing length theory and other simplifying assumptions to derive an expression for C_θ^2, model equations were derived for $\in_\theta$ and ζ (variance of vorticity or enstrophy) = $\in/\nu$, with ν being the kinematic viscosity

3.Rather than employ ad hoc empirical equations for $\in_\theta$ and ζ, equations were derived from the exact Navier-Stokes equations and then parameterized. Similar approach was used to derive a TKE and an equation for the variance of potential temperature.

Proposed Approach Con'd

4.Advantage of above procedure is that one ends up with a set of equations that are tensorially consistent, Galilean invariant, coordinate system independent and contain all relevant physics

5.Because grid resolution is such that LES cannot resolve all scales, a Reynolds Averaged Navier-Stokes (RANS) formulation is seamlessly blended with the LES formulation. This approach ensures that contribution of all scales are taken into consideration

Proposed Approach Con'd

6.As an illustration the TKE has the form

$$\frac{\partial}{\partial t}(\bar{\rho}k) + \frac{\partial}{\partial x_j}(\bar{\rho}\tilde{u}_j k) = \frac{\partial}{\partial x_j}\left[\left(\frac{\mu}{3} + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + \tau_{ij}\frac{\partial \tilde{u}_i}{\partial x_j}$$
$$- (1-\Gamma)\left(\frac{1}{C_k}\frac{\mu_t}{\bar{\rho}}\frac{\partial \bar{\rho}}{\partial x_i}\frac{\partial \bar{P}}{\partial x_i} + C_1\frac{\bar{\rho}k}{\tau_\rho} + \mu\zeta\right) - \Gamma C_d \bar{\rho}\frac{k^{3/2}}{\Delta}$$
$$+ \frac{\bar{\rho}}{\tilde{\theta}}\left[g\delta_{i3} + 2\Omega_0\epsilon_{ijk}\eta_j\tilde{u}_k\right]\widetilde{\theta'' u_i''}$$

$$\nu_t = \frac{\mu_t}{\bar{\rho}} = (1-\Gamma)\nu_{t,RANS} + \Gamma\nu_{t,LES}$$

$$\nu_{t,RANS} = C_\mu \frac{k^2}{\nu\zeta}$$

Proposed Approach Con'd

$$\nu_{t,LES} = C_s \sqrt{k} \Delta$$

$$\Gamma = \tanh\left(\frac{l_\epsilon}{\alpha_1 \Delta}\right)^2$$

$$l_\epsilon = \frac{k^{3/2}}{\nu \zeta}$$

$$\vec{\eta} = [0, \cos\phi, \sin\phi]; \qquad \phi \text{ is the latitude}$$

Proposed Approach Con'd

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$$C_\theta^2 = 2.8\, \epsilon_{\theta,hybrid} / \epsilon_{hybrid}$$

$$\epsilon_{hybrid} = (1-\Gamma)\nu\zeta + \Gamma\frac{k^{3/2}}{\Delta}$$

$$\epsilon_{\theta,hybrid} = (1-\Gamma)\epsilon_\theta + \Gamma C_{h,d}\frac{\widetilde{\theta''^2}^{5/4}\sqrt{C_p}}{\Delta}$$

Comparison with Experiment

Table 1. Model Initialization time and Balloon Launch Time

	Model Initialization Time	Balloon #	Balloon Launch Time
Vandenberg Case	20-Oct-2001 1200 UTC	1	20-Oct-2001 2320 UTC
		2	21-Oct-2001 0235 UTC
		3	21-Oct-2001 0413 UTC
Holloman Case	26-Oct-2003 1200 UTC	1	27-Oct-2001 0252 UTC

Table 2. Attributes of MM5 Grids (Vandenberg case)

Nest	1	2	3
Horizontal Grid Spacing (km)	45	15	5
Time Step (sec)	60	20	$6\frac{2}{3}$
Horizontal Grid Size (number of nodes)	73×73	88×88	121×121
Vertical Grid Size	80		

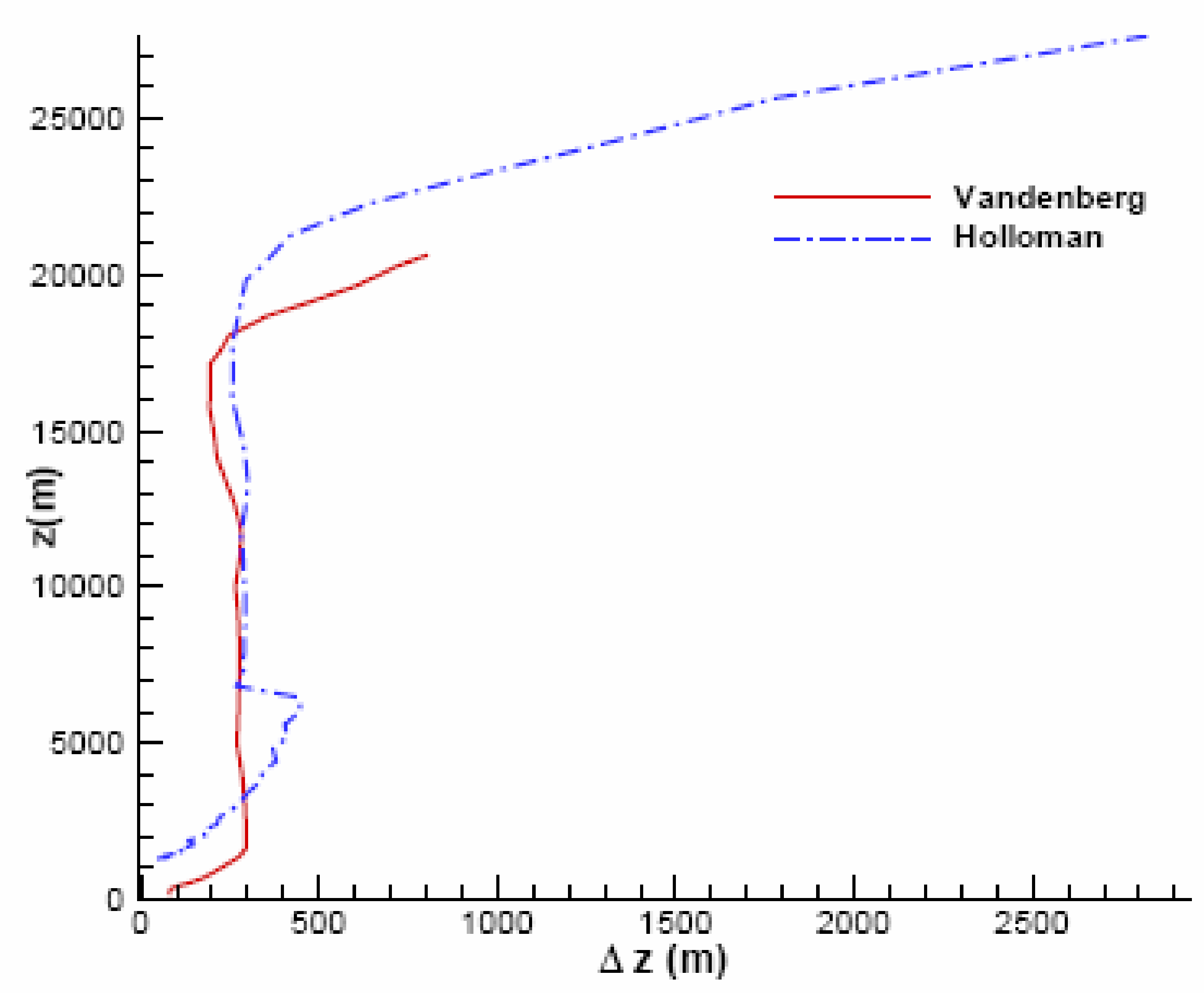

Figure 1. Mesh spacing in the vertical direction

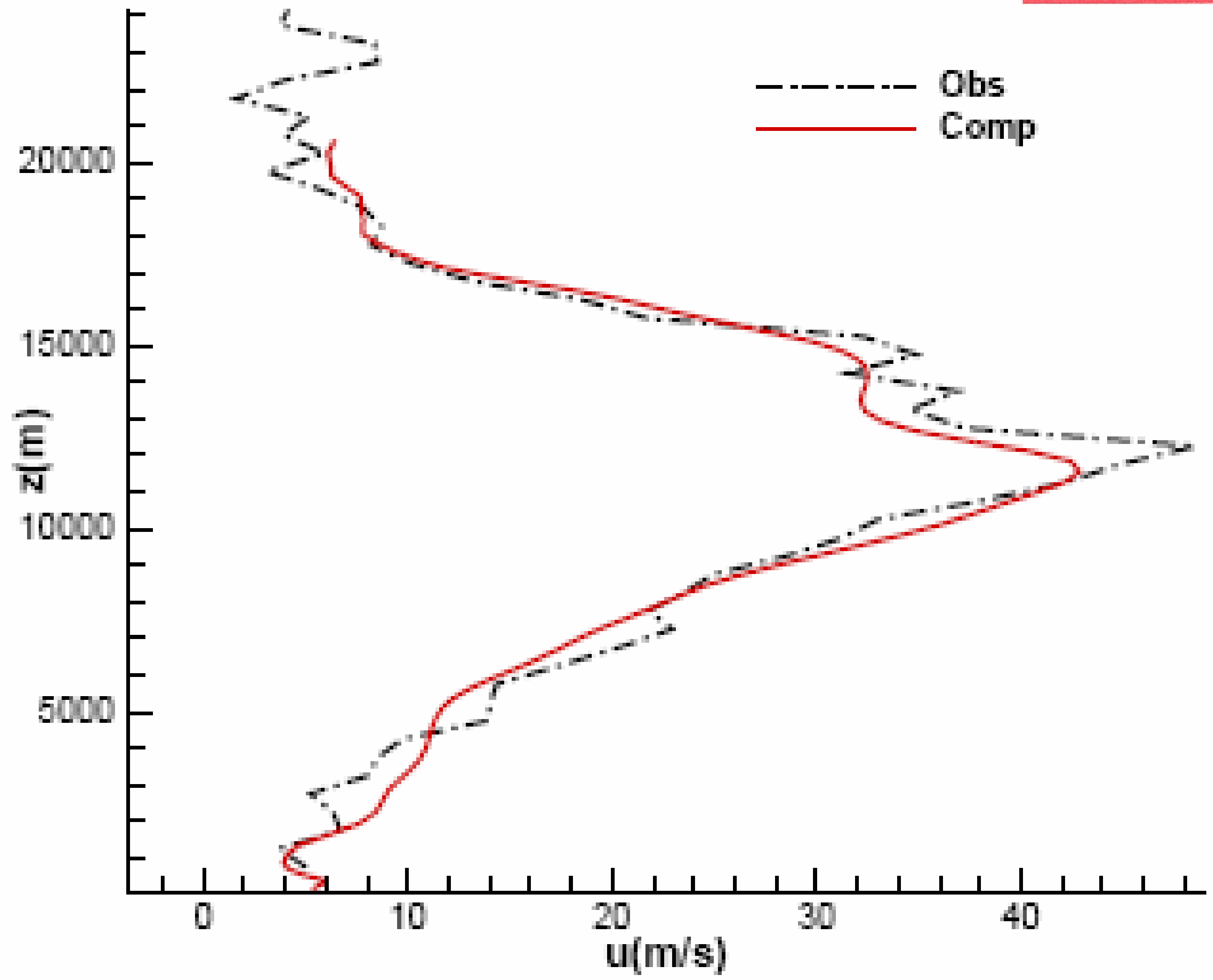

Figure 2. Comparison of *u* Profiles, Vandenberg Case, Balloon 1

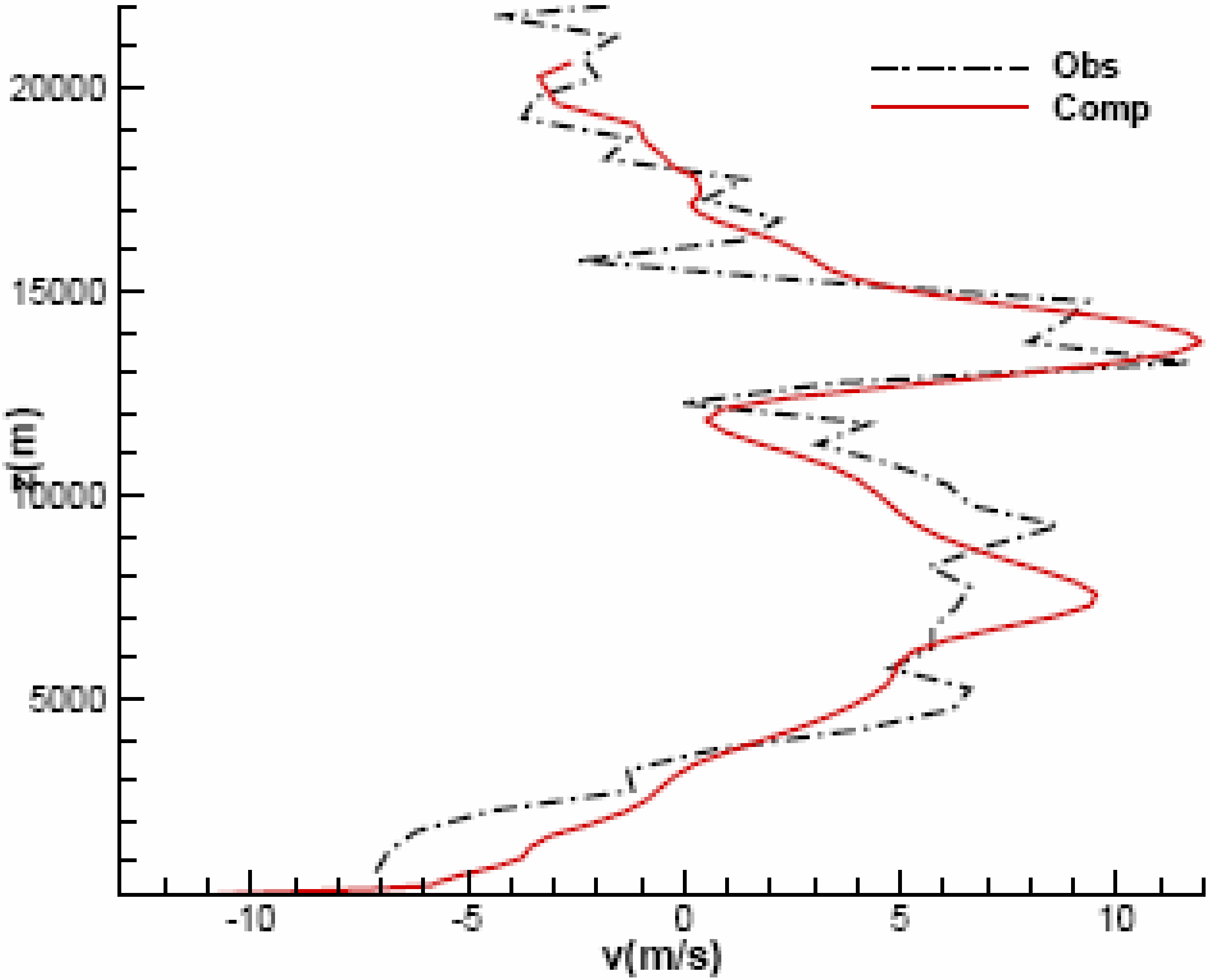

Figure 3. Comparison of ν Profiles, Vandenberg Case, Balloon 1

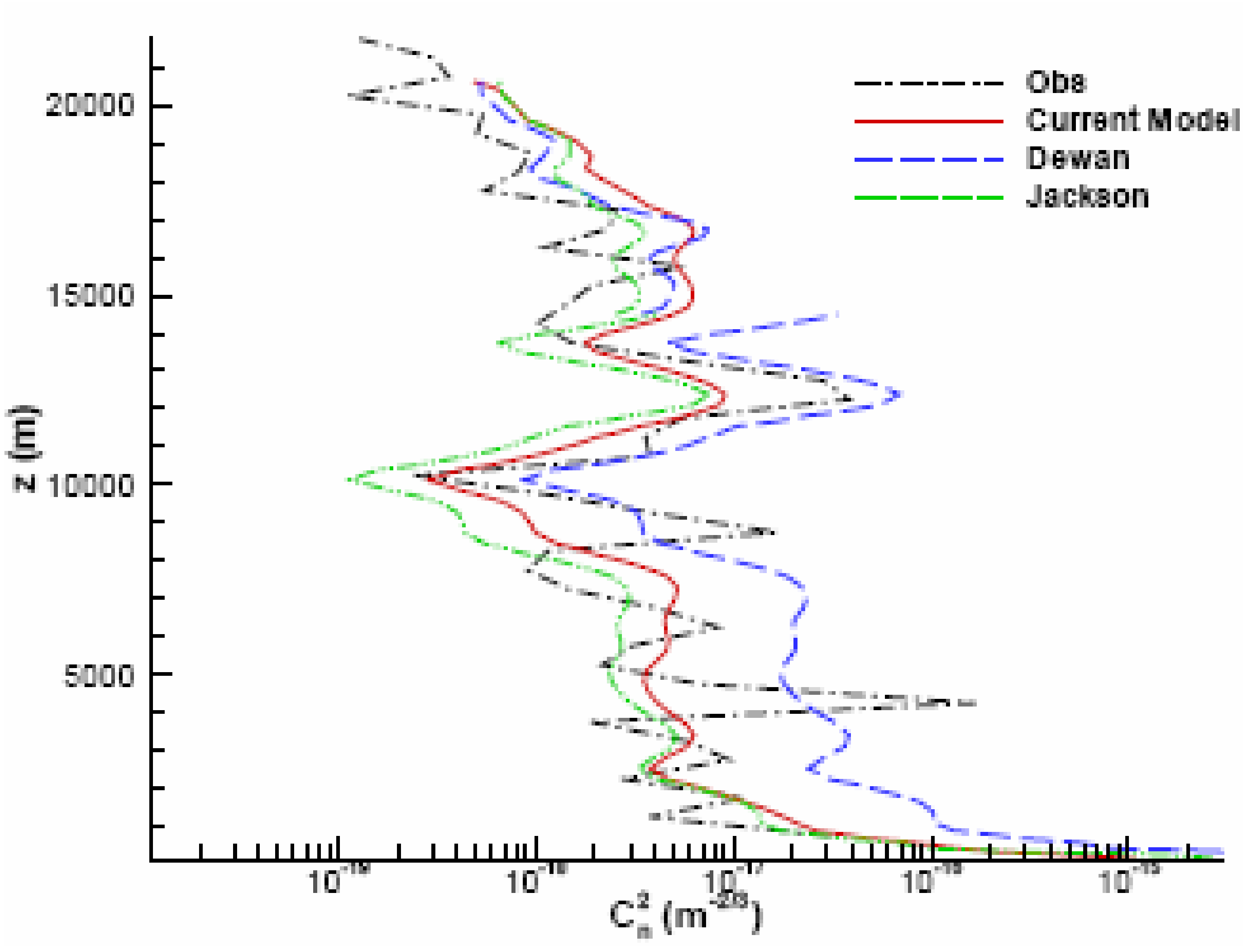

Figure 4. Comparison of C_n^2 Profiles, Vandenberg Case, Balloon 1

Table 3. Attributes of MM5 Grids (Holloman case)

Nest	1	2
Horizontal Grid Spacing (km)	15	5
Time Step (sec)	30	10
Horizontal Grid Size (number of nodes)	109 × 109	163 × 163
Vertical Grid Size	80	

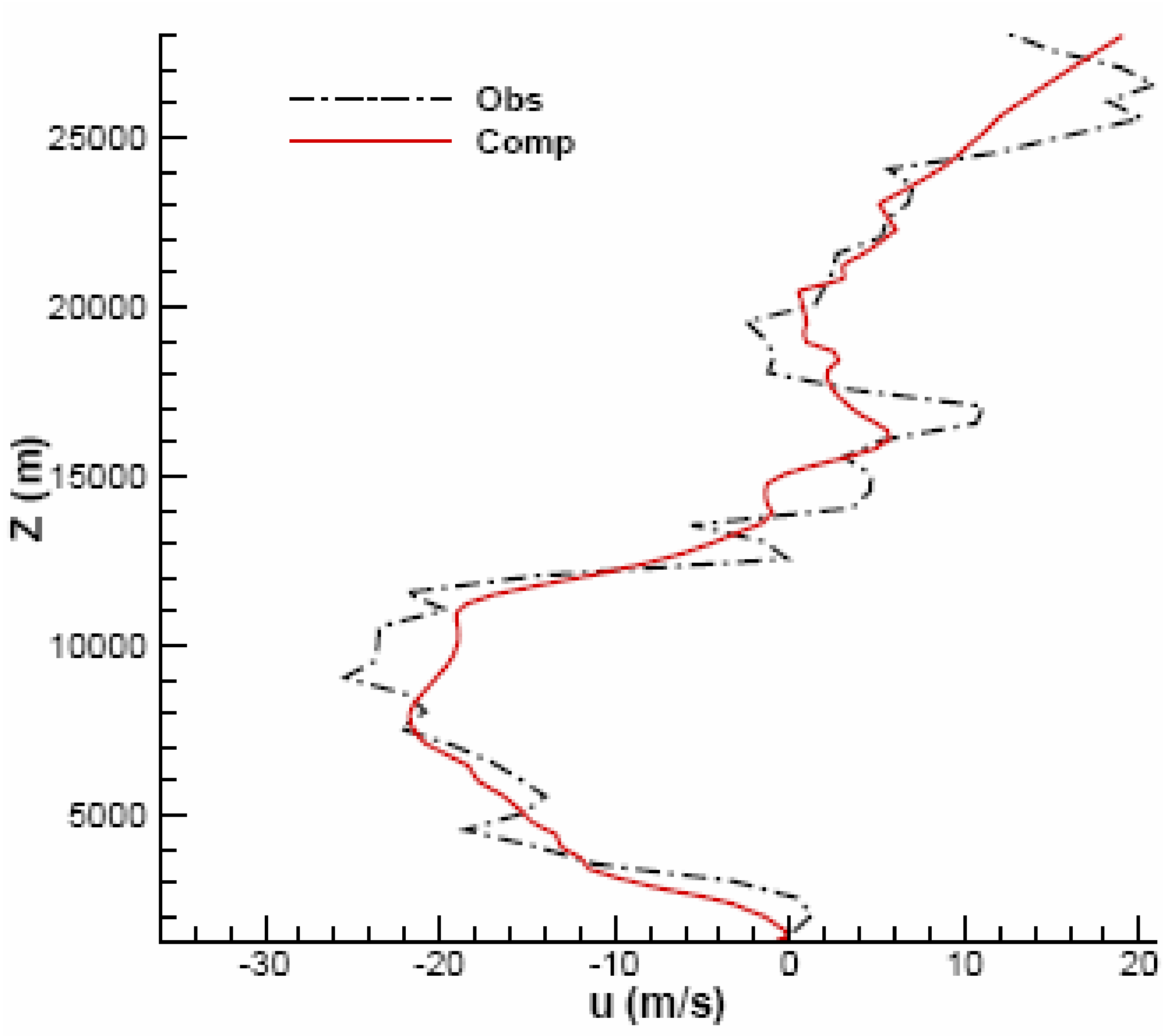

Figure 5. Comparison of *u* Profiles, Holloman Case

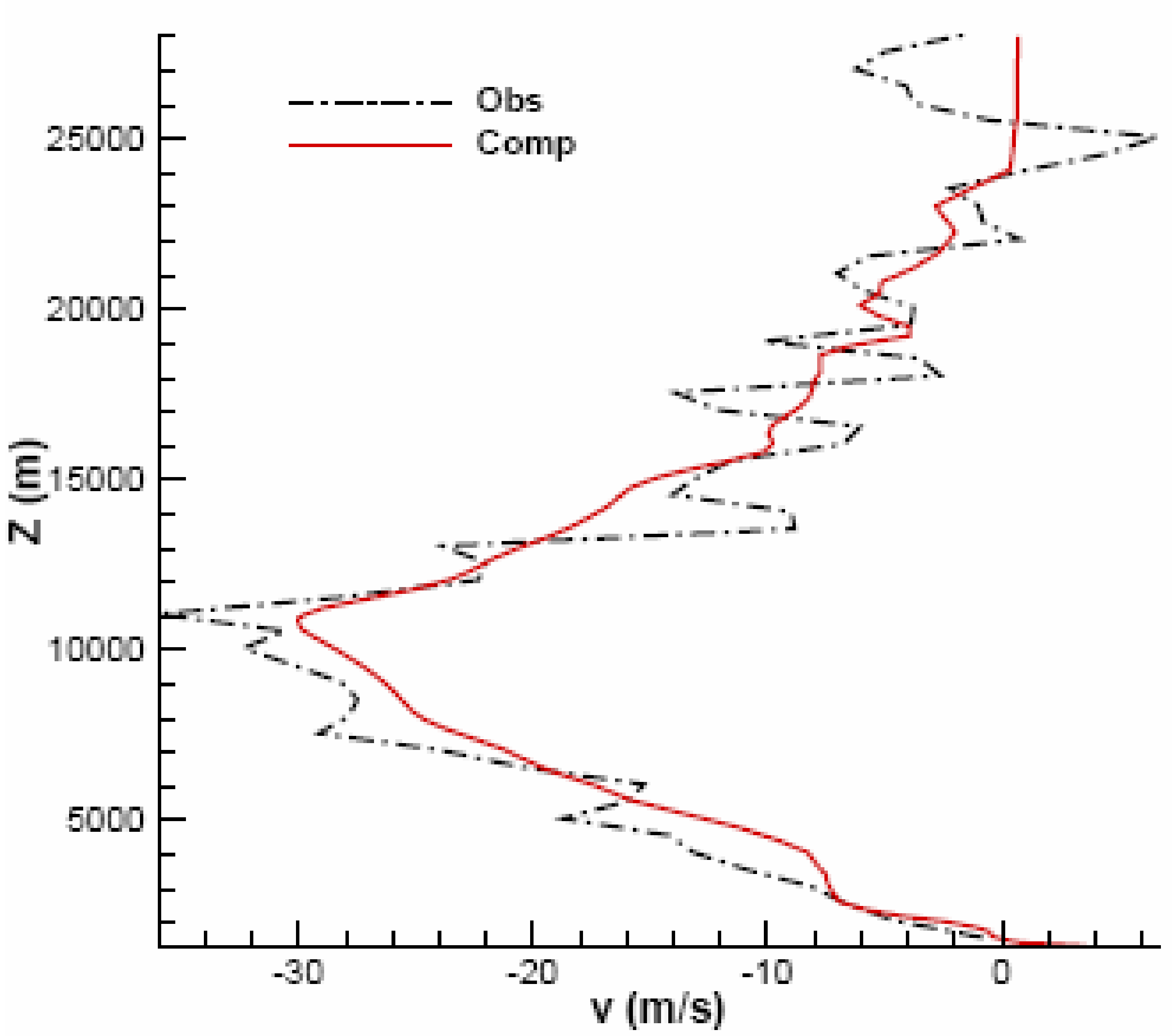

Figure 6. Comparison of *v* Profiles, Holloman Case

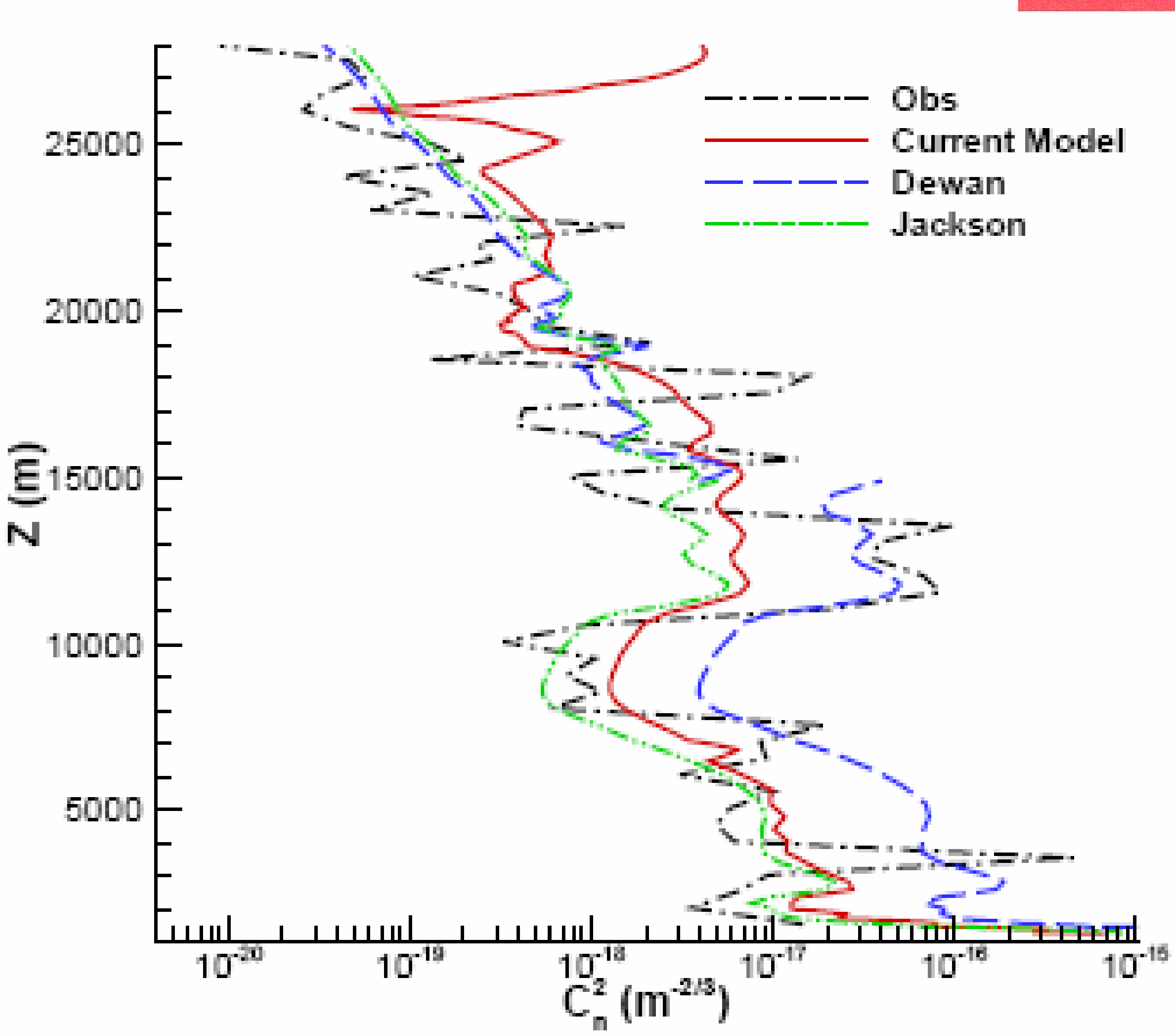

Figure 7. Comparison of C_n^2 Profiles, Holloman Case

Suggestions for Improving NWP Codes

1. Every effort should be made to reduce damping in numerical schemes to the absolute minimum. Moreover, damping should be scaled such that it is reduced when the grid is refined

2. There is a need to improve surface boundary conditions to reflect more accurately the shape and roughness of the torrain.of the terrain

3. There is a need to improve or replace the sponge boundary condition

4. LES cannot resolve all scales. Therefore, there will always be a need to add a RANS component to account for unresolved scales. In this case additional blending functions should be explored.

Suggestions for Improving NWP Codes

5. Some consideration should be given to developing a version of WRF by utilizing preconditioning. The net effect of this is to provide various filtering of acoustic modes depending on local conditions.

Conclusions

1. In spite of the damping that exists in MM5, turbulence models based on the Navier-Stokes equations provide a viable alternative to ad hoc turbulence models and should be used in current and future NWP codes

2. Current model is capable of predicting optical turbulence if numerical damping can be reduced and finer grids are employed in NWP codes.