Simulating Airflow over Terrain using Overture's Cgins Solver

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LLNL-?????

Abstract:
This document describes how to (1) obtain terrain data (elevation data) from the USGS National Map Viewer for a specified region, (2) generate an overlapping grid for this region using Ogen, and (3) simulate the air flow over the terrain using the Cgins incompressible flow solver.

Contents

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1 Introduction

Cgins is an incompressible flow solver built upon the Overture framework. Cgins solves the incompressible Navier-Stokes equations (with Boussinesq approimation for temperature dependent buoyant flows). See [?] and [?] for further details.

The steps for simulating flow over some specified terrain are as follows.

1. Obtain terrain (elevation) data for the domain of interest from the National Elevation Dataset (NED) available from the USGS *National Map Viewer* web site.
2. Use the `readTerrain.m` matlab script to convert the USGS terrain data (in longitude-latitude coordinates) into horizontal coordinates measured in meters and output the result in a data file with format understood by the Overture NURBS mapping.
3. Use the Ogen script `terrainGrid.cmd` to generate an overlapping grid, using the terrain data file from step 2.
4. Use the Cgins script `terrain.cmd` to simulate the flow using Cgins.

These steps are described in further detail in the following sections. Note the relevant scripts (`readTerrain.m`, `terrainGrid.cmd` and `terrain.cmd`) can be found in the directory `cg/ins/runs/terrain` of the CG distribution.

2 Obtaining terrain (elevation) data from the USGS National Map Viewer

Terrain data for a specified region can be obtain from the USGS *National Map Viewer*. Here are the steps.

1. Goto to `http://viewer.nationalmap.gov/viewer/`. (For help see `http://nationalmap.gov/-viewer.html`).
2. Zoom on the map to locate your area of interest (see Figure 1(a)). The pointer coordinates (shown near the bottom) indicate the latitude/longitude of the pointer's current location. This can be used to locate map coordinates for particular latitudes and longitudes. Normally for Cgins you would choose a region that is say 1-10 kilometers on a side.
3. Choose the `Download Data` button (near the top).
4. Choose `click here` to download the current map extent.
5. Check the box to the left of the `Elevation` theme and select `GridFloat` in the options to the right (see Figure 1(b)).
6. You may also want to check the box to the left of `US Topo` to get a topographic figure (pdf file) of a region that includes the domain you selected, or else save the image from the web-browser by printing to a file (this is how map on the right of Figure 2 was created).
7. Enter `next`.
8. Select the box beside *National Elevation DataSet (NED) (1/3 arc second)* (see Figure 1(c)). You may also choose higher resolution *1/9 Arc Second* or lower resolution, *1 Arc Second*, if available. **NOTE:** Choosing *Pre-packaged Float format* will NOT return the selected region but rather a larger region that contains the domain of interest.
9. Enter `next`.

10. On the left panel choose `Checkout` (there is no cost).

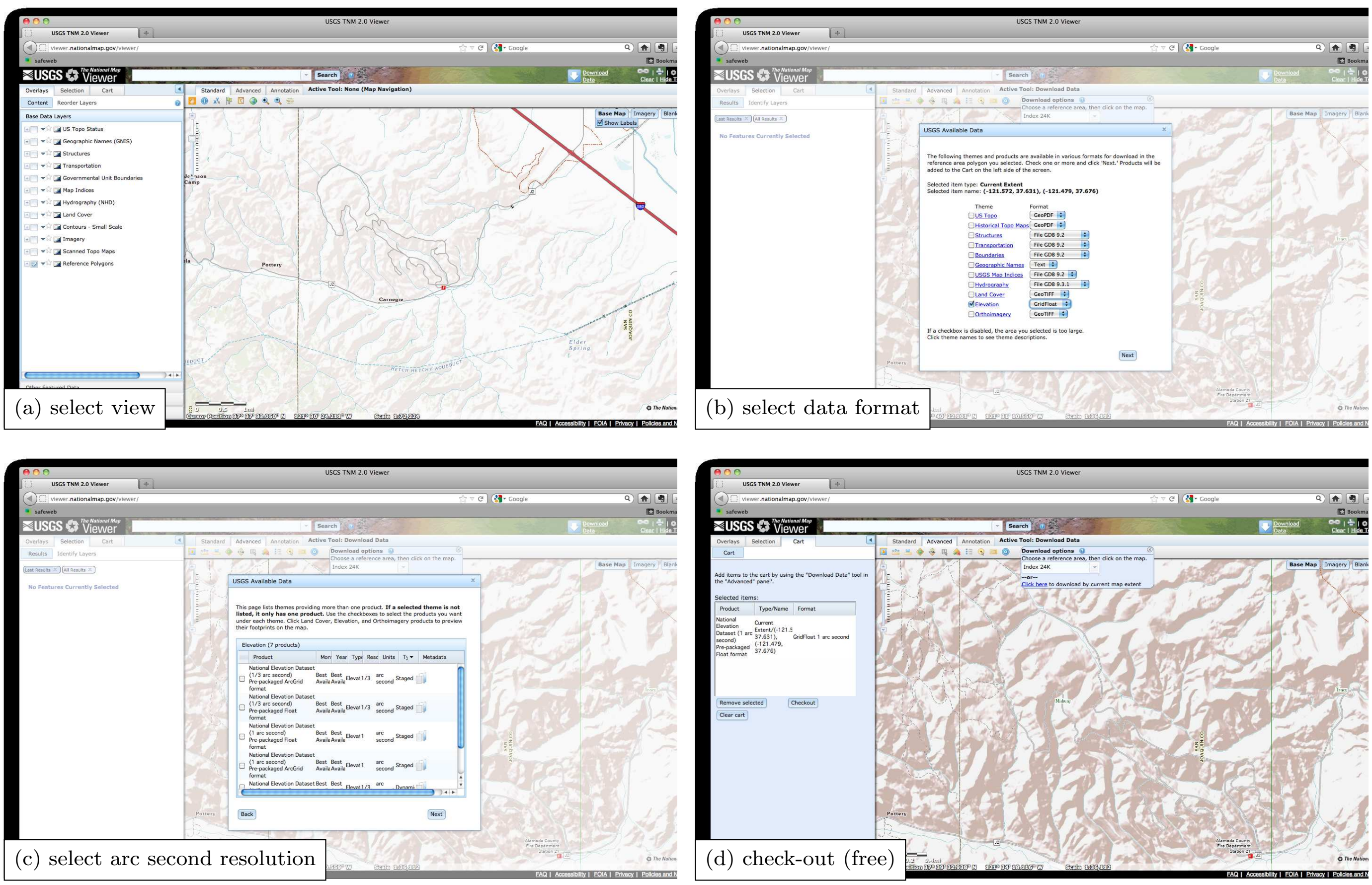
11. On the left panel enter your email address and choose `Place Order` (see Figure 1(d)).

12. You will receive an email with a download link. Download the file and unzip it. This will create a subdirectory (e.g. NED_81691785).

13. The `readTerrain.m` matlab script (see section 3) will read two files in this sub-directory, e.g. `NED_81691785/ned_81691785.hdr` (short header text file) and `NED_81691785/ned_81691785.flt` (elevation data).

Notes:

1. With the 'Index 24K" option (at step 3. above) you can click on the map to choose an area outlined by green lines.



(a) select view (b) select data format (c) select arc second resolution (d) check-out (free)

Figure 1: The National Map Viewer can be used to download terrain data. (a) viewport after zooming to select a region of interest. (b) selecting a format for the data set. (c) selecting the arc second resolution of the data set. (d) *check-out* (it's free of charge).

3 Preprocessing the NED terrain files

The Matlab script `readTerrain.m` (found in `cg/ins/runs/terrain`) reads the NED (National Elevation Dataset) terrain files that were obtained from the USGS web site (Section 2) and generates the files that are needed for generating an overlapping grid with Ogen. The `readTerrain.m` script can be used to

1. extract a sub-domain,
2. extract a cross-section for a two-dimensional simulation,
3. smooth the terrain data,
4. add buffer zones around the terrain region.

See the comments at the top of the `readTerrain.m` script to see the various options.

Figure 2 shows the surface created from a NED file for the region near the Altamont Pass in California. The data files for this region, `AltamontPass.hdr` and `AltamontPass.flt`, are found in `cg/ins/runs/terrain`. The region is centered near $(-121.643519^o, 37.724444^o)$ (longitude 121^o $38'$ 36.6" W and latitude 37^o $43'$ 27.84" N) and the surface was created with the command,

```
readTerrain -file=AltamontPass -name=AltamontPass -plotOption=1 -long0=-121.643519
-lat0=37.724444 -xWidth=3000 -yWidth=3000
```

In this case we have selected a region of size $3000m \times 3000m$ centered at a longitude of -121.643519^o and latitude of 37.724444^o.

In later sections we will consider the flow over the terrain in a part of LLNL's *Site 300* property (see Figure 6). The NED data files for this region are `site300.hdr` and `site300.flt` and are found in the directory `cg/ins/runs/terrain`. Here is the Matlab command to create `site300.dat`,

```
readTerrain -file=site300 -name=site300 -plotOption=2 -smooth=1 -yCrossSection=725
-xCrossSection=600
```

Note that `readTerrain.m` converts the lat-long coordinates from the NED file into meters. This is done using a formula for the arclength between two points on a sphere (known as the haversine formula, see wikipedia)

$$\mathbf{x}_{i,j} = 2R_{\text{earth}} \sin^{-1}\Big(\sqrt{\sin^2((\phi_j-\phi_0)/2) + \cos(\phi_0)\cos(\phi_j)\sin^2((\lambda_i-\lambda_0)/2)}\Big),$$

where $R_{\text{earth}} = 6.3781 \times 10^6 m$ is the radius of the earth, (λ_0, ϕ_0) are the long-lat coordinates (in radians) of the lower left corner of the region and (λ_i, ϕ_j) are the long-lat coordinates of grid point (i, j). **Note 1:** the haversine formula is well conditioned for small distances but has troubles near the poles. **Note 2:** that there is some approximation made in this formula since we are projecting the sphere onto a plane. This approximation should be good if the region is only a few kilometers wide.

As noted, the `readTerrain.m` script can select a sub-domain of the entire terrain data based on a latitude/longitude location and a bounding box. The selected elevation data may be smoothed (this is recommended) using a fourth-order filter in the interior and a second-order filter near the boundary. The extra smoothing near the boundary is done to make the surface more or less horizontal near the boundary. This makes it easier to generate a volume grid where the grid lines on the edges are vertical and thus match to the Cartesian background grids. The terrain data, before and after smoothing, can be plotted from using `readTerrain.m`. Usually the smoothed terrain is nearly indistinguishable from the orginal data in the interior of the domain, while the boundary regions have clearly been smoothed.

The terrain data can also optionally be sliced along a constant value of x or y in order to generate a two dimensional curve for use in two-dimensional Cgins simulations. It is highly recommended that one first perform some two-dimensional calculations in order to get a familiar with Cgins and the various options.

Once the data have been manipulated as desired, they are saved to a data file (e.g. named `AltamontPass.dat` for the command above, `-name=AltamontPass`). This file is read by the Ogen script `terrainGrid.cmd` (see Section 4) to generate an overlapping grid. The data in the file actually defines points on a surface that are used to construct a NURBS (Non-Uniform Rational B-Spline).

Buffer regions can be extended from the terrain region in selected directions in order to provide a smooth terrain profile near the boundaries of the computational region, see Figure 3. A buffer zone may be

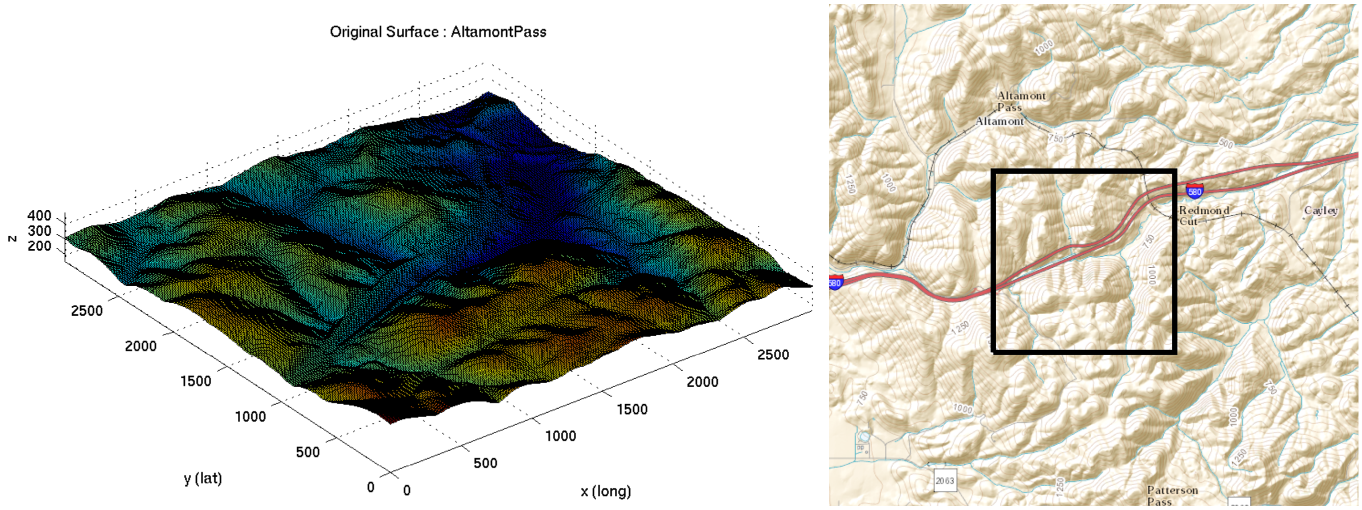


Figure 2: Terrain near the Altamont Pass, CA. Left, surface from `readTerrain.m`. Right: topographic map. The terrain on the left corresponds roughly to the region outlined on the right.

needed at outflow boundaries to prevent strong recirculation regions (from steep terrain near the outflow) from hitting the outflow boundary and causing a locally strong inflow condition that may cause difficulties in the flow solver. The Cgins flow solver has an option `expect inflow at outflow` that can be used at outflow boundaries and with this option buffer zones may not be needed.

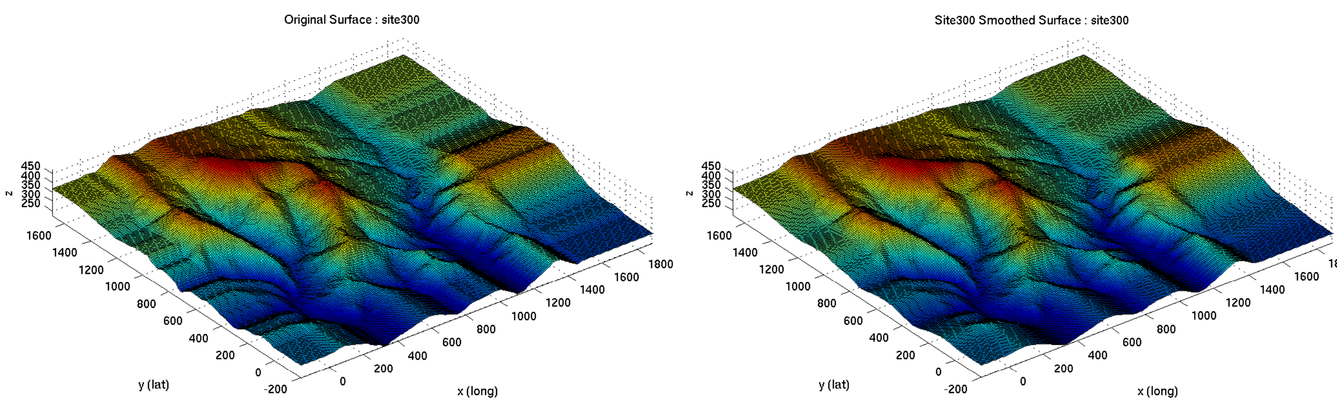


Figure 3: The `readTerrain.m` Matlab script can be used to add buffer zones and smooth the elevation data. Top: original terrain data with buffer zones added (The buffer zones are 20 grid points wide on three sides and 50 grid points wide on the fourth side). Bottom: smoothed terrain data.

4 Generating an overlapping grid with Ogen

Ogen is Overture's overlapping grid generator and is used to cut holes and determine interpolation points [**?**]. The Ogen command file `terrainGrid.cmd` can be used to generate a three-dimensional overlapping grid for a region above the terrain. Here is an example command that generates a grid:

```
ogen -noplot terrainGrid -interp=e -site=site300.dat -prefix=site300 -topLevel=700
-order=4 -factor=4 -ml=2
```

This example generates a fourth-order accurate (-order=4) grid with explicit interpolation (-interp=e) with a target horizontal grid spacing of $20/4 = 5$ m (-factor=4) with two multigrid levels (-ml=2). The grid extends in the vertical direction to a height of $700m$ (-topLevel=700) above the lowest point on the terrain. See the comments at the top of `terrainGrid.cmd` for a full description of the options.

Here are some more details on the grid:

- The data file (e.g. `site300.dat`) generated from `readTerrain.m` (see Section 3) is included in the Ogen script `terrainGrid.cmd`. Note that this data file contains the bounds of the grid in the x and y directions (used to dimension the background grids), in addition to the data points that define the NURBS surface.
- The basic overlapping grid for the terrain consist of a surface-fitted curvilinear grid near the ground surface, a refined Cartesian background grid near the surface (by default extending to a height `-midLevel=300` above the lowest point on the terrain), and a coarsened background grid that extends upward to a height specified by `-topLevel`. A two-dimensional terrain grid is shown in Figure 4, while a three-dimensional grid is shown in Figure 7. The curvilinear grid near the surface is stretched in the normal direction to decrease the spacing near the ground.

5 Simulating the flow over terrain using Cgins

The commands used to run the examples in this Section can be found in `cg/ins/runs/terrain/Readme`.

5.1 Two dimensional computations

We start by first performing some two-dimensional computations. We choose a cross-section through the three-dimensional data. This curve in shown in Figure 6. The two-dimensional grid is shown in Figure 4. Let $\mathcal{G}^{(j)}$ denote the overlapping grid for this domain with a target grid spacing of $\Delta s^{(j)} = 20/j$. A narrow curvilinear *terrain* grid is located next to the terrain surface. This grid is stretched in the normal direction. A fine Cartesian grid is located above the surface. The grid resolution of this grid is $\Delta s^{(j)}$ and matches that of the outer spacing on the terrain grid. A coarser back-ground grid is placed above both these grids with grid spacing $\Delta s^{(j)} \times 2$. The upper elevation of this grid is at 700m above the lowest point on the terrain.

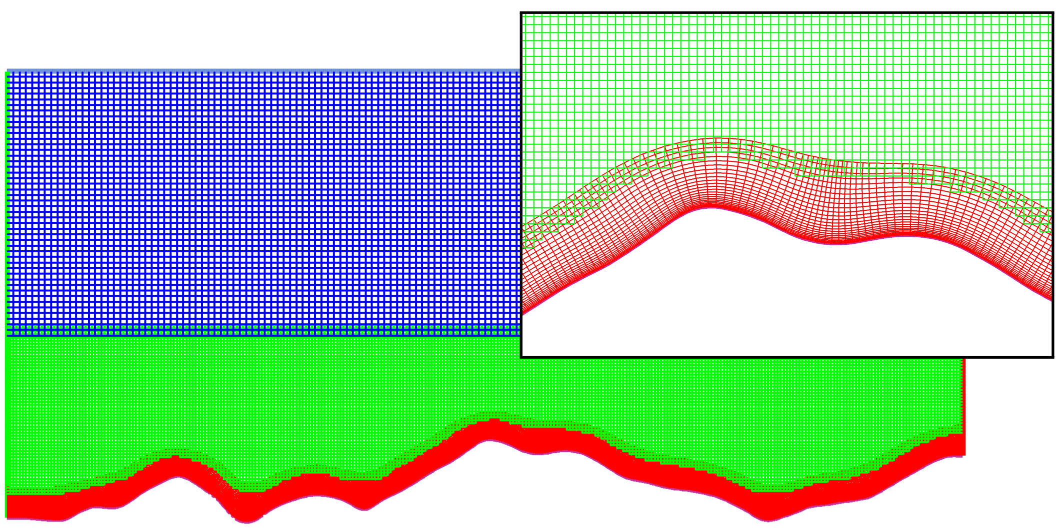


Figure 4: Two-dimensional overlapping grid for a cross-section through the terrain. Grid $\mathcal{G}^{(4)}$ (second-order accuracy) is shown along with a magnified view of the grid near the surface.

Figure 5 shows results for different grid resolutions and different orders of accuracy. The velocity at inflow was specified as a parbolic profile (over a height of 50m) with a maximum value of $10m/s$ ($22.4mph$).

Since we are using an LES model, finer grids will have finer features. The fourth-order accurate results (AF24) are seen to generate much finer scale features and to have less dissipation.

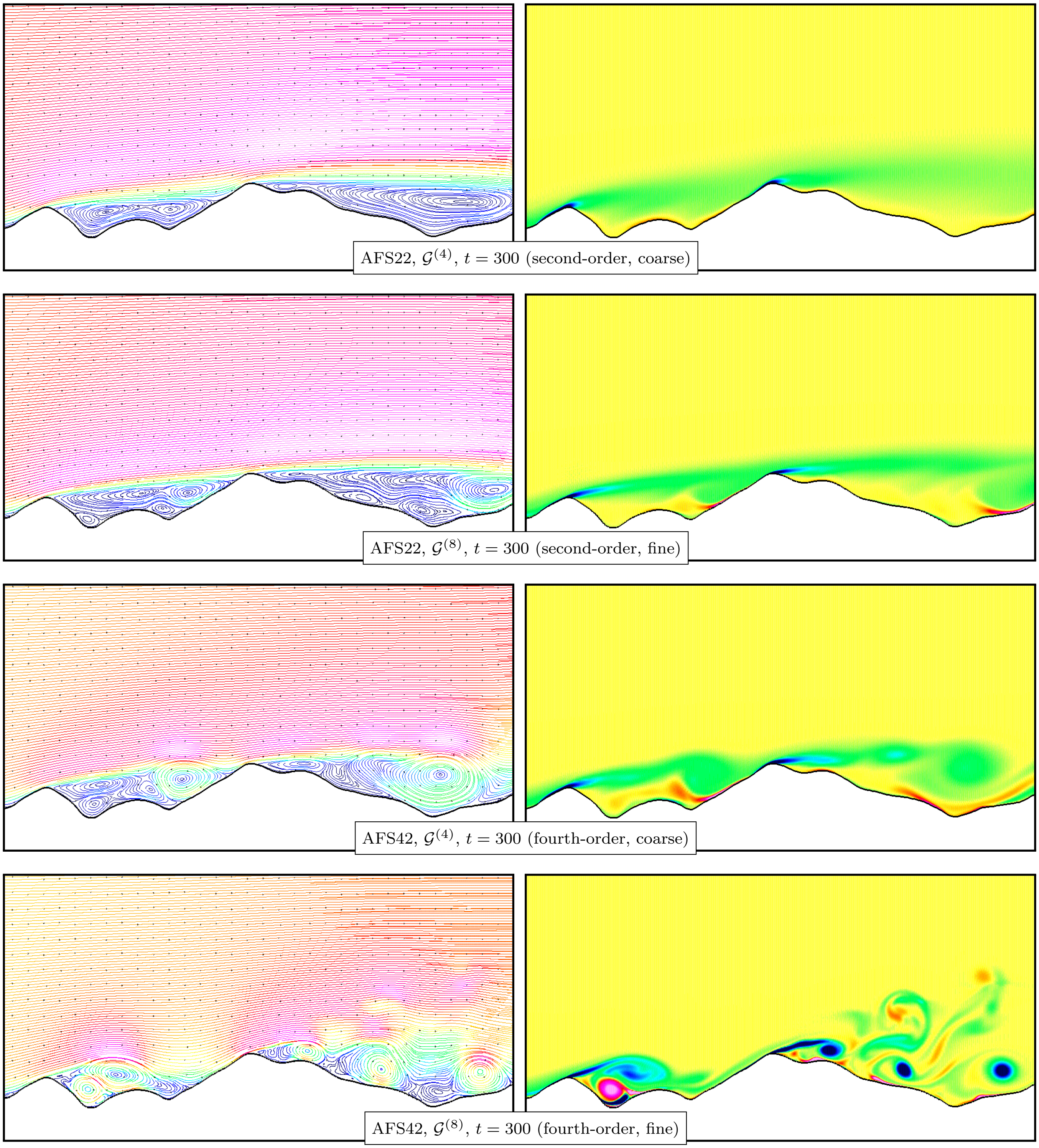


Figure 5: Computed solution for the two-dimensional domain. Streamlines and contours of the vorticity (scaled to $\xi \in [-1, 1]$) are shown. Results are shown using the scheme AFS22 (second-order accurate) and AFS24 (fourth-order accurate in space).

5.2 Three dimensional computations

Some sample three-dimensional computations over terrain are presented in this section.

Figure 6 shows some terrain near Site 300 (part of LLNL). The domain is centered around longitude $121^o\ 33'\ 17.333334''$W and latitude $37^o\ 38'\ 45.33333''$N. The size the of the domain is approximately $1.5km \times 1.5km$ in the horizontal directions.

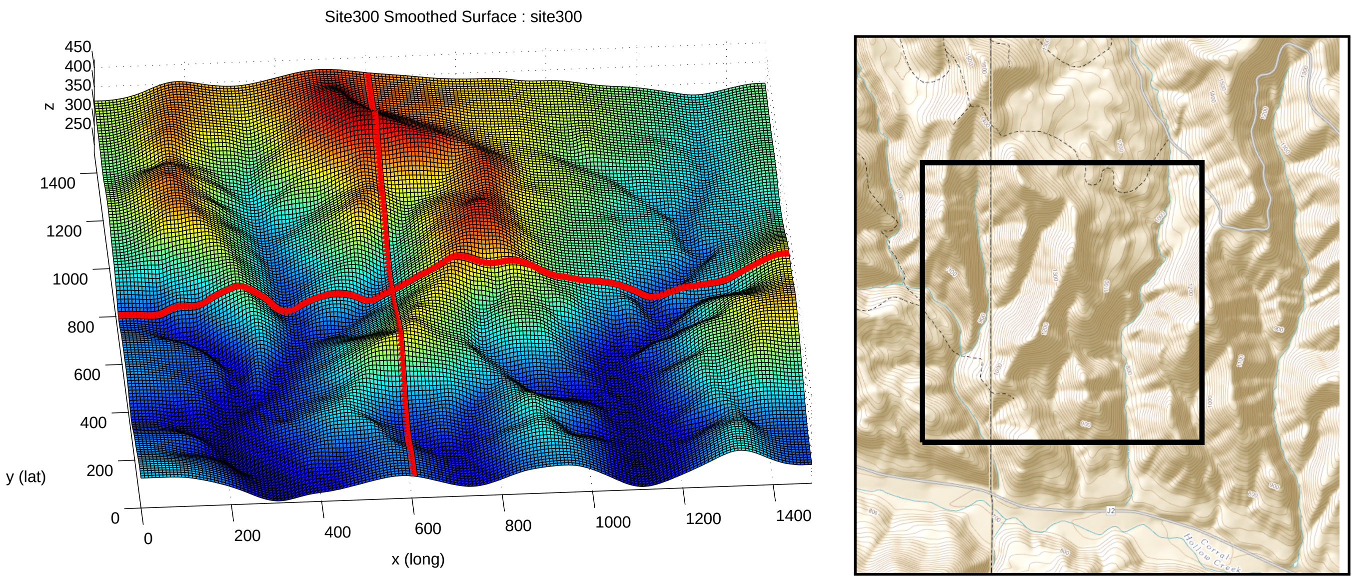


Figure 6: Left: smoothed terrain data near Site 300. Also shown are two cross-section curves. Right: topographic map. The terrain on the left corresponds roughly to the region outlined on the right.

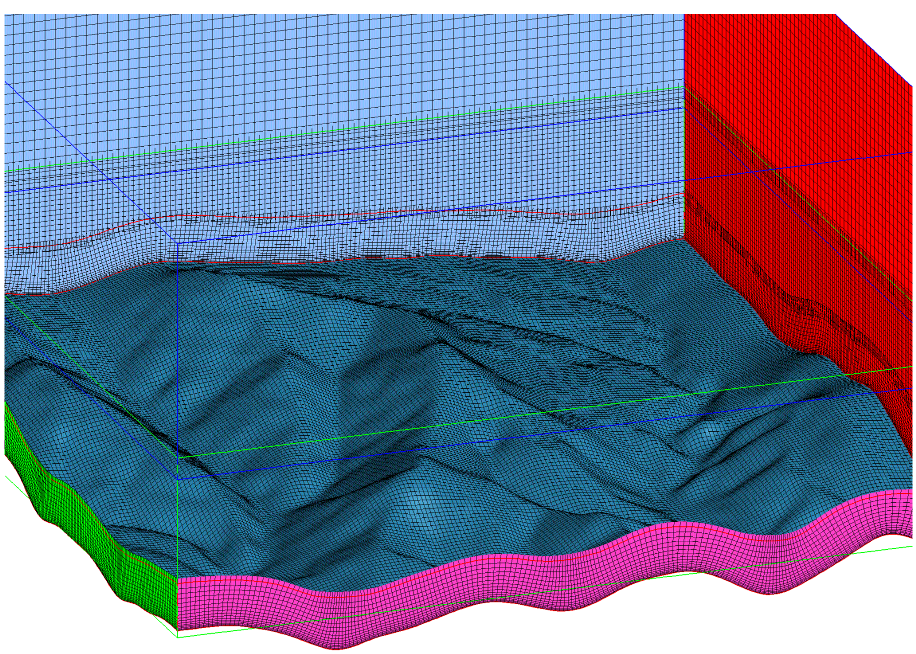


Figure 7: Composite grid $\mathcal{G}^{(2)}$ (second-order accurate).

The overlapping grid for a three-dimensional domain is shown in Figure 7. As in the two-dimensional case there are three grids, a surface grid, a near surface Cartesian background grid and a coarser background grid.

Figure 8 shows some results from the fourth-order accurate scheme AFS24-MG on grid $\mathcal{G}_t^{(4)}$ (10M pts). The size the of the domain is approximately $1.5km \times 1.5km$ in the horizontal. Note that this domain has buffer zones added on the edges, with a longer buffer at outflow. (The buffer zones were initially added to address some instability with inflow at the the outflow boundary, but this issue was fixed and so the buffer zones may not be necessary). The grid spacing near the surface is approximately $5m$ in the horizontal and $.4m$ in the vertical for the grid cell next to the surface. The flow enters the domain from the west ($x = 0$ plane). The inflow profile is parabolic (transitioning from 0 to 10 over the first 50m), with a maximum inflow velocity of $10m/s$ (22.4mph) . The computation was performed in parallel on 4 nodes (32 cores).

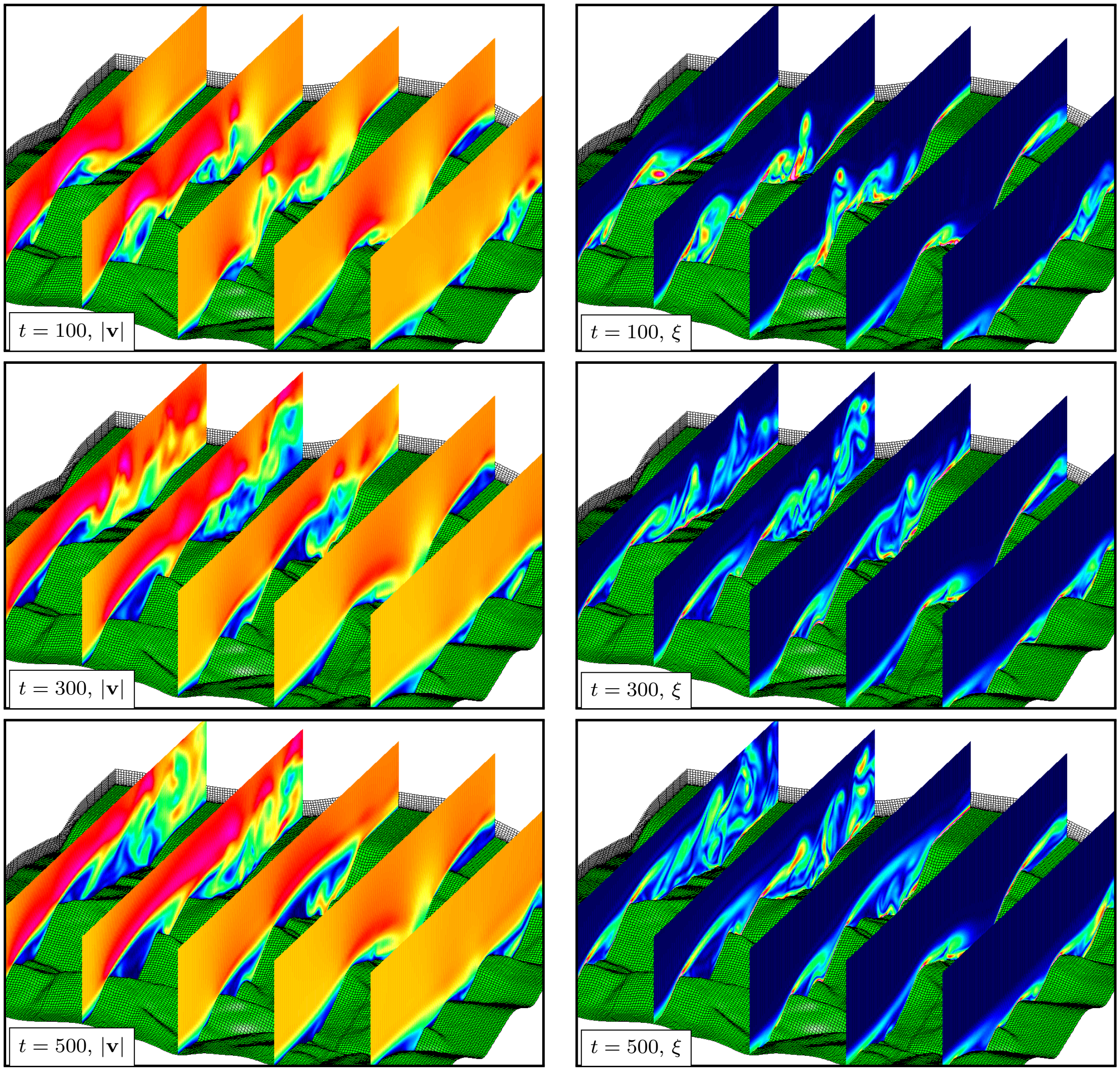


Figure 8: Flow over site300 terrain using grid $\mathcal{G}_t^{(4)}$ (10M pts) and scheme AFS24. The flow speed, $|\mathbf{v}|$ and enstrophy, ξ ($\xi \in [0, 1]$), are shown. The contour planes do not extend to the full height of the computational domain. The surface grid is coarsened by a factor of 2 for plotting purposes.

Figure 9 shows results from a computation on a finer grid $\mathcal{G}_t^{(8)}$ (60M pts) and scheme AFS24-MG. The near surface grid spacing was about 2.5m in the horizontal with a vertical grid spacing of .17m at the surface. The inflow profile was parabolic (over the first 50m), with a maximum inflow velocity of $10m/s$. The computation was performed in parallel on 16 nodes (128 cores).

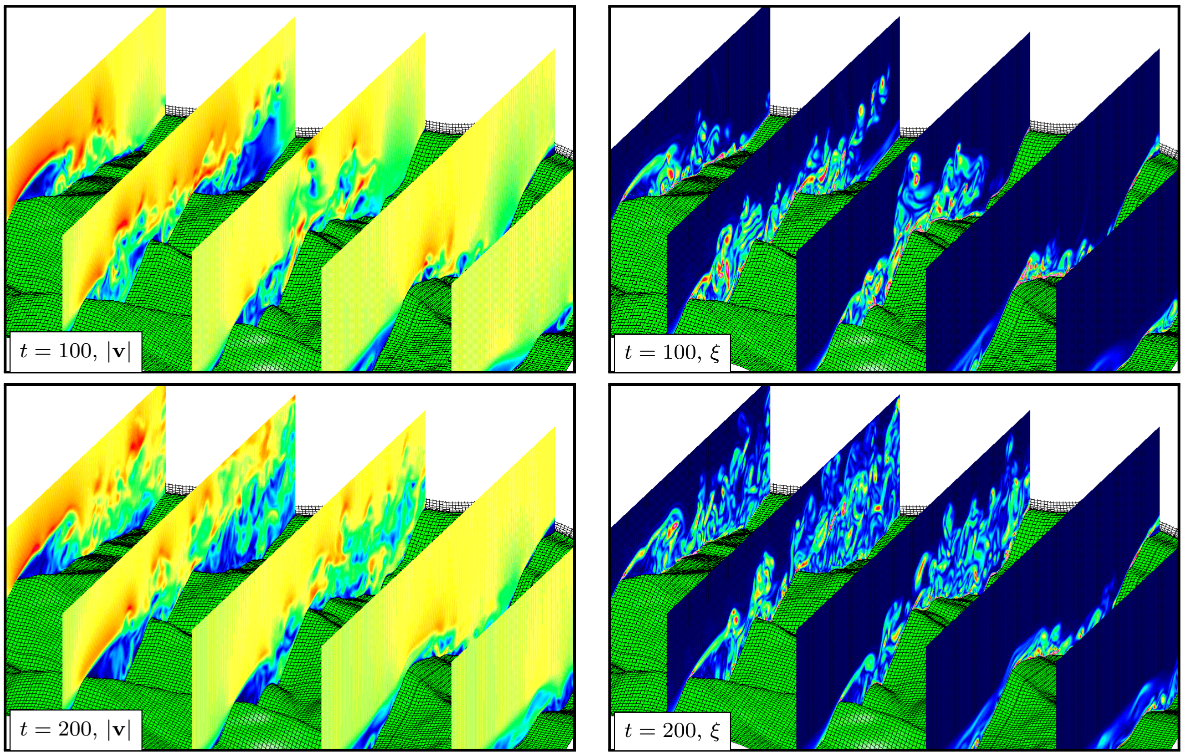


Figure 9: Flow over site300 terrain using grid $\mathcal{G}_t^{(8)}$ (60M pts) and scheme AFS24. The flow speed, $|\mathbf{v}|$ and enstrophy, ξ, ($\xi \in [0, 2]$), are shown. The contour planes do not extend to the full height of the computational domain. The surface grid is coarsened by a factor of 4 for plotting purposes.

References