16.3 NEAR-SURFACE WINDS FROM AN ENHANCED MICRO- MESOSCALE SIMULATION SYSTEM

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1. INTRODUCTION

Our goal is to improve weather support by adding high resolution, micro-scale model output to form more representative field support products that are valid for all terrain scenarios. Some barriers exist in regard to accomplishing our goal. For example, high resolution forms of numerical weather prediction (NWP) often employ sub-grid parameterizations designed for larger scales and take long run times on high performance computers (HPC) at these higher resolutions. High resolution engineering solutions, such as computational fluid dynamics (CFD), produce ultra-high resolution solutions, but require very long run times on HPC. In pursuing our approach, the surface layer high resolution model, HRW (Cionco. 1985), was previously coupled to the meso-scale BFM code (Henmi and Dumais, 1998). The capability of running the micro-scale model of canopy flow coupled to the surface layer, CCSL (Cionco, 1985), in place of HRW has been added to the system. This also introduces terrain-following levels in the computation. Under consideration is the transition from BFM to MM5 to drive the micro-scale codes. This is considered for use also in the NOWCAST approach we are pursuing. Also in progress is the development of a 3-D version of our high resolution wind analysis. Plans are defined to evaluate and verify the coupled system with a meso-microscale meteorological data base such as our Project WIND Data Base (Cionco, 1989).

2. OBJECTIVES

Our objective is to attain higher resolution surface layer wind analyses than is available currently from meso-scale NWP models for a variety of 'terrains' of interest. The micro-scale analyses will be derived at meso-scale NWP model forecast hours. By using CCSL, the micro-scale analysis can be extended to recover first order vertical structure in the surface layer. The potential to transfer this technology from basic research to a variety of applied research projects is there to be realized. The scope of this potential runs the scale from a.) activities of terrorism for urban, rural, and agricultural cases as well as their water sources, b.) to agricultural and forestry aerial spray and disease control, c.) to HAZMAT and other toxic accidents, d.) to even the more mundane urban planning, e.) and, of course, our detection of and defense against weapons of mass destruction (WMD).

The higher resolution analysis can serve as the first guess of flow field to be used for quick response analyses that are directly applicable to open terrain areas, vegetated and forested areas, built-up areas, and as overlays of wind fields onto high resolution situational maps. Coarser meso-scale resolution applications will be improved with this finer scale analysis of aggregate influences which now includes very local variations of terrain and surface morphology features. Potential is there to provide a first guess wind field for even higher resolution techniques such as an initialization field for CFD or similar techniques.

3. THE MODELS

The micro-scale model, CCSL, will replace HRW within the previously coupled simulation system that includes the meso-meteorological BFM model/code. The Navy's larger scale Navy Oceanographic Global Atmospheric Prediction System (NOGAPS, Bayler & Lewit, 1992) is used to initialize the BFM. Other codes are used also to further analyze the BFM output before the CCSL input files are prepared. ARL's Atmospheric Sounding Program (ASP, Passner, 1999) is used to establish mandatory levels as a vertical sounding profile. The EPA-approved CALMET Model (Scire, et. al., 2000) is used to derive slope winds to enhance the analysis of BFM output used to initialize CCSL.

3.1 BFM Code

The BFM code (Henmi and Dumais, 1998) was adapted and customized from Yamada's Higher Order Turbulence Model for Atmospheric Circulations (Yamada and Bunker, 1989). BFM is a hydrostatic code that uses the Boussinesq approximations. It also uses an alternating direction implicit numerical scheme. The Arakawa staggered C-grid is implemented. Prognostic equations for perturbed quantities of u, v, q, virtual potential temperature, turbulence length scale & kinetic energy are used. BFM is configured for 32 vertical computational levels starting at 2 m and extending to 7 km above highest terrain elevation for domains of several hundred kilometers horizontally. A sigma Z terrain-following vertical coordinate system is used. Both Pressure (exner function) and the vertical wind component, w, are computed diagnostically. Pressure is computed from potential temperature and w is set equal to zero at the surface and at the top of the domain. Pressure is computed from potential temperature and w is set equal to zero at the surface and at the top of the domain. This version of BFM is reported by Haines, et al. (1997).

3.2 High Resolution Wind Models

Transitioning from the HRW model to the CCSL model, the horizontal wind field analysis of HRW is enhanced to calculate vertical wind profiles above open, vegetated, and urbanized terrain and within the canopy layer. CCSL, therefore, couples canopy flow to the ambient surface layer field. In addition to terrain elevation, the quantification of surface morphology features also is required to analyze canopy flow.

HRW: A brief reminder of HRW's characteristics is included here in regard to CCSL. HRW Model simulates the horizontal wind field over complex terrain on a high resolution grid. It is a two dimensional, time-Independent, micro-scale, diagnostic code that uses Gauss' Principle of Least Constraints (Lanczos, 1962) (which requires forces to be minimized to satisfy the equations of motion) and a variational relaxation scheme on the wind and temperature fields. Typical domain sizes addressed can be 2km x 2km to 10km x 10km while computational grid spacing is usually 100 or 50m. The resultant wind fields are given at a level above the terrain linked to the grid spacing by a factor of 1/10. Each parameter is calculated for an array of flux boxes. The model's output is composed of the u and v wind components, potential temperature, friction velocity, Richardson Number, Power Law Exponent, and a terrain-induced component of the vertical motion (not always the total w component). The vector field and a field of streamlines also can be calculated from the u and v components. HRW has been validated by Cionco and Byers (1995) using the MADONA Field Study data base (Cionco et. al., 1999).

CCSL: Given the horizontal wind field and the friction velocity from HRW, CCSL uses the wind solution at each grid point and the terrain-morphology data to construct ambient and canopy wind fields. Above the canopy and open terrain, the ambient profile is the logarithmic relationship (Businger, 1973 and others):

$$U_Z = U_* \,(\mathrm{Ln}\,[\,(Z-D) / Z_0\,])\,/\,k \qquad 1)$$

Where U is the mean wind speeds at any height, Z, and U_* is the friction velocity. D and Z_0 are the zero-plane displacement and surface roughness, respectively and k is the von Karman Constant (k = 0.4). Equation (1) is for neutral conditions. Businger and Paulson's unstable and stable factors are also used.

Within the canopy, the exponential wind-height relationship developed by Cionco (1962, 1965) is used in combination with the canopy type to form the vertical wind profile:

$$U_Z = U_H \,\mathrm{EXP}\,[\,a((Z/H) - 1)] \qquad (2)$$

Where H is the reference height as the top of the canopy and a is the Canopy Flow Index (as an attenuation coefficient) defined as:

$$a = HS/\,C_D \qquad (3)$$

H is the canopy height, C_D is the drag coefficient of the canopy surface, and

$$S = A\, C_D' / 2 . \qquad (4)$$

Here, A is the leaf area index of vegetation or the frontal area of urban elements and C_D' is the drag imposed upon the vertical faces of these urban and non-urban elements.

Recently, Macdonald (2000) validated the applicability of this exponential relationship for a simulated array of urban structures in his wind tunnel studies. Macdonald arrived at the same relationship and used the a^3 expression from Cionco, 1962 and 1965 given as:

$$a^3 = H^3\, S / 2 l_c^2 \qquad (5)$$

where H and S are the same definition and l_c is the mixing length in the canopy.

Canopy type, height and location data are derived from methods reported by Ellefsen (1985) and Cionco and Ellefsen (1998) for both vegetative and urban canopies. This feature allows one to analyze neighborhood scale meteorology (Cionco and Luces, 2002). Introducing the digitized morphology data as dominate features into the flux box arrays result in feature type resolution usually less than one to one. That is, data noted as vegetation or buildings are usually clusters of trees or adjacent buildings. In that, a cell may contain more than one feature,only that which dominates in terms of foot print and / or height is selected and coded into the data file for model input. Therefore, the analysis resolves the effect of morphology on a cell by cell basis and not for individual trees, buildings, etc. The CCSL analysis is for the micro-alpha and micro-beta scales.

4. SIMULATIONS

Previously, the coupled system (Luces and Cionco, 2001) was applied to several scenarios with 100m and 50m grid resolution and for areas 4km to 10km squared areas of the San Francisco Bay area, a training facility, and Salt Lake City.

4.1 Earlier simulations

Figures 1a and 1b show the enlarged BFM and the cropped HRW plots of vectors (black), streamlines (orange), terrain (shades of green), and the water of San Pablo Bay (gray) near SFO. . BFM's smooth flow field is for 2.5km resolution in a 200km x 200km domain while the more deformed HRW fields are for 100m grids in a 5km x 5km domain. The BFM flow field shows long smooth streamline flow at this resolution. HRW's flow field during these unstable atmospheric conditions displays steering the westerly flow over the water surface to become northwesterly flow into the small canyon just to the east of the cross marker. There is also notable deformation about the hill located in the upper right corner that also is not seen in the BFM solution.

Figure 2a and 2b exhibit HRW simulated flow fields (now limited to 3km x 3km) for the terrain-only scenario (figure 2a) and then for terrain with morphology features (figure 2b) added to the simulation. The terrain-influenced wind field is relatively smooth with flow off the bay onto the land where the canyon and the small hill produce modest interactions on this local scale (100m). When morphology features are added as shown in figure 2b, there are many more very local interactions with the surface features as well as with the terrain before the canyon and its influence. A closer inspection of these very local interactions on the neighborhood scale can be viewed better in figure 3 as an extraction of 1km x 1km areas is displayed from the small box in figure 2b. Note that flow speeds and directions are responding to the morphology features cell by cell (100m x 100m) up to the steering in to the canyon as was noted before. None of these finer scale motions were generated by the meso-scale analysis because of its coarser resolution.

4.2 Inclusion of morphology features and data

The introduction of morphology in the above simulations (shown in figures 2b and 3) can be interpreted from the following code. Buildings are coded as red, trees are green, grass is yellow, simple surfaces (streets, highways, parking lots etc) as white, and water surfaces as white (or blue). Not shown in the above figures is bare soil which is normally coded as brown. Because of the cell structure of dominant features that represent each flux box, street and road configurations are not always preserved. Nor are the individual trees, buildings etc preserved on a one to one. The simulated flow field, therefore, is the result of the drag exerted upon the flow passing an object or over open terrain. It is important to remember that urbanized areas (city, town, village etc) as shown in figure 2b and another to follow are not just buildings. Vegetation is a notable portion of most urbanized areas.

4.3 Criteria to observe

Applying CCSL permits one to construct the vertical structure as wind profiles at each grid point in the high resolution horizontal wind field. One, therefore, can simulate profiles above the open terrain, within and above vegetative canopies, and above and about suburban and urban canopies. Incorporating the presence and effects of surface morphology within the computational cells as dominant features is the key for the analysis. It is worth noting what is beyond the CCSL formulation. CCSL does not: address individual buildings unless one fills the cell; does not maintain street structure unless they are very wide; and can not compute street canyon vortices.

Guidance from OKE (1992) on the occurrence of street canyon flow sets the criteria for where and when these vortices will occur. See criteria in figure 4 derived from Oke (1992). When the width (W) of the street or space (W) between adjacent buildings is greater than the height (H) of the adjacent buildings, then one has isolated roughness flow and vortices do not form. When W is less than H, and the flow above the building roof tops is greater than 2m/s, one has skimming flow and vortices can generate. See figure 4 taken from Oke (1992). In that our approach uses the dominant feature method and the cell width (W) is usually 100m (or 50m), W is virtually always greater than H. We, therefore, do not attempt to simulate canyon flow. The adjective 'virtually' is used because the largest of cites may have a place or two where H could be greater than W within the computational domain, for example - New York City. In the example simulation domain that follows, there are no cells where W is equal to or less than H, the cell height.

4.4 Wind Speed Profiles from CCSL

Examples of wind profiles are shown in figure 5 for flow a.) over a parking lot, b.) within and above a cell of 12m trees, and c.) within and above 10cm grass. An example for a cell of buildings is not given, but would resemble the tree example except that the building space would be a no-wind space. Note how the value of the wind at the 2m level varies for each profile. Which ever morphology feature that dominates that cell modifies the flow directly. As noted earlier, the ambient flow is logarithmic and the canopy flow is an exponential function of height. These profiles are coupled at the height of the canopy by a canopy flow coupling parameter reported by Cionco (1983).

4.5 Current simulations for Salt Lake City

The object is to simulate winds near the surface, say at the nose level (~2m), in between the cells as a result of drag imparted upon the flow by the cells of morphological features. Digitized terrain, digitized morphology (specifically see figure 6), and meteorological inputs were prepared to simulate wind fields over Salt Lake City as a 10km x 10km domain with 50m grid spacing. For this scenario, the domain size was increased from 5km x 5km and the grid spacing was reduced from 100m. The morphology is characterized by the dominant cell method and again does not maintain street structure or individual buildings or vegetation. Within this computational domain there are no spaces (W) between cells that approach the height of adjacent features.

The resultant flow field serves as a first guess for finer analyses. Profiles are computed at each grid point using the logarithmic relationship for ambient flow and the exponential relationships within the canopy layer. Given the mean speed, friction velocity, height and type of the morphology feature, profiles are computed similar to those shown in figure 5. During the presentation an animated view of the simulation is shown. Unfortunately it is not replicated herein. Figure 7 does display the wind field above the city structures. This field is the end result of the animation. As a point of reference, the wind speed at the cross is approximately 2m/s from the southwest. Although there are changes in the wind field through out the domain, the most notable changes are occurring in the northeast quadrant of the figure. Extracting wind values at the 2m level through out the domain permits a plot of the near surface wind field (~2m level) as shown in figure 8. Wind speeds clearly decrease and although there are directional changes they are not discernable on this plotting scale. Variations can more easily be seen in the northeast quadrant again.

5. SUMMARY

It is shown that very local mean wind fields can be generated with a micro-scale model using grid resolutions of 100m and 50m driven by a meso-scale model. The enhancement of computing vertical wind profiles allows one to construct and view winds at different levels above and within an urbanized area asa well as rural areas. The CCSL model is used to construct vertical structure above open, vegetated, forested, rural, and urbanized areas (excluding cities such as New York City, etc). Including dominant feature morphology (by cells) in the simulations can develop greater detail in the surface layer winds. A variety of applications can benefit from an estimate of the winds at 'nose' level over 'all terrains', especially along a street. It should noted again that when using the dominant feature approach per cell, criteria for street canyon flow is not usually met and, therefore, is not calculated within this simulation system. For analysis of street canyon flow, use a diagnostic CFD Model.

6. REFERENCES

Bayler, G. and H. Lewit, 1992: The Navy Operational Global and Regional Atmospheric Prediction System at the Fleet Numerical Oceanography Center, Weather and Forecasting, Vol. 7, No. 2.

Businger, J. D., 1973: Turbulent Transfer in the Atmospheric Surface Layer. Chapter 2 of Workshop on Micrometeorology. Ed by D.A. Haugen, Amer. Meteor. Soc., Boston, MA.

Cionco, R. M. and S. A. Luces, 2002: Coupled Mesoscale-Microscale Model to Compute Neighborhood Scale Wind Fields, Proceedings of 4th Symposium on the Urban Environment, Amer. Meteor. Soc., Boston, MA.

Cionco, R. M. et al., 1999: An Overview of MADONA: A Multinational Field Study of High Resolution Meteorology and Diffusion over Complex Terrain, Bull. AMS,
Vol. 80, 1, p.5-19.

Cionco, R.M., 1989: Design and Conduct of Project WIND, Proceedings of 19th Conference on Agriculture and Forest Meteorology, AMS, Boston, MA.

Cionco, R. M., 1985: Modeling Wind fields and Surface Layer Profiles over Complex Terrain and Within Vegetative Canopies, Forest-Atmosphere Interactions, B. A. Hutchinson and B. B. Hicks, Editors, D. Reidel Publishing Co., Holland.

Cionco, R. M., 1983: On the Coupling of Canopy Flow to Ambient Flow for a Variety of Vegetation Types and Densities, Boundary-Layer Meteorology, Vol. 26, p325-335. D. Reidel Publishing Co., Holland.

Cionco, R. M., 1965: A Mathematical Model of Air Flow in a Vegetative Canopy, J. Applied. Meteor., Vol. 4, 4 p. 517-522, AMS, Boston, MA.

Cionco, R. M., 1962: A Preliminary Model for Air Flow in the Vegetative Canopy, Bull. Amer. Meteor. Soc. Vol. 43, p.319, Boston,MA.

Cionco, R. M. and R. Ellefsen, 1998: High Resolution Urban Morphology Data for Urban Wind Flow Modeling, Atmos. Env, Special Issue on Urban Forest, Vol. 32, No.1, p7-17 Elsevier Science, Great Britain.

Cionco, R. M. and J. H. Byers, 1995: Initializing the HRW Model with Meteorological Inputs from Different Sites to Optimize Model Output, Proc. 11th Symposium on Boundary Layers and Turbulence, Amer. Meteor. Soc, Boston, MA.

Ellefsen, R., 1985: Urban Terrain Classification System, Quadrapartite Advisory Publication 32, US Army TRADOC Systems and Analysis Activity, White Sands Missile Range, NM

Haines, P. et al., 1997: Meteorological Data Processing Methods in the Computer-Assisted Artillery Meteorology System (Battlescale

Forecast Model), TR-559, US Army Research Laboratory, WSMR, NM.

Henmi, T and R. Dumais, Jr., 1998: Description of the Battlescale Forecast Model, TR-1032, US Army Research Laboratory, WSMR, NM, 1998.

Lanczos, C., 1962: The Variational Principles of Mechanics, The University of Toronto Press, Toronto, Canada.

Luces and Cionco, 2001: Coupling a Micro-scale Model to a Meso-scale Model, 2001 BACIMO Conference, US Army Research Laboratory, White Sands Missile Range, NM

Macdonald, R. W., 2000: Modelling the Mean Velocity Profile in the Urban Canopy Layer. Boundary-Layer Meteorology, Vol. 97, pp. 25-45.

Oke, T., 1992: Boundary Layer Climates, Routledge Publishers, London, UK.

Passner, Jeffrey, 1999; “Weather Products from a Mesoscale Model”, Proceedings of the ITEA Workshop: Modeling and Simulation Using Modeling and Simulation for Testing – Are We ready for the Next Millennium?, 6-9 Dec. 1999, Las Cruces, NM.

Scire, Joseph, et al., 2000: A User's Guide for the CALMET Meteorological Model, Earth Tech, Inc, Concord, MA.

Yamada, T. and S. Bunker, 1989: A Numerical Model Study of Nocturnal Drainage Flows with Strong Wind and Temperature Gradients, J. Applied Met, Vol. 28, pp. 545-554. .

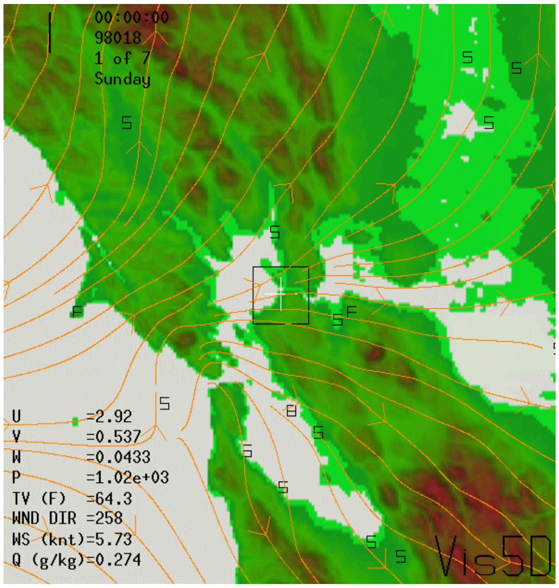

Figure 1a. Meso-scale wind field of streamlines (orange) for a 200km x 200km domain and xy grid is 2.5km. Square box indicates location of HRW domain (5km x 5km).

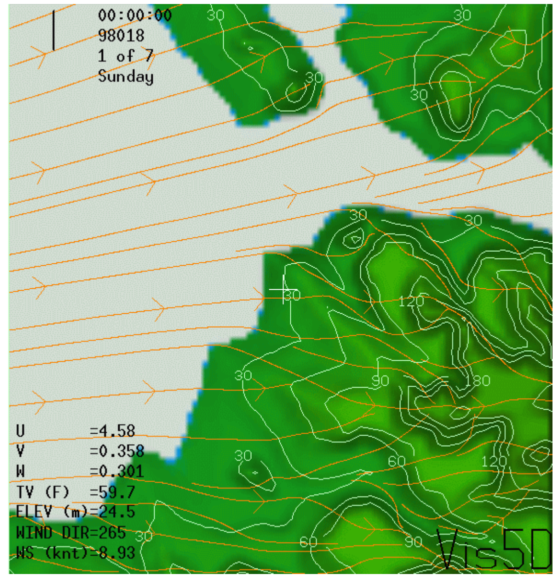

Figure 1b. Micro-scale winds as streamlines (orange) for a 5km x 5km domain with elevation contours (white) along San Pablo Bay, CA

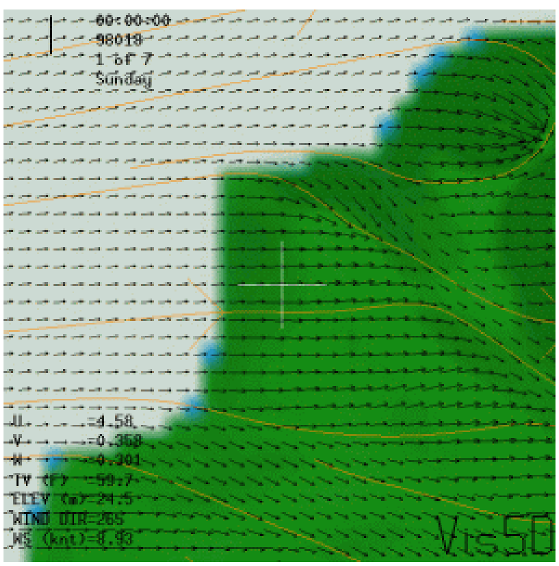

Figure 2a. HRW wind field interacting with terrain (canyon and hill) viewing 3km x 3km of figure 1b; xy grid is 100m.

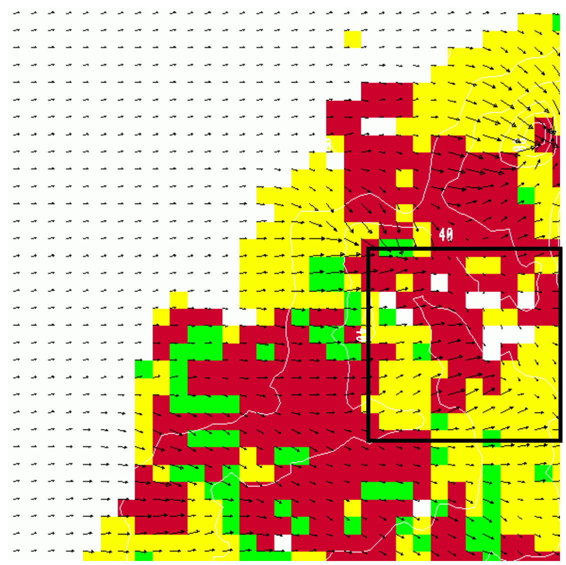

Figure 2b. HRW wind field interacting with morphological features added (color code in text and figure 5) for the same 3km x 3km area of figure 1b. Box outline is for figure 3 analysis.

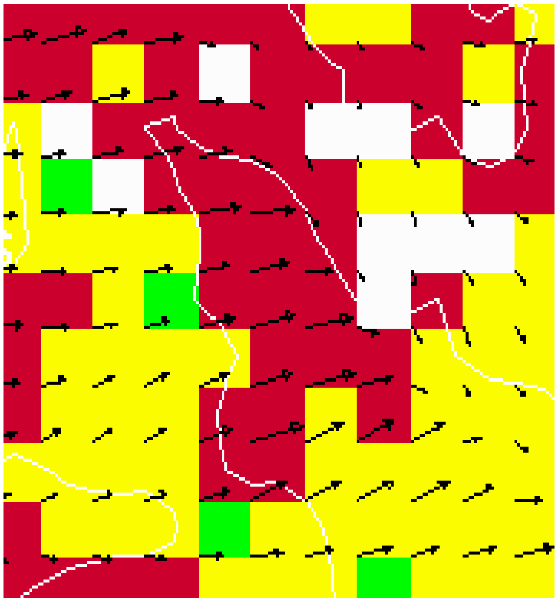

Figure 3. Neighborhood scale winds for a 1km x 1km area extracted from figure 2b noted by the box outline. Elevation contours are white lines.

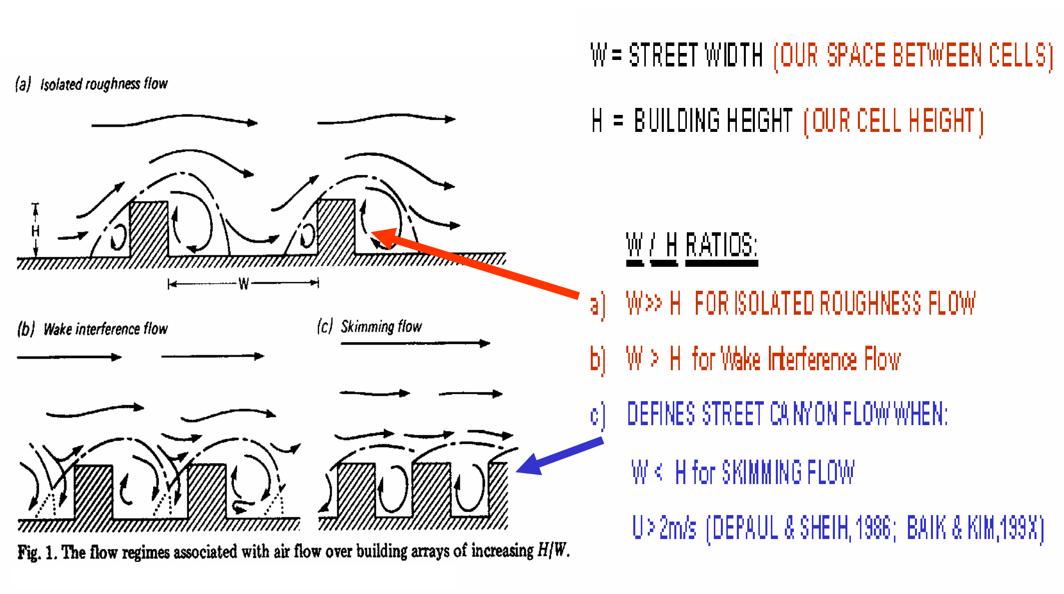

Figure 4. Guidance (after Oke, 1992) for defining gradations of urban flow regimes

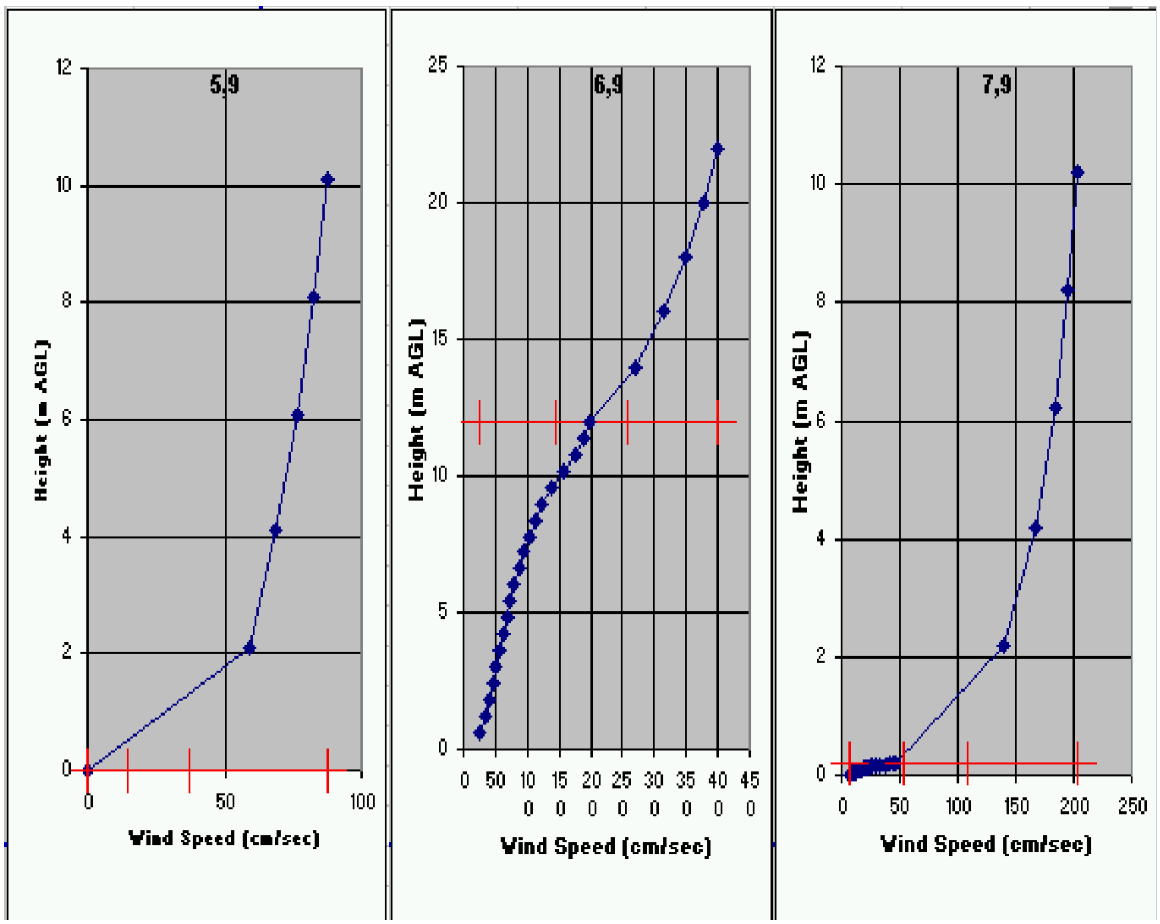

Figure 5. Examples plots of wind profiles for various morphology features. Note values of speed at the 2m level of each plot: parking lot (left), 12m trees (center), and 10cm grass (right)

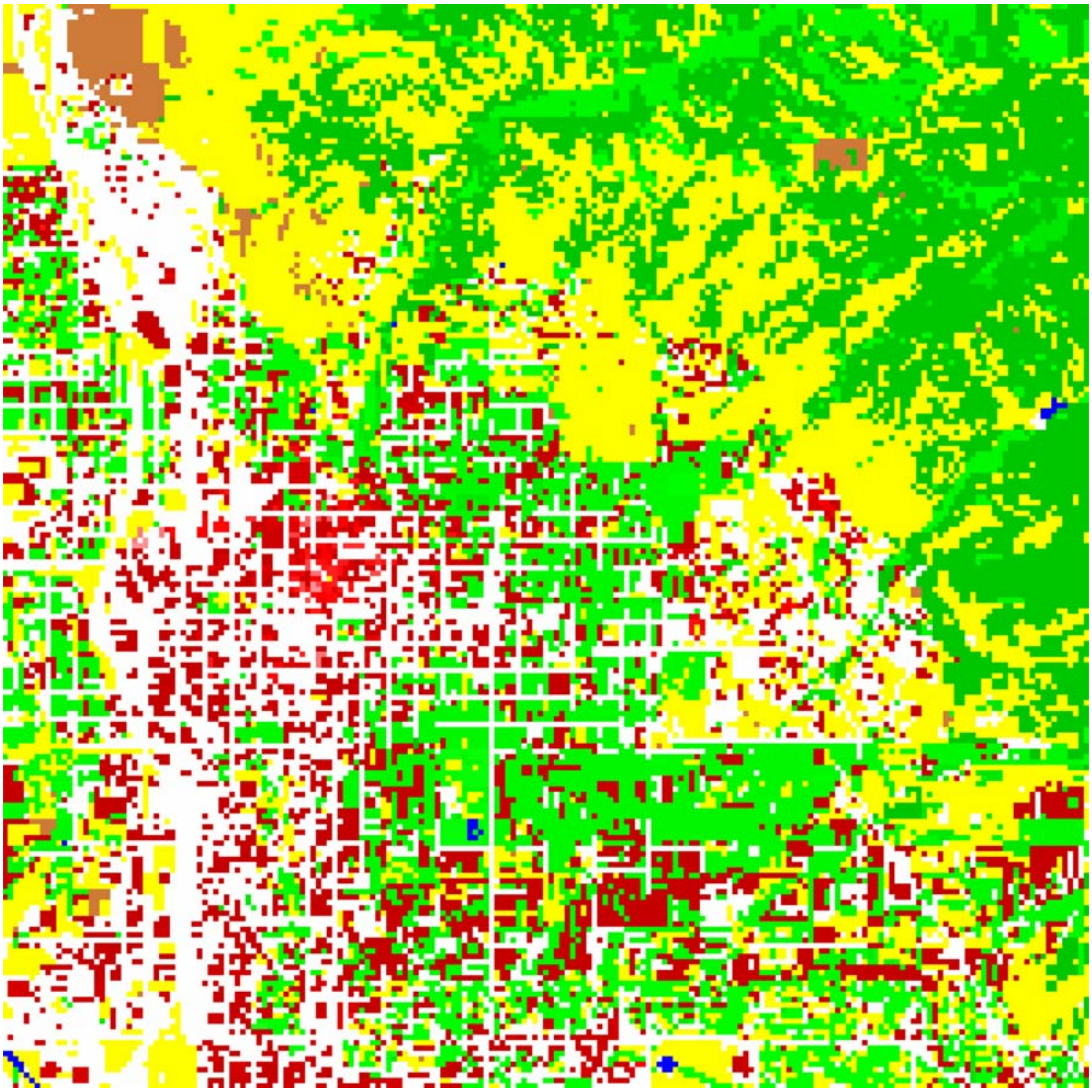

Figure 6. Morphology map for central portion of Salt Lake City showing dominate features per cell with 50m resolution in a 10km x 10km domain. The domain is composed of buildings, vegetation and simple surfaces coded as:
-BUILDINGS, -TREES and SHRUBS, -GRASS, -BARE SOIL, -WATER,
-PAVEMENT, PARKING LOTS, & HIGHWAYS (white)

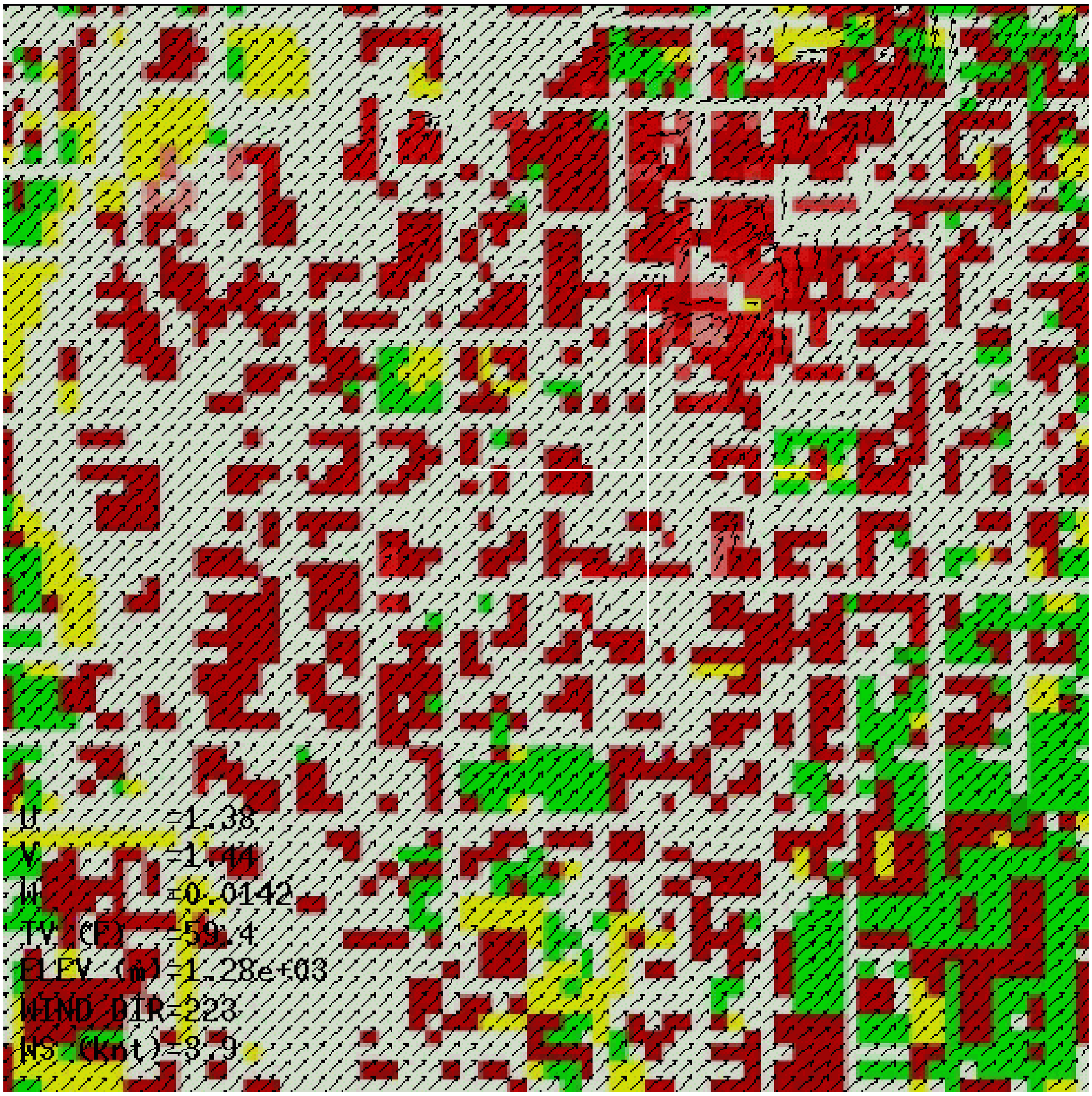

Figure 7. CCSL simulated winds above the city centered on the CBD of this 3km x 3km area. Most notable interactions with the morphology are located in the northeast quadrant.

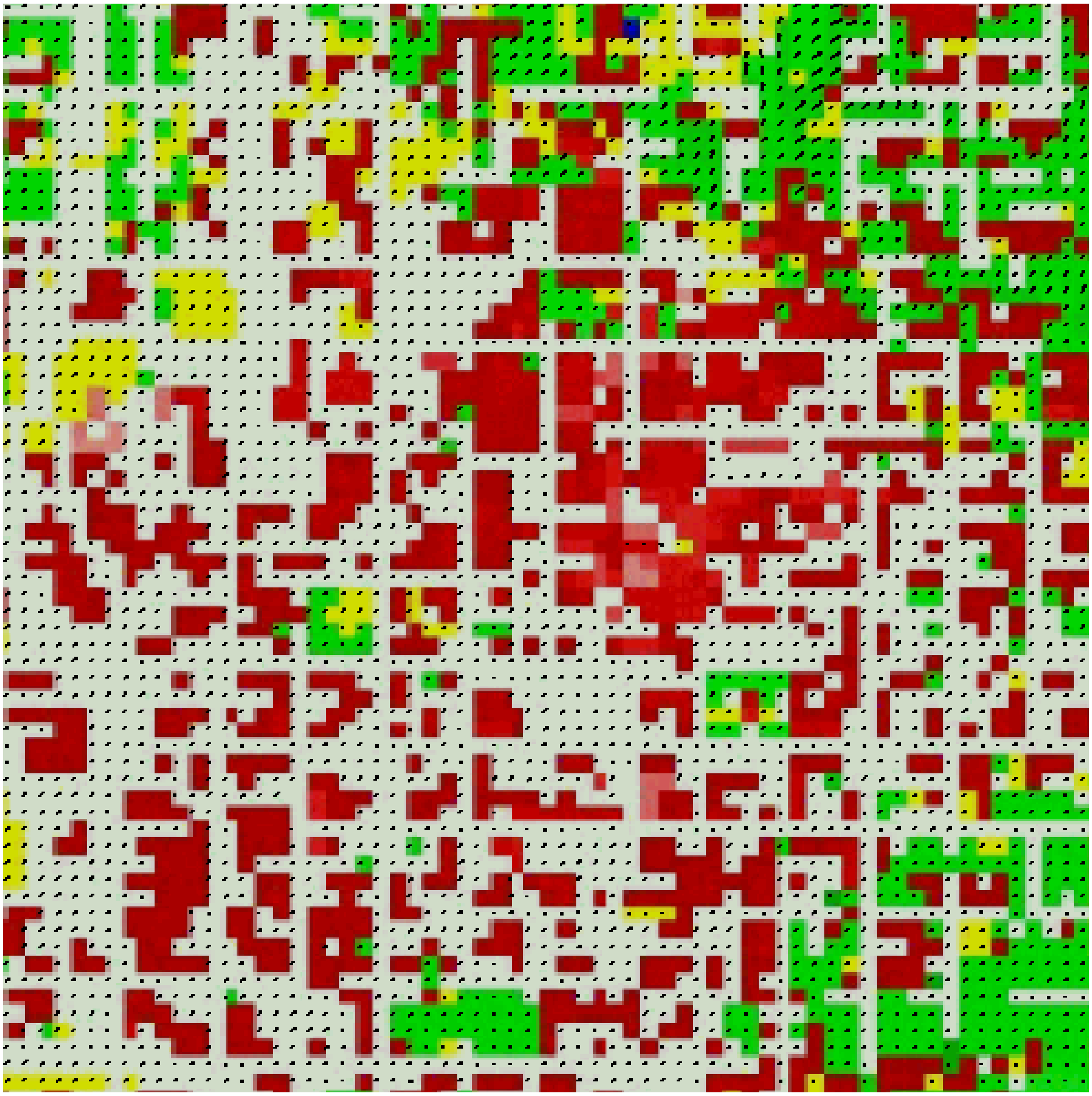

Figure 8. CCSL simulated winds near the surface (~2m level) somewhat shifted eastward and northward from figure 7 and now as a 3.25km x 3.25km area. Note that the speeds have decreased along with directional changes (barely discernable). Most interactions remain in the northeast quadrant.