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Downscaling mesoscale meteorological models for computational wind engineering applications

Tetsuji Yamada [a,*], Katsuyuki Koike [b]

[a] Yamada Science & Art Corporation, 13 Heiwa, Santa Fe, NM 87506, USA
[b] IDEA Consultants, Inc., Yokohama, Kanagawa, Japan

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ABSTRACT

Considerable interest exists in joining the capabilities of mesoscale meteorological models (MMM) with those of computational wind engineering (CWE) models to produce realistic simulations, which address emerging issues in wind engineering and environmental applications. The model equations are similar for MMM and CWE, but there are significant differences in the objectives and approaches. Complete synthesis of these models is still premature and computational burdens are enormous. Appropriate procedures for joining these models have not been established yet and measurement data required for verification is limited.

For convenience in presentations and discussions, coupling methods are divided into four groups: (1) coupling MMM and CWE models for up-scaling or downscaling, (2) up-scaling a CWE model to include the mesoscale meteorological influences, (3) downscaling an MMM to include the CWE capabilities, and (4) a combination of the above three approaches. Mochida et al. (this issue) focuses on up-scaling CWE from an engineering point of view and the present paper focuses on downscaling MMM from a meteorological point of view.

Topics addressed here are (1) to understand the differences in the purposes and approaches of MMM and CWE models and (2) to identify issues and explore ways of coupling MMM and CWE modeling capabilities.

1. Introduction

The American Meteorological Society (AMS) sponsored a short course entitled "Mesoscale Atmospheric Modeling by Original Model Developers", 9 January, 2000, Long Beach, CA. In this course Gross (2000) presented micro-scale applications of a mesoscale model FITNAH. These micro-scale applications included airflow simulations in a street canyon, around a single tree, and building complexes.

After the 9/11/2001 disaster, considerable efforts were made in the US both in field observations and laboratory experiments, to understand airflows and transport and dispersion in urban areas (e.g., Oklahoma City, Salt Lake City, and New York City). A suite of numerical models, ranging from diagnostics to LES, were applied to investigate issues important for the homeland and societal security.

To further foster collaboration of experimentalists, modelers, and decision makers, AMS offered a workshop, "Merging Mesoscale and CFD Modeling Capabilities", January 11, 2004, Seattle, WA. Moeng (2004) introduced coupling of MM5 (now WRF) and LES at this meeting.

The model equations are similar for CWE and MMM, but their objectives and approaches are significantly different. CWE investigates the airflows and pressure distributions around structures, while MMM focuses on the topographic influences and thermal effects on airflows. Temporal and spatial scales are also different; CWE scales are shorter and smaller than those for MMM. More discussions on the spatial scales of CWE and MMM are given in Section 2.

Recently, the boundaries and differences between CWE and MMM have blurred. By nesting multiple domains, some MMM models (e.g., Nicholls et al., 1993; Gross, 2000; Schlunzen et al., 2003; Yamada, 2004) used horizontal grid spacing of a few meters for simulations of airflows in and around buildings. In other words, both meso- and micro-scale phenomena were simulated simultaneously in a single model where high resolution computational domains were nested in the mesoscale domain. Values simulated in the mesoscale domain provided the boundary conditions for the nested domains. This is an example of downscaling MMM to include CWE capabilities. The model included both mesoscale and micro-scale capabilities in a single model. It is an interesting question whether this kind of model should be called a mesoscale model since the model has both mesoscale

* Corresponding author. Tel./fax: +1 505 989 7351.
E-mail addresses: yamada@ysasoft.com (T. Yamada), kik19605@ideacon.co.jp (K. Koike).

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and micro-scale capabilities. A more specific name such as a "meso–micro scale" model may be appropriate. In this paper, however, it is still called a mesoscale model since it was originally a mesoscale model.

CWE has been used often in micro-scale simulations where atmospheric stability is neutral and weather conditions are in steady state. Real atmosphere is always unsteady and changes in both time and space. For example, the efficiency of a wind turbine is strongly influenced by the diurnal and seasonal variations of winds. Design of a tall building is subjected to severe weather conditions such as storms and tornadoes. Recently, CWE's interest expanded into a low wind (wind speed of a few m s^{-1}) environment where the thermal effects on the airflows become important. Calm winds cause the worst air pollution episodes under the stable density stratifications.

Plenary Session 4 of CWE 2010 offered an opportunity to exchange ideas and learn from each other's experiences and knowledge between CWE and MMM. Prof. Mochida and the author shared keynote speeches: Prof. Mochida addressed issues from the CWE point of view (Mochida et al., this issue) and the author addressed issues from the MMM point of view. In this paper, the terms of CFD and CWE are used interchangeably.

2. Mesoscale meteorological model

Mesoscale in atmospheric science is defined as the horizontal extent between the synoptic/global and micro-scales (Orlanski, 1975). The synoptic/global scale is for a horizontal extent of greater than 2000 km all the way to the entire globe. The micro-scale is for the horizontal extent of smaller than 2 km. Thus, the mesoscale covers the horizontal extent between 2 and 2000 km. The mesoscale is further divided into meso-α (200–2000 km), meso-β (20–200 km), and meso-γ (2–20 km). Pielke (1984) termed the regional (synoptic) scale, which corresponds to Orlanski's meso-α and larger. Schlunzen et al. (this issue) presented a diagram that showed a relationship between the spatial and temporal scales of the atmospheric phenomena and how these phenomena were treated in the MMM and CWE models.

The micro-scale (less than 2 km in horizontal extent) corresponds to the CWE scale in this presentation. Most wind engineering issues, such as (a) wind energy and building structure dynamics, (b) dispersion of traffic pollutants, ventilations, and indoor toxic gas dispersion, and (c) pedestrian comfort including comfort indexes reflecting temperature, humidity and radiation, are in the micro-scale.

The core of numerical models is Navier–Stokes equations from which Direct Numerical Simulation (DNS), Large Eddy Simulation (LES), and Reynolds Averaged Navier–Stokes (RANS) models were developed. There are a dozen or more mesoscale meteorological models currently in use. Some of them are listed in Table 1.

Schlunzen et al. (this issue) discussed issues and challenges in coupling MMM and CWE and reviewed mesoscale and micro-scale models including those developed under the European projects COST728 and COST732. The COST models inventory link is: http://www.mi.uni-hamburg.de/costmodinv.

Table 1
Partial list of the mesoscale meteorological models. The models in the parentheses are the micro-scale versions of corresponding mesoscale models.

Models	Developers
A2C	YSA Corporation
ANEMOS	Japan Weather Association
COAMPS	Naval Research Laboratory
Eta	NOAA/NCEP
FITNAH	Univ. Hanover, Germany
LOCALS	ITOCHU Techno-Solution Corporation, Japan
MEMO (MIMO)	Aristotle University, Thessaloniki, Greece
MERCURE	CEREA, France
METRAS (MITRAS)	University of Hamburg, Germany
WRF/MM5	NCAR/Penn. State Univ.
NHM	Meteorological Research Institute, Japan
OMEGA	Science Applications International Corp
RAMS	Colorado State Univ.

3. Coupling MMM and CWE model capabilities

Several methods have been used to couple CWE and mesoscale meteorological models. In the first method, the mesoscale model results are used as the boundary conditions for a CWE model. For example, Weather and Research Forecast (WRF) provided the boundary conditions to an LES (Liu et al., this issue) to simulate two days of real-case wind circulations at a northern Colorado wind farm, with six simultaneous nested-grid domains with grid spacing of 30, 10, 3.3, 1.1 0.370, and 0.123 km. The four coarse domains were run with mesoscale model settings while the two finest mesh domains were run with LES model settings. This is the most direct approach to implement meteorological influences into CWE applications. This method is defined as a "multi-models up/downscaling", or simply a "multi-models scaling". In this example, neither MMM nor CWE has both MMM and CWE capabilities, but a coupling of CWE and MMM accomplishes the objectives. All MMM are based on the ensemble averaged turbulence model, while LES requires instantaneous values at the boundaries. It is an important issue how MMM provides instantaneous boundary values to LES. Schlunzen et al. (this issue) discussed other issues when MMM and CWE are coupled.

The next two methods are to either up-scale a CWE model to include MMM capabilities, or down-scale an MMM model to include the CWE model capabilities (e.g., Nicholls et al., 1993; Gross, 2000; Schlunzen et al., 2003; Yamada, 2004). The former is referred to as "single-model up-scaling" and the latter as "single-model downscaling". The result, in each case, is a single model used for both the CWE and MMM applications. This single model approach is attractive. Both the CWE and MMM phenomena are simulated interactively and seamlessly by nesting the computational domains. In other words, the MMM variations are reflected into the CWE simulations and the CWE results are returned to the MMM variables by using a two-way nesting method.

A fourth approach is a hybrid of the first, second, and third approaches discussed above. For example, an MMM provides boundary conditions to a "single-model up-scaling" or a "single-model downscaling" model. Yamada and Koike (2010) coupled A2C with WRF where WRF provided the boundary conditions to A2C. Li et al. (2010) coupled FLUENT with RAMS (Walko and Tremback, 1997) where RAMS provided the boundary conditions to FLUENT.

Table 2 summarizes the above approaches used for coupling MMM and CWE capabilities.

Table 2
Classification of approaches used for coupling MMM and CWE capabilities.

Approaches	Examples
(1) Multi-models up/downscaling	LES coupled with WRF
(2) Single-model up-scaling	FLUENT
(3) Single-model downscaling	MISKAM, RAMS, FITNAH, A2C
(4) Hybrid	A2C coupled with WRF; FLUENT coupled with RAMS