Applied Geography 52 (2014) 135–143

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

Scale compatibility analysis in geographic process research: A case study of a meteorological simulation in Hong Kong

Chunxiao Zhang [a], Hui Lin [a,b,c,*], Min Chen [a,c], Rongrong Li [a], Zhichao Zeng [a]

[a] Institute of Space and Earth Information Science, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
[b] Department of Geography and Resource Management, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
[c] The Chinese University of Hong Kong Shenzhen Research Institute, ShenZhen 518057, China

Keywords:
Scale compatibility
Geographic processes
Meteorological simulation
Digital elevation model (DEM)
Weather research and forecasting (WRF) model

A B S T R A C T

Scale is a fundamental concept in geography. Although multiscale data, models and other products are considered when studying geography, scale mismatching can produce adverse results. Thus, scale compatibility is becoming crucial for decoding dynamic and interactive geographic processes. This paper presents a definition of scale compatibility for studying geographic processes and partitions this concept into four levels: multiple processes, dimensional, type and component. These four levels operate differently, as described in detail to support the implementation of scale compatibility. Applying the procedure to assess scale compatibility, a meteorological simulation case study in Hong Kong was investigated with regard to the use of multiscale digital elevation model (DEM) data and the Weather Research and Forecasting (WRF) model. This case study considered spatial dimension, measurement scale type and component level. The experiments showed that using DEM data and a model with different resolution and grid spacing, respectively, affected the dynamic simulation capacity, even accounting for 38% of the mean absolute error (MAE) for temperature. Furthermore, our 3 and 30 arc sec resolution DEM data are relatively more compatible with the WRF model of 1 km grid spacing. This case study not only helps to improve meteorological simulations by considering scale compatibility as an issue but also explains the significance and implementation of scale compatibility in geographic processes research.

Introduction

In the discipline of geography, scale has always been a major issue (Meentemeyer, 1989). As widely accepted, changes in scale may alter significant and relevant variables (Di Vittorio & Miller, 2014; Kachanoski, 1988; Openshaw, 1983; Palmer & White, 1994). Similar to multiscale geographic patterns, such as landscape patterns (Wu, 2004), geographic processes also exhibit scale-related problems (Brown, Riolo, Robinson, North, & Rand, 2005; Hofer, 2009; Yuan, 2007). Due to the scale dependence and cross-scale linkage of multiscale geographic processes, the specification of an appropriate analysis scale and the representation of hierarchical relationships are important components (Goodchild, 2009; Syphard & Franklin, 2004). Furthermore, multiple geographic processes may interact to shape patterns or phenomena in the geographic world (e.g., soil erosion may be influenced by climate change, vegetation distribution and human activities), which would require exploration at a suitable scale. Therefore, methods in which to conduct research with regard to data, models, analyses, etc. at a compatible scale have attracted attention from researchers and institutions (Cash et al. 2006; Syphard & Franklin, 2004).

To answer the question of how to assess scale compatibility (or fitness of scale), a generic scale-matching framework concerning the data-model-problem was developed (Lilburne, Webb, & Benwell, 2004). However, this framework did not pay sufficient attention to understanding scale compatibility, which is a precondition for scale compatibility analysis and management. Poole et al. (2004) and Li, Liu, and Afshari (2006) recognized this multiscale feature and proposed a hierarchical patch dynamics paradigm (HPDP); however, this paradigm is still abstract such that the scale matching is difficult to consider during practical implementations. Thus, scale compatibility in multiscale and interplaying geographic processes remains a vulnerable issue in studying and managing geographic processes.

* Corresponding author. Rm 201, FYT Remote Sensing Science Building, The Chinese University of Hong Kong, Shatin, Hong Kong, China. Tel.: +852 39436010; fax: +852 26037470.
E-mail addresses: chunxiaozhang@cuhk.edu.hk, zhangcx0@gmail.com (C. Zhang), huilin@cuhk.edu.hk (H. Lin).

http://dx.doi.org/10.1016/j.apgeog.2014.05.005
0143-6228/

This paper aims to address scale compatibility in dynamic geography, attempting to reduce the negative effects that result from scale mismatching. By partitioning scale compatibility into hierarchical levels from the abstract to the operational level based on the definition of scale, scale compatibility becomes more manageable in practice. The remainder of the paper is organized as follows. Section 2 presents the concept of scale compatibility and decomposes it into four different operational levels to make it manageable. Section 3 discusses procedures that assess scale compatibility with assessment criteria. Applying the procedure to assess scale compatibility, Section 4 presents a case study of a meteorological simulation involving a multiscale meteorological model and digital elevation model (DEM) data. The article is concluded with a discussion and summary.

Scale compatibility in geographical processes

Concept of scale compatibility

Although scale matching or compatibility has been discussed in previous work (Lilburne et al. 2004; Taleai, Sharifi, Sliuzas, & Mesgari, 2007), a definition of scale compatibility is lacking, hindering our understanding and estimation of such issues. In this research, scale compatibility is proposed to indicate the degree to which two or more of geographic data, models, visualizations and analyses, are integrated into the study of geographic processes, without a significant negative impact from scale mismatching. Enabling scale compatibility to be assessed in geographic studies, this concept is decomposed into the following four groups with different operational levels that range from the abstract to the operational: multiple processes, dimensional, type and component (Fig. 1). The scale compatibility between multiple processes is the most abstract and is identified as the first group because effective research across multiple processes is dependent on a thorough understanding of each process studied at a compatible scale (Adger, Arnell, & Tompkins, 2005; Syphard & Franklin, 2004). The remaining three levels are identified according to the theoretical three-tiered concept of scale: dimension, type and component (Gibson, Ostrom, & Ahn, 2000; Wu & Li, 2006).

Decomposition of scale compatibility

Scale compatibility considering multiple processes (e.g., hydrology, meteorology, land surface and human behavior)

Geographic patterns and processes that operate in the same spatial-temporal space may exhibit "overlay" effects (Peterson & Parker, 1998). For example, the distribution of vegetation may be influenced by both hydrological and meteorological processes. However, this "overlay" effect might be limited to a range of scales, and the mutual effects may be dissimilar for different scale ranges. Scale compatibility of the multiple processes level refers to the matching of scales within multiple interactive processes when studying geographic processes (i.e., hydrology, meteorology, land surface, human behavior, etc.). Concerning such level of scale compatibility, the goal of the Susquehanna River Basin Experiment (SRBEX) was to simulate the basin's hydrologic response to atmospheric forcing at various time scales (Yarnal et al. 2000).

Scale compatibility within different scale dimensions

The spatial, temporal, hierarchical and semantic levels represent the four primary scale dimensions (Zhang, Lin, & Chen, 2014). In addition to the well-known spatial and temporal dimensions, the hierarchical level is a directional ordering of interacting entities that have distinctive process rates and thus form different levels (Wu, 2007). Furthermore, the semantic dimension describes the detail extent of geographical objects and their attributes in geographical information. For example, in a semantic respect, a patch of land can be classified as a paddy field, farmland or agriculture land at different semantic scales. Similarly, a road may be described as a village road, county highway, provincial highway or national highway according to the semantic scales defined by its users (Liu, Wu, & Hu, 2007). Therefore, complementary to the spatial and temporal dimensions, the hierarchical and semantic dimensions are useful for specific geographic studies and applications (Liu et al. 2007; Worboys, 2001).

The above mentioned dimensions interactively affect the study of geographic processes (Wu & Li, 2006). Therefore, separating one dimension from another is not scientific. In this context, the goal of dimensional level scale compatibility is to assess the matching of different dimensions. For instance, when resolving a meteorological feature at a more local scale, a finer spatial resolution, as well as a shorter time step must be used to capture more frequent variations. It should also be remembered that the hierarchical and semantic levels might change with changes in the spatial-temporal dimensions. Thus, considering dimensions compatibility is valuable. However, studying a geographic process within one dimension is relatively simple; when multiple dimensions are considered simultaneously, this process becomes difficult. Although some preliminary work has been reported on the multiple dimension interactions, such as the spatial-temporal dimensions (Young,

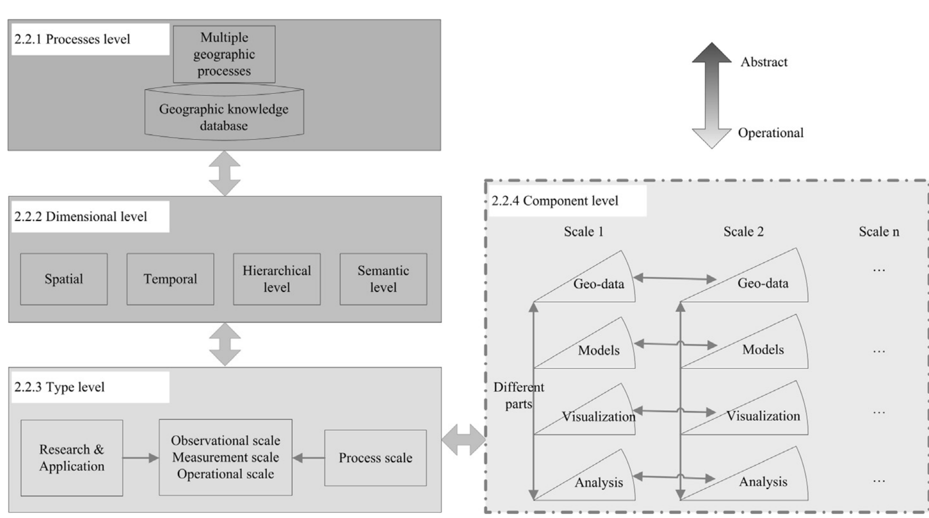

Fig. 1. Four groups of scale compatibility concerning multiscale geographic processes with different operational levels.

2003), relatively few quantitative studies have considered multiple dimensions.

Scale compatibility within different scale types

For each scale dimension, the following four types of scales are identified as the second tier of scale concept: process, observational, measurement and operational. The definitions of each scale type are listed in Table 1.

Using the intrinsic geographic process scale and corresponding objective as guidance, other types of scales can be estimated to achieve scale matching (Fig. 1). On this level, scale compatibility refers to the matching of different scale types (i.e., process scale, observational scale, measurement scale and operational scale). Fig. 2 shows the possible mismatching of scale types (Chave & Levin, 2003). In this figure, the dots indicate the measurement scale (grain), and the squares enclosing the dots specify the observational scale (extent); the others denote the patterns that are derived based on the process scale. In the left example, the sampling scheme extent is too small to detect the local features because all of the samples are within the process extent. In the right example, the coarseness of the sample is too large relative to the patterns, and thus, not enough samples to capture the patterns result. As is shown, mismatching may hinder the discovery and understanding of geographic patterns.

In studying and managing geographic processes, researchers have realized scale compatibility on this level. Due to the scale matching between measurement and process scales, decreasing the spatial grid spacing of a meteorological model allows more mesoscale factors to be included in a numerical solution and vice versa (Pielke & Uliasz, 1998). Concerning process and operational scales, a mismatch problem might emerge between the scale of what is known about the world and at which action is taken (Kates et al. 2001). For example, there is a grave mismatch between the knowledge that is needed to act locally by different countries (or states, counties, etc.) and what is currently being done globally to generate knowledge about climate change, its impacts and responses to concerns (Sullivan, Ternan, & Williams, 2004; Wilbanks & Kates, 1999).

Scale compatibility of component level

Scale components are the third tier of scale concept (Wu & Li, 2006). It is proposed such that the scale is manageable for each scale type in each dimension, denoted as resolution (grain), extent, zone window, sampling space, cartographic scale, etc. For example, if the spatial scale compatibility of landscape indices was estimated, which scale types to use must be considered, for instance, the observational and measurement scales; and then to make it quantifiable, the extent and grain size are used respectively to compute the scale effect and achieve our target (Mochizuki & Murakami, 2013; Simova & Gdulova, 2012). In this context, component level scale compatibility refers to the matching of scales within components (i.e., resolution, extent and grain size) between

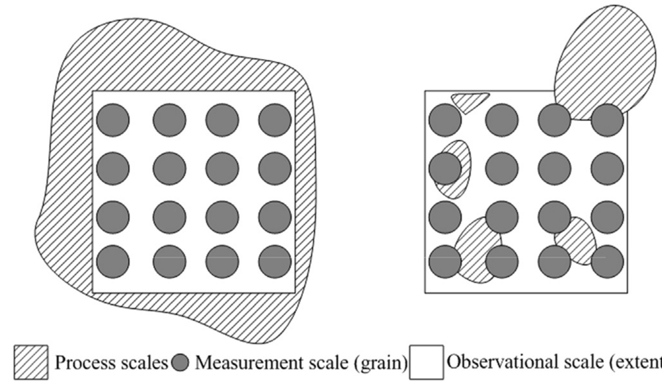

Fig. 2. Two possible explanations for mismatching process, measurement and observational scales.

data, models, visualization and analyses. This level of scale matching is very familiar in traditional research, especially for the multiscale organization of geographic data and visualization (Edsall, Harrower, & Mennis, 2000; Wu, 2004; Yuan & Hornsby, 2007). However, much work is required before these components can be comprehensively matched with regard to different dimensions and scale types concerning data, models, etc., as shown in Fig. 1 (Armstrong & Martz, 2003; Syphard & Franklin, 2004).

Implementation of scale compatibility

Procedure to assess scale compatibility

The aim of scale compatibility identification and decomposition is to account for scale compatibility in our study, i.e., to implement scale compatibility. To systematically consider such an issue, the relationships between the aforementioned four levels of scale compatibility are investigated in detail. As shown in Fig. 3, scale compatibility is assessed for multiple interactive processes based on the interactive processes (e.g., meteorology and hydrology). To generate a concise figure, only the link for the first items of each level is plotted. For each process, scale compatibility is estimated with respect to different dimensions. Furthermore, for each dimension, different scale types must be considered. Each scale type is reflected as the corresponding scale component. Therefore, the top level is used as guidance for the lower levels of compatibility, and the scale compatibility acceptability at the bottom level represents the foundation for the higher compatibility levels. With such a procedure, partitioning the scale compatibility step-by-step from multiple processes to dimensions, types and components is feasible.

Criteria to assess scale compatibility

When reaching the component level, the method in which to evaluate this compatibility must be regarded. This paper proposes

Table 1
Definitions of scale types.

Term	Definition	Remarks
Process scale (Schulze, 2000)	The scale at which natural phenomena occur or operate, including spatial-temporal dimensions, extent and unit aspects.	Similar to operational scale (Crawford, 2009), phenomenon scale (MOntello, 2001) and instinct scale (Wu & Li, 2006).
Observational scale (Schulze, 2000)	The scale at which humans choose to collect samples of observations and study phenomena.	Similar to experimental scale (Wu & Li, 2006).
Measurement scale (Crawford, 2009)	The smallest observable (or observed) parts of a spatial entity, e.g., resolution or granularity.	Similar to observational scale (Wu & Li, 2006).
Operational scale (Schulze, 2000)	The working scale at which management actions and operations focus.	Similar to policy scale (Wu & Li, 2006).

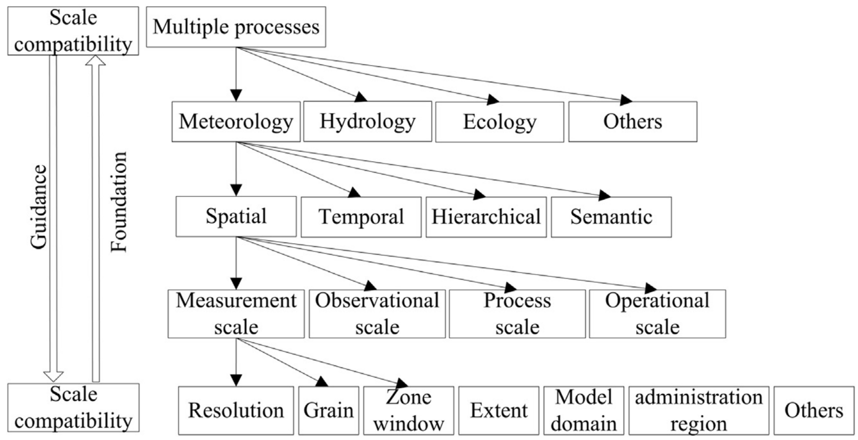

Fig. 3. Step-by-step implementation of scale compatibility.

to use accuracy, efficiency, redundancy and other relevant factors as evaluation indicators, focusing on geographic dynamics, as based on previous reports (Costanza & Maxwell, 1994; Papanastasiou, Melas, & Lissaridis, 2010; Zhang & Zhang, 2011). The criteria to estimate scale compatibility can be comprehensively described by the following expression:

$$\text{Scale Compatibility} = F(\text{accuracy}, \text{efficiency}, \text{redundancy}, \text{others}). \quad (1)$$

The accuracy of a modeled system depends on how closely the reproduction of a quantity reflects that quantity's actual (observed) value (JCGM200, 2008). How to estimate the accuracy remains an important but problematic necessity (Willmott & Matsuura, 2005). Time efficiency usually describes the extent to which time is well used for an intended task or purpose (Xu et al. 2010). In general, accuracy and time efficiency change when different scales of data, models and visualizations are employed. Redundancy is another factor that can affect both accuracy and efficiency. Other factors, such as storage cost, feasibility and cognoscibility, may also be used to estimate scale compatibility, and must be adjusted according to a specific application and research goal.

Scale compatibility estimation in a meteorological simulation

Scale compatibility is very complex due to different processes, dimensions, types and components. In addition, this concept permeates all stages of the study of geography, including data, models, visualizations and analyses. However, for specific research projects, the procedures proposed in the above section enable the estimation of scale compatibility. For instance, if spatial dimension is focused on, scale compatibility can be partitioned into component level, according to Fig. 3. As an application of such an implementation, the following case study illustrates this procedure by estimating the scale compatibility between multi-resolution DEM data and a meteorological model in spatial dimension and measurement scale at the component level (first column of Fig. 3).

Experimental description

Study area and model setting

Many previous studies have shown the significance of topography in generating sea land breezes and in affecting environmental conditions (Aalto et al. 2006; Miao, Kroon, de Arellano, & Holtslag, 2003). The study area, Hong Kong and its surrounding region, is situated on China's southern coast and features a complex coastline and numerous islands. The topography in this region is regarded as complex due to the dominance of hills (comprising 75% of the studied area), as shown in Fig. 4 (Liu, Chan, & Cheng, 2001). To investigate the scale compatibility between multiscale topography and the model, multi-resolution DEM data (3 and 30 arc sec and 2 and 10 arc min, as processed in ArcGIS 10.0 using a simple averaging aggregation method) were imported into the meteorology model. The data source was the Shuttle Radar Topography Mission (SRTM) with a resolution of 90 m and was obtained in 2003 (CGIAR-CSI, 2012).

The Weather Research and Forecasting (WRF) model (WRF, 2012) was applied to reproduce the meteorological field over Hong Kong and its surrounding region. The WRF model is a fully compressible and nonhydrostatic model. The vertical coordinate for the WRF model is the terrain following hydrostatic pressure, and the dynamics conserve scalar variables (Papanastasiou et al. 2010). The WRF model runs with horizontal grid spacing of 1, 3, 9 and 27 km, centered at 113.367°E, 24.716°N, and the physical setting is reported in Table 2 with reference to Jiang (2012) due to their successful application over the studied area.

Experimental design

The WRF system includes a pre-processing tool that prepares geographic and meteorological data for simulation. Regardless of the scale of the DEM data that is imported into the WRF model, the model will reprocess the data with the nearest neighbor interpolation method to a corresponding model grid spacing by up- or down-scaling (WRF, 2012). Due to this process, the capacity to express topography using a dynamic model is affected by the scales of the DEM data and model. This fact raises a scale-matching issue between the multiscale DEM data and the WRF model, which may further affect the capacity to reproduce a meteorological field, an important component of geographic dynamics. The flowchart of the experiment, designed to explore the solutions to this problem, is shown in Fig. 5. After the data were imported into the multiscale model, monitored elevation data from 45 validation stations in Hong Kong (blue dots in Fig. 4(in web version)) were used to evaluate the expression capability of the multiscale data and model. Furthermore, a meteorological field was simulated in January and July of 2006 to estimate the scale compatibility between the data and model based on the observed meteorological variables at daily resolution from eight typical weather stations (Table 3; pink dots in Fig. 4(in web version)). The observations were provided by the Hong Kong Observatory with information regarding instrumentation and observation methods (HKO, 2007). In the validation process, four meteorological variables were considered (T2 refers to

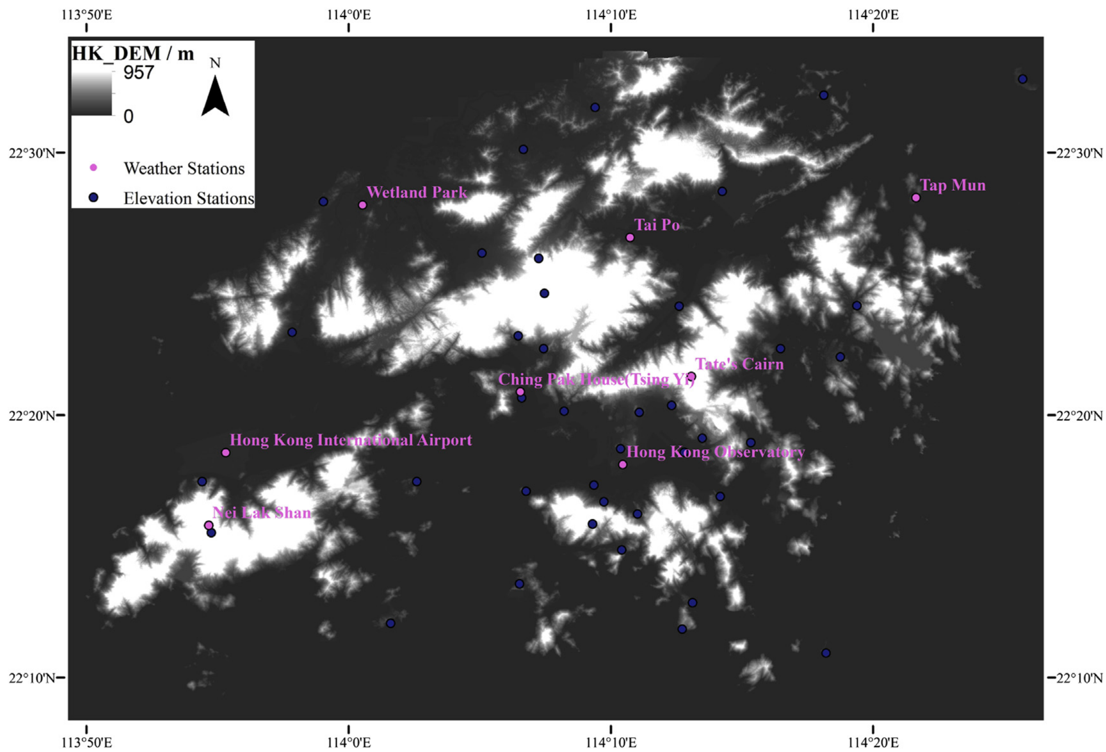

Fig. 4. Topography map of Hong Kong with validation stations (HKO, 2012).

2 m temperature, RH to relative humidity, WD to wind direction and WS to wind speed). Based on the results from these two perspectives, the scale compatibility between the multiscale DEM data and model was analyzed.

Scale compatibility between the multiscale DEM data and the model

Evaluation of the capacity to express topography

Monitored elevation data were used to compare topographic surface biases for the multiscale DEM data and models. For each DEM from the corresponding model, vertical elevation errors between the observed and abstracted models were calculated for each point from 45 stations using the following equation:

$$E(S_i) = P(S_i) - M(S_i). \quad (2)$$

Here, $E(S_i)$ is the error at location S_i, $P(S_i)$ represents the predicted value of the DEM at location S_i and $M(S_i)$ denotes the measured value at location S_i. The root mean square error (RMSE) and mean absolute error (MAE), based on definitions by Wang et al. (2009) (e.g., unsigned error), were also calculated to measure the global accuracies of the surfaces (Table 4).

Two points can be concluded based on the analysis in Table 4. First, the residual RMSE and MAE between surfaces and validation points indicate that the 3 arc sec DEM from the 1 km model provides the best expression. Second, for a finer scale model, finer scale DEM data provide a better topography expression. However, this situation is different for coarser scale models.

Does this divergence in the capacity to express topography affect the meteorological field simulation? If the answer to this inquiry is ‘yes’, then what scale, data and model demonstrate more compatibility to reproduce the meteorology over the studied area?

Table 2
Model physics and dynamics options.

Options	Schemes
Microphysics	SBU-YLin, 5-class scheme
Longwave radiation	RRTM scheme
Shortwave radiation	Dudhia scheme
Surface layer option	Monin-Obukhov scheme
Soil layer option	Noah land surface model
Land surface option	Unified Noah land surface model
Boundary layer option	YSU scheme
Cumulus option	Kain-Fritsch scheme

Capacity evaluation to reproduce meteorological processes

To investigate the scale compatibility between the data and model, we evaluated the dynamic simulation accuracy using the MAE to measure the scalar variable. This computation of MAE was revised accordingly to estimate circular variance (wind direction). Fig. 6 shows the validation results for the multiscale DEM data and models with reference to observations from eight typical weather stations. For temperature and relative humidity, the finer the data, the more accurate the simulation results. Within the same model scale (i.e., 1 km), discrepancies in DEM data due to different resolutions constituted as much as 38% of the total MAE in temperature reproduction (Fig. 6a). This result implies the scale compatibility significance when data are used in simulations. Meanwhile, estimating the uncertainty of dynamic simulations from imperfect data is advantageous. Furthermore, when considering wind velocity, high-resolution DEM data still provide better simulation results, although the trend is not as significant. However, the trend is less clear for wind direction, most likely because the time scale used in the validation was unsuitable. In Hong Kong, wind is extremely variable due to complex topography and sea-land breeze. Therefore, the daily average wind direction might not be typical enough to estimate the scale compatibility between topographic data and the model. In summary, considering the four meteorological variables from four domains in a dynamic model, DEM data with 3 and 30 arc sec resolutions and a 1 km model provide the best reproduction.

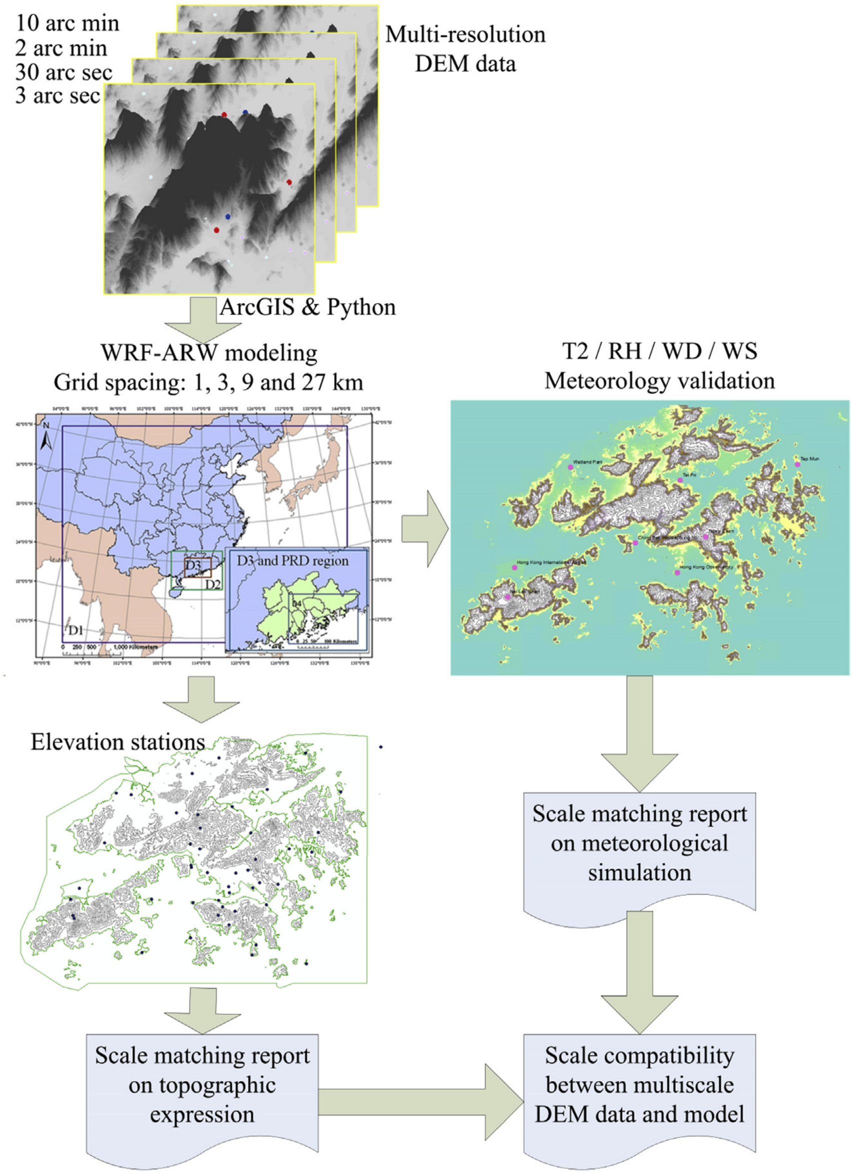

Fig. 5. Scale compatibility study framework of multiscale DEM data and the WRF model.

Discussion

To evaluate scale effect and compatibility, computational efficiency was also considered in this analysis. The results showed that the time taken to obtain the simulation results was not significantly lengthened when using detailed DEM data. The differential equation computations that determined meteorological conditions were more time consuming than DEM data processing.

Based on the experimental results, the following conclusions regarding the scale compatibility between multiscale DEM data and models in simulating a meteorological field over the studied area were drawn. 1) The different resolutions of DEM data and model setting affected the capacity of dynamic simulation, even accounting for 38% of the MAE. 2) Finer scale models are more sensitive to changes in DEM scale data than coarser ones, as illustrated by the MAE of topographical expression capacity, temperature and relative humidity simulation. As shown in Fig. 6a and b, the MAE decreases dramatically for the 1 km grid spacing model (domain 4), and the slope weakens when the model grid spacing becomes large. However, given the dependence of model scale and meteorological variables, it is difficult to conclude that the error decreases in the modeling results as the spatial resolution of the input data are improved, which may be due to the coherent effect from both model and input data. 3) Regarding the MAE of topographic expression and simulated meteorological field, the 3 and 30 arc sec

Table 3
Eight selected stations for meteorological validation.

Station name	Longitude	Latitude	Elevation (m)
Hong Kong Observatory	114.1742	22.3019	32
Nei Lak Shan	113.9111	22.2633	747
Hong Kong International Airport	113.9219	22.3094	6
Ching Pak House (Tsing Yi)	114.1092	22.3481	122
Tate's Cairn	114.2178	22.3578	575
Tai Po	114.1789	22.4461	15
Wetland Park	114.0089	22.4667	4
Tap Mun	114.3606	22.4714	15

Table 4
Global statistics summarizing the validation errors for multiscale DEM data and the model.

Model domain	Model grid spacing (km)	DEM resolution	MAE (m)	Min error (m)	Max error (m)	Range (m)	RMSE (m)
1	27	10 arc min	105.458	−74.17238	893.21913	967.39151	209.7969
1	27	2 arc min	104.9682	−57.67582	894.85195	952.52777	210.2143
1	27	30 arc sec	106.7903	−74.47359	885.15499	959.62858	210.007
1	27	3 arc sec	124.3945	−107.4932	849.9256	957.4188	207.5968
2	9	10 arc min	107.1517	−89.1978	859.36944	948.56724	206.3295
2	9	2 arc min	102.0897	−126.2455	808.0195	934.265	198.0149
2	9	30 arc sec	102.7571	−127.5296	814.7288	942.2584	198.1462
2	9	3 arc sec	115.1197	−153.4283	787.9332	941.3615	197.7991
3	3	10 arc min	106.3394	−94.4999	844.5648	939.0647	203.7569
3	3	2 arc min	91.78251	−143.6018	640.998	784.5998	162.1727
3	3	30 arc sec	84.22306	−137.0462	557.7419	694.7881	143.3935
3	3	3 arc sec	85.29091	−146.4543	546.2455	692.6998	143.7579
4	1	10 arc min	106.0111	−97.5142	841.547	939.0612	203.08
4	1	2 arc min	86.47708	−139.8105	557.8616	697.6721	147.0135
4	1	30 arc sec	54.50903	−94.77366	313.1541	407.92776	81.30814
4	1	3 arc sec	50.86265	−104.7876	295.9706	400.7582	79.07633

resolutions DEM data are relatively more compatible with the WRF model of 1 km grid spacing in this case study. Other DEM data and model resolution combinations might have unacceptable scale compatibilities from the perspective of the modeler.

Conclusions

Along with research into the dynamics of geography, multiscale characteristics constitute a key problem facing geographic researchers. Thus, with increasing geographic data and models, scale matching has become a significant issue when attempting to determine appropriate scale ranges to study geographic dynamics. In this paper, based on a three-tiered scale concept, scale compatibility was identified and partitioned into four groups with different operational levels. For each compatibility group, relevant recent literature was reviewed to improve the understanding of such issues. Thus, by partitioning the complex scale compatibility into more manageable groups with procedures that account for multiple processes, dimensions, types and components of scale, understanding and assessing scale compatibility have become practical. Some commonly used indicators to estimate scale compatibility was also discussed. The output from this work will help researchers to systematically evaluate scale compatibility, reducing the negative effects from scale mismatching by considering scale matching.

Applying the proposed procedure to assess scale compatibility, we used a meteorological simulation in Hong Kong as a case study

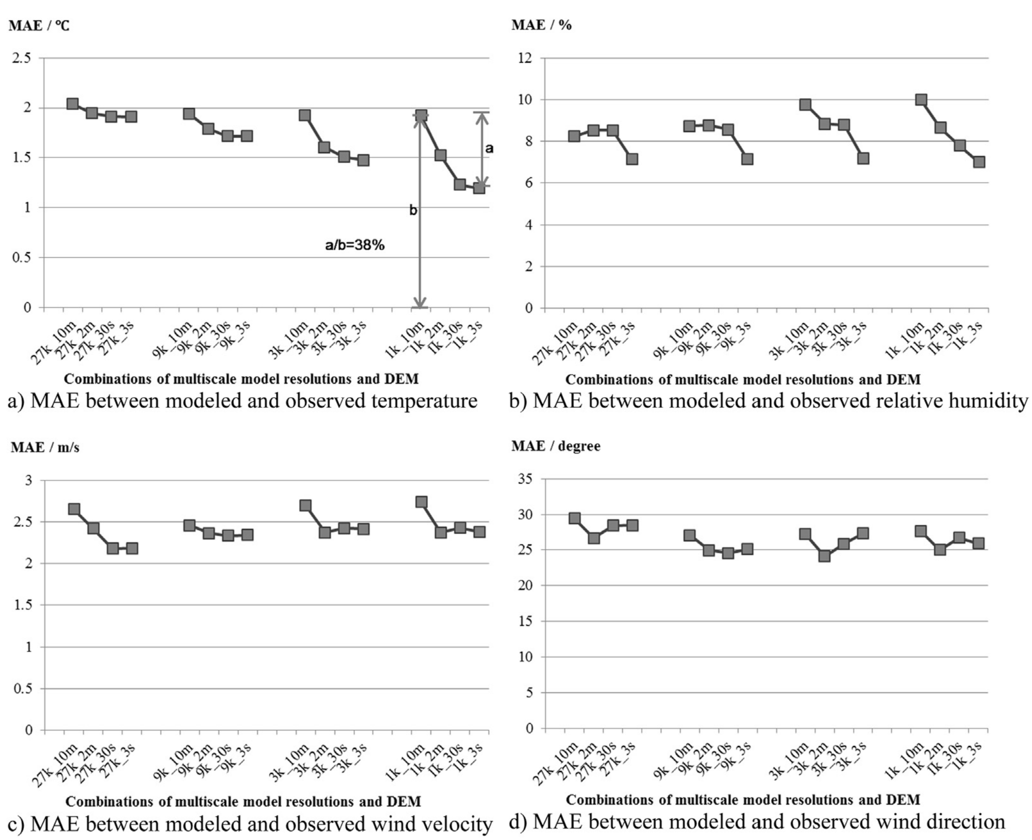

Fig. 6. Comparison of modeled and observed variables to identify the effects of scale on the simulation results in the data and model (10 m and 2 m represent 10 and 2 arc min, respectively; 30 and 3 s denote 30 and 3 arc sec, respectively).

and investigated the scale compatibility between multiscale DEM data and the WRF model. Through the reproduction of this meteorological field over Hong Kong, our findings showed that DEM data with 3 and 30 arc sec resolutions are relatively more compatible with the WRF model of 1 km grid spacing in such a case study. Simultaneously, the MAE induced by scale mismatching was stronger than the model grid spacing variation that has been identified as the sixth most important factor in the forecasting capacity of mesoscale meteorological models (Zhu & Xu, 2004). As shown in Fig. 6, the differences between the four domains with the same DEM scale data are not as great as the differences when the same domain is used with DEM data of different scales. Thus, with the implementation of scale compatibility, this case study might provide a practical contribution to meteorological simulations.

Acknowledgments

We are grateful to Mr. Dong Chen for the work in data processing and two anonymous reviewers for constructive suggestions. The research presented in this article was supported by the National Natural Science Foundation of China (grant nos. 41171146, 41101370, 41371388 and 41371424), the Innovation and Technology Fund of Hong Kong (grant no. ITS/042/12FP) and the Chinese University Hong Kong Direct Grant (grant no. 4052007).

References

Aalto, T., Hatakka, J., Karstens, U., Aurela, M., Thum, T., & Lohila, A. (2006). Modeling atmospheric CO2 concentration profiles and fluxes above sloping terrain at a boreal site. *Atmospheric Chemistry and Physics, 6*, 303–314.
Adger, W. N., Arnell, N. W., & Tompkins, E. L. (2005). Successful adaptation to climate change across scales. *Global Environmental Change-Human and Policy Dimensions, 15*(2), 77–86.
Armstrong, R. N., & Martz, L. W. (2003). Topographic parameterization in continental hydrology: a study in scale. *Hydrological Processes, 17*(18), 3763–3781.
Brown, D. G., Riolo, R., Robinson, D. T., North, M., & Rand, W. (2005). Spatial process and data models toward integration of agent-based models and GIS. *Journal of Geographical Systems, 7*, 25–47.
Cash, D. W., Adger, W. N., Berkes, F., Garden, P., Lebel, L., Olsson, P., et al. (2006). Scale and cross-scale dynamics: governance and information in a multilevel world. *Ecology and Society, 11*(2).
CGIAR-CSI. (2012). *SRTM 90m digital elevation data*. Available from http://srtm.csi.cgiar.org/index.asp. Cited 21 August 12.
Chave, J., & Levin, S. (2003). Scale and scaling in ecological and economic systems. *Environmental & Resource Economics, 26*(4), 527–557.
Costanza, R., & Maxwell, T. (1994). Resolution and Predictability - an approach to the scaling problem. *Landscape Ecology, 9*(1), 47–57.
Crawford, T. W. (2009). Scale analytical. In R. Kitchin, & N. Thrift (Eds.), *International encyclopedia of human geogarphy* (1st ed.) (pp. 29–36). Oxford: Elsevier.
Di Vittorio, A. V., & Miller, N. L. (2014). Reducing the impact of model scale on simulated, gridded switchgrass yields. *Environmental Modelling & Software, 51*(0), 70–83.
Edsall, R. M., Harrower, M., & Mennis, J. L. (2000). Tools for visualizing properties of spatial and temporal periodicity in geographic data. *Computers & Geosciences, 26*(1), 109–118.
Gibson, C. C., Ostrom, E., & Ahn, T. K. (2000). The concept of scale and the human dimensions of global change: a survey. *Ecological Economics, 32*(2), 217–239.
Goodchild, M. F. (2009). Geographic information systems and science: today and tomorrow. *Proceedings of the International Conference on Mining Science & Technology (Icmst2009), 1*(1), 1037–1043.
HKO. (2007). *Summary of meteorological and tidal observations in Hong Kong 2006* (pp. 24–27). Hong Kong.
HKO. (2012). *Information of weather station*. Available from http://www.weather.gov.hk/cis/annex/hkwxstn_e.htm. Cited 25 Apr. 2014.
Hofer, D.-I. B. H. (2009). *A language to describe geographic physical processes*. Vienna: Vienna University of Technology.
JCGM200. (2008). *International vocabulary of metrology — Basic and general concepts and associated terms (VIM)*. Available from http://www.bipm.org/utils/common/documents/jcgm/JCGM_200_2008.pdf. Cited 23 Nov. 2012.
Jiang, F., Liu, Q., Huang, X. X., Wang, T. J., Zhuang, B. L., & Xie, M. (2012). Regional modeling of secondary organic aerosol over China using WRF/Chem. *Journal of Aerosol Science, 43*(1), 57–73.
Kachanoski, R. G. (1988). *Processes and soils — from pedon to landscape*. New York: John Wiley and Sons.
Kates, R. W., Clark, W. C., Corell, R., Hall, J. M., Jaeger, C. C., Lowe, I., et al. (2001). Environment and development — sustainability science. *Science, 292*(5517), 641–642.
Lilburne, L. R., Webb, T. H., & Benwell, G. L. (2004). The Scale Matcher: a procedure for assessing scale compatibility of spatial data and models. *International Journal of Geographical Information Science, 18*(3), 257–279.
Li, S. G., Liu, Q., & Afshari, S. (2006). An object-oriented hierarchical patch dynamics paradigm (HPDP) for modeling complex groundwater systems across multiple-scales. *Environmental Modelling & Software, 21*(5), 744–749.
Liu, H. P., Chan, J. C. L., & Cheng, A. Y. S. (2001). Internal boundary layer structure under sea-breeze conditions in Hong Kong. *Atmospheric Environment, 35*(4), 683–692.
Liu, K., Wu, H., & Hu, J. (2007). Fundamental problems on scale of geographical information science. Proc. of SPIE, Nanjing, China. In Y. P. Jingming Chen (Ed.), *Geoinformatics*.
Meentemeyer, V. (1989). Geographical perspectives of space, time, and scale. *Landscape Ecology, 3*(3–4), 163–173.
Miao, J. F., Kroon, L. J. M., de Arellano, J. V. G., & Holtslag, A. A. M. (2003). Impacts of topography and land degradation on the sea breeze over eastern Spain. *Meteorology and Atmospheric Physics, 84*(3–4), 157–170.
Mochizuki, S., & Murakami, T. (2013). Scale dependent effects in resource selection by crop-raiding Japanese macaques in Niigata Prefecture, Japan. *Applied Geography, 42*, 13–22.
MOntello. (2001). Scale in geography. In N. J. Smelser, & P. B. Baltes (Eds.), *International encyclopedia of the social and behavioral sciences* (pp. 13501–13504). Oxford: Pergamon Press.
Openshaw, S. (1983). *The modifiable areal unit problem* (Vol. 38). Norwick, Norfolk: Geo Books.
Palmer, M. W., & White, P. S. (1994). Scale dependence and the species—area relationship. *American Naturalist, 144*(5), 717–740.
Papanastasiou, D. K., Melas, D., & Lissaridis, I. (2010). Study of wind field under sea breeze conditions; an application of WRF model. *Atmospheric Research, 98*(1), 102–117.
Peterson, D. L., & Parker, V. T. (1998). *Ecological Scale: Theory and applications*. New York: Columbia University Press.
Pielke, R. A., & Uliasz, M. (1998). Use of meteorological models as input to regional and mesoscale air quality models — limitations and strengths. *Atmospheric Environment, 32*(8), 1455–1466.
Poole, G. C., Stanford, J. A., Running, S. W., Frissell, C. A., Woessner, W. W., & Ellis, B. K. (2004). A patch hierarchy approach to modeling surface and subsurface hydrology in complex flood-plain environments. *Earth Surface Processes and Landforms, 29*(10), 1259–1274.
Schulze, R. (2000). Transcending scales of space and time in impact studies of climate and climate change on agrohydrological responses. *Agriculture Ecosystems & Environment, 82*(1–3), 185–212.
Simova, P., & Gdulova, K. (2012). Landscape indices behavior: a review of scale effects. *Applied Geography, 34*, 385–394.
Sullivan, A., Ternan, J. L., & Williams, A. G. (2004). Land use change and hydrological response in the Camel catchment, Cornwall. *Applied Geography, 24*(2), 119–137.
Syphard, A. D., & Franklin, J. (2004). Spatial aggregation effects on the simulation of landscape pattern and ecological processes in southern California plant communities. *Ecological Modelling, 180*(1), 21–40.
Taleai, M., Sharifi, A., Sliuzas, R., & Mesgari, M. (2007). Evaluating the compatibility of multi-functional and intensive urban land uses. *International Journal of Applied Earth Observation and Geoinformation, 9*(4), 375–391.
Wang, X. M., Chen, F., Wu, Z. Y., Zhang, M. G., Tewari, M., Guenther, A., et al. (2009). Impacts of weather conditions modified by urban expansion on surface ozone: comparison between the pearl river delta and yangtze river delta regions. *Advances in Atmospheric Sciences, 26*(5), 962–972.
Wilbanks, T. J., & Kates, R. W. (1999). Global change in local places: how scale matters. *Climatic Change, 43*(3), 601–628.
Willmott, C. J., & Matsuura, K. (2005). Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance. *Climate Research, 30*(1), 79–82.
Worboys, M. F. (2001). Nearness relations in environmental space. *International Journal of Geographical Information Science, 15*(7), 633–651.
WRF. (2012). *The weather research & forecasting model*. Available from http://www.wrf-model.org/index.php. Cited 2 Apr. 2012.
Wu, J. G. (2004). Effects of changing scale on landscape pattern analysis: scaling relations. *Landscape Ecology, 19*(2), 125–138.
Wu, J. (2007). Scale and scaling: a cross — disciplinary perspective. In J. Wu, & R. Hobbs (Eds.), *Key topics in landscape ecology*. Londan: Cambridge University Press.
Wu, J., & Li, H. (2006). Concepts of scale and scaling. In J. J. Wu, K. Bruce, Habin Li, & Orie Loucks (Eds.), *Scaling and uncertainty analysis in ecology: Methods and applications* (pp. 1–13). Dordrect, Netherlands: Springer.
Xu, B. L., Lin, H., Chiu, L. S., Tang, S., Cheung, J., Hu, Y., et al. (2010). VGE-CUGrid: an integrated platform for efficient configuration, computation, and visualization of MM5. *Environmental Modelling & Software, 25*(12), 1894–1896.
Yarnal, B., Lakhtakia, M. N., Yu, Z., White, R. A., Pollard, D., Miller, D. A., et al. (2000). A linked meteorological and hydrological model system: the Susquehanna River Basin Experiment (SRBEX). *Global and Planetary Change, 25*(1–2), 149–161.
Young, O. R. (2003). *The institutional dimensions of environmental change: Fit, interplay, and scale*. Cambridge: MIT Press.
Yuan, M. (2007). *Geographic information systems (GIS) approaches for geographic dynamics understanding and event prediction — Art. no. 65781A*. In R. Suresh (Ed.),

Defense transformation and net-centric systems 2007 (Vol. 6578); (pp. 34–37). Bellingham: Spie-Int Soc Optical Engineering.
Yuan, M., & Hornsby, K. S. (2007). *Computation and visualization for understanding dynamics in geographic domains: A research agenda*. CRC Press.
Zhang, C., Lin, H., & Chen, M. (2014). Discussion about scale adaptability in virtual geographic environments. *ACTA GEOGRAPHICA SINICA, 69*(1), 100–109.
Zhang, N., & Zhang, H. Y. (2011). Scale variance analysis coupled with Moran's I scalogram to identify hierarchy and characteristic scale. *International Journal of Geographical Information Science, 25*(9), 1525–1543.
Zhu, R., & Xu, D. (2004). Multi-scale turbulent planetary boundary layer parameterization in mesoscale numerical simulation. *Journal of Applied Meteorological Science, 15*(5), 543–555.