Urban Weather and Modeling

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Topics

• Effects of cites on weather
• Modeling urban processes in mesoscale numerical weather prediction models
• Examples of urban model applications
• Challenge in urban modeling
Urban Sprawl: Growth of Baltimore, Maryland, from 1792-1992

Courtesy USGS

Lecture at the UT-Austin, Austin, 19 October 2006.
Urbanization Issues

• Nearly 300 cities have a million or more inhabitants

• Adverse urbanization effects:
  – Poor air quality, toxic contaminant dispersal
  – Deterioration of visibility
  – Adverse impacts on human health
  – Damage to agriculture and ecosystems
  – Water and energy supply/demand
  – Impact on climate (ozone and aerosol, greenhouse radiation budget)
  – Emergency response
Air pollution is not a local problem

March - December 2004 TERRA/MOPITT images
Concentration of carbon monoxide (CO) at 15,000 feet
Red colors: highest levels of CO (450 parts per billion)
Blue: lowest levels of CO (50 ppb)

John Gille, ACD/NCAR
Lecture at the UT-Austin, Austin, 19 October 2006.
Why Care About Urban Meteorology?

- An increasing fraction of the population lives/works in cities
- The weather in cities is distinct from that of rural areas
- Urban effects on the atmosphere have regional and global implications
- Predicting the transport of hazardous material
- National security applications
Outline

• Effects of cites on weather
• Modeling urban processes in mesoscale numerical weather prediction models
• Examples of urban model applications
• Challenge in urban modeling
At Small and Urban Scales:
The Generation By Cities of Their Own Weather

- Urban heat island
- Enhanced precipitation
- Modification of the large-scale winds by increased roughness
The Urban Heat Island: Its Causes and Consequences

• Causes
  – Low reflectivity of urban surface – more solar absorbed
  – Reduction of solar radiation at surface, esp. for low sun elevation
  – Large daytime large sensible heat flux to carry heat from urban canyon: ~ 60-70 percent of net radiation
  – Low evaporation
  – Large nighttime source heat flux
  – Anthropogenic heating

• Consequences
  – Temperature is higher, esp. at night
  – Low-level winds converge on city, and rise
Temperatures in most cities are warmer than suburban rural areas.

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Recent Temperature Trends in Cities
The Atlanta, Columbia, Birmingham Heat Islands
Sacramento

White, red – Hot, 60 C, 140 F

Blue, green – Cool, 30 C, 90 F

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Weather Modified by Urban Heat Island: In-land Breeze
Weather Modified by Urban Heat Island:
Generation/Enhancement of Rainfall

1. In big cities, heat-absorbing roofs, blacktop pavement and auto exhaust trap the sun's rays and warm the air.
2. Late in the day, the accumulated heat starts to be released. The lighter, warmed air begins to rise.
3. In cities near large bodies of water, moist air flows in toward the rising urban air.
4. The moist air and warm city air collide and drive each other higher, hitting the cooler layer of air above and creating clouds and rain.
5. The prevailing wind blows the clouds. Areas downwind of cities get more rain than those upwind.

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Effect of Large Cities on Weather-Map Scale Processes

• Approaching fronts are distorted by metro area

• Large-scale precipitation patterns are perturbed
Observing Urban Weather
DCNet locations

The intent is to set up 10 – 20 stations in the downtown DC area.

The area covered will be expanded as funding permits.

Lecture at the UT-Austin, Austin, 19 October 2006.
DCNet – UrbaNet tower configuration: (DCNet is the central Washington demonstration project. UrbaNet will be the extension to larger areas and other cities.)

Meteorology by NOAA

Rad and Chem sensors by DOE,

Communications by DOE and others

Dispersion forecasts by NOAA.

Bio threat danger by NOAA
Urban Heat Island Phenomenon

• Increase the demand for energy
  – 1/6 of the electricity consumed in the U.S. is used for cooling purposes ($40 billion/year)

• Higher air temperatures increase the amount of ground level ozone, or smog

• May enhance heat waves within cities
  – The mortality rate during a heat wave increases exponentially with the maximum temperature, an effect that is exacerbated by the urban heat island
  – European Heat Wave of 2003: as many as 50,000 people died in Europe
Outline

• Effects of cites on weather
• **Modeling urban processes in mesoscale numerical weather prediction models**
• Examples of urban model applications
• Challenge in urban modeling
Embrace the New-era of Urban Modeling and Application

• Urban problems can only be addressed in mesoscale/fine-scale modeling framework
• We can now bridge the gap between traditional mesoscale (~ 10 km) and fine-scale urban modeling (~ 10 m)
  – NWP models running at 1-km grid spacing
  – Availability of high-resolution urban data
  – Land data assimilation techniques
  – Techniques to couple NWP and CFD-type models
Developing an Integrated Urban Modeling Framework for WRF and WRF-Chem

- Urban models
- Integrate new *in-situ* and remotely sensed data for better representing urban characteristics
- Integrate natural (biogenic, wildfire) and anthropogenic emissions
- High-resolution land data assimilation system
- Information transferable to decision support systems

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Urban Modeling Methods

• In-building scale (typical grid resolution: < 1 meter; forecast time: seconds to minutes)

• Features
  – Computational Fluid Dynamic (CFD) model explicitly solve the interior structure of a building
  – Provide indoor airflow and dispersion
  – Very complex and expensive to run

Indoor air flow
Urban Modeling Methods (Cont.)

- Single to many building scale (grid: 1-100 m; forecast time: minutes to a few hours)
- Features
  - CFD model solve exterior 3-D structures of buildings
  - Direct effects of building channeling and blockage;
  - Provide 3-D airflow and dispersion around buildings
  - Multiple urban layers; very expensive to run
Urban Modeling Methods

• In-building scale modeling (typical grid resolution: < 1 meter; using Computational Fluid Dynamic (CFD) model; forecast time: seconds to minutes)

• Single to many building scale modeling (typical grid resolution: 1-100 meter; using CFD model; forecast time: minutes to a few hours)

• Urban-canopy model parameterization (> 100 meters; forecast time: many hours)
Sky view factor (at street center) $\psi = \cos \{\tan^{-1}(2z_h/W)\}$

Roof area ratio: $A_r = \sum (a_i / A)$

Aspect ratio: $A_s = z_h/W$
Degree of complexity of urban modeling

We have been developing two methods for urban land-use modeling

- Simple bulk parameterization of urban effects in the MM5/Noah land surface coupled model
- More complex coupled Noah/Urban-Canopy Model for WRF
Simple Parameterization of Urban Effects in the Noah LSM

• Large roughness length
  – turbulence generated by roughness elements
  – drag due to buildings

• Small albedo
  – radiation trapping

• Large thermal capacity and thermal conductivity
  – heat storage in soil

• Low evaporation

• Implemented in MM5 V3.7 and WRF V2.0 (2004)
WRF/Noah LSM/Urban-Canopy Coupled Model

- Single layer urban-canopy model (UCM, Kusaka et al., 2004)
- Noah handle natural surfaces, UCM treats man-made surfaces
  - 2-D urban geometry (orientation, diurnal cycle of solar azimuth), symmetrical street canyons with infinite length
  - Shadowing from buildings and reflection of radiation
  - Multi-layer roof, wall and road models

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Integrate new remote sensing data for better representing urban characteristics

ASTER - 15m  
Beijing land-cover  
April 9, 2004

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Integrate surface Emission Model
MEGAN: Model of Emissions of Gases and Aerosols from Nature

- Global biogenic emissions model
  - 1 km² spatial resolution
  - Predicts emissions of > 50 VOC

\[ \text{Emission}_i = \text{AEF}_i \times \text{MEA} \times \text{WEA} \times \text{HEA} \]
High-resolution land surface and urban modeling and assimilation system

Vegetation type
Soil texture
Urban type
Terrain
snow
Leaf area index

High resolution land data assimilation system (HRLDAS)

Obs. Precipitation
Radiation, T, Q, U, V

Soil moisture, soil temperature, snow cover, canopy water, wall/roof/road temperature

Noah land surface model, Urban canopy model

Boundary layer parameterization

Coupled mode
Outline

• Effects of cites on weather
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Verification of Coupled MM5/WRF Urban Models

Salt Lake City: Diurnal wind direction (URBAN-2000)

Oklahoma City: 2-m temperature (JU-2003)

Beijing and Tokyo: surface weather, precipitation

Houston: Diurnal cycle of wind profile (TexAQS-2000)

Hong Kong: 10-day surface wind

Joint Urban 2003 (OKC)
RTFDDA URBAN SIMULATION
Land use and water body on Domain 4 (1.5-km)
defined by USGS (1994) + Terra MODIS (2002) landuse data

Aerial picture

~7% larger urban area based on MODIS landuse
Average of 9 clear-sky days in July 2003, at 06Z, 1.5-km grid
Lecture at the UT-Austin, Austin, 19 October 2006.

JUT 2003 (OKC) RTFDDA
URBAN SIMULATION
Case examples – Nocturnal PBL – 06Z June 24

PBL Height (m)

Wind Speed (m/s; LLJ)

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Domain 1: 40.5km
Domain 2: 13.5km
Domain 3: 4.5km
- 1km grid size
- Much more urban areas
- Better river network and water bodies

Main Land Use Categories (USGS based):

- Urban
- Dryland Crop.
- Past.
- Irrigated Crop.
- Past.
- Shrubland
- Crop./Grs.
- Mosaic
- Evergreen
- Broadlf.
- Wooded
- Wetland
- Grassland
2. The upper level land breeze pushes the polluted air toward the PRDCZ, where pollutants meet and well mix.

1. The sun heats up the ground, and cause polluted air to rise.

4. Pollutants disperse around the region and come back to the coast.

3. Polluted air cools and sinks to the surface.

Figure 9: Schematic representation of the pollutants trapping mechanisms by the sea breeze circulation over PRD. From Lo et al., 2006, JGR.

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High-Resolution WRF/Noah/Urban Modeling Capability

Domains: 40.5, 13.5, 4.5, 1.5, 0.5 km

Complex terrain on WRF nested D-5 (0.5 km grid spacing) over the Slat Lake City area

Single layer Urban Canopy Model

Complex Urban land use distribution over SLC
High-Resolution WRF/Noah/Urban Modeling Capability: Coupled to CFD-Urban

WRF-Noah/UCM coupled model forecast

CFD-Urban: Hi-Res Urban Model

Coupling

Down-Scale

Up-Scale

CFD-Urban: T&D

10m-Wind (m/s) & Terrain (m)
06Z25Oct2000
Diurnal Wind Direction in North Downtown

Red: Obs, Green: WRF/Noah, Blue: WRF/Noah/UCM
WRF/UCM - CFD Transport and Dispersion
Preliminary Results: Urban IOP 10 Urban 2000

• Urban 2000: Field Test conducted in Salt Lake City
  • SF6 released in Central Business District
  • Samplers located in CBD and on “arcs” located downstream
• Statistical Comparison of Predicted to Measured Concentration Data
WRF/UCM - CFD Transport and Dispersion
Preliminary Results: Urban IOP 10 Urban 2000

• Entire IOP 10
  • 3 Releases/Pauses
• WRF Data for BC
• Quasi-steady approach:
  • Wind/Turbulence fields at 15 minute intervals
  • Unsteady T&D using Unified Frozen Hydro Solver
• Flow turning is replicated, which causes plume to travel NNW

Gas Dispersion (Measurement vs. Prediction)
IOP10 (Gas Release 3600-7200s, 10800-14400s, 18000-22600s)

TIME = 3540.0 sec

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Gas Dispersion Prediction

Using WRF 12-h forecast (left panel) significantly improve FAC2 (FAC>0.5 acceptable) and MG (0.7<MG<1.3 acceptable) over using single sounding approach (right panel).

Courtesy of Bill Coirier, CFD Research Corporation

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Outline

• Effects of cites on weather
• Modeling urban processes in mesoscale numerical weather prediction models
• Examples of urban model applications
• Challenge in urban modeling
Challenge

• Specification of urban land use
• Initializing state variables of urban models (urbanized HRLDAS)
• Verification of urban simulations
• Degree of complexity of urban modeling
  – Specification of parameter required for more complex urban canopy models
Integrate high-resolution detailed urban landuse data

Aggregated to WRF 1-km domain

30-m Landsat land-cover Houston

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Initialize WRF/UCM Modeling System
substrate temperature simulated by urbanized HRLDAS
WRF/UCM Configuration for Houston Case

• WRF 4 nested Domains
  – 85X68 (domain1, at 27km)
  – 145X106 (domain2, at 9km)
  – 190160 (domain3, at 3km)
  – 199X154 (domain4, at 1km)

• WRFV2.1.2/UCM Simulation:
  – Using 3-hourly EDAS for initial and lateral boundary condition.
Wind Profiler at Ellington 25 Aug 2000

WRF/UCM simulation

Observations

PBL depth
Which diagnostic variable is more representative?

Traditional WRF: 2-m T and 10-m Wind

UCM: Temperature and wind in urban canyon

Observations (e.g., surface fluxes) are obtained in the urban roughness sublayer

Solid Red: T in the canyon
Dash Black: Observed
Solid Black: 2-m T

Solid Red: Wind speed in the canyon
Dash Black: Observed
Solid Black: 10-m wind speed

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Simple Bulk Scheme vs Urban Canopy Model

Five key parameters

- Surface albedo
- Surface emissivity
- Thermal conductivity/diffusivity
- Fractional urban coverage
- Soil moisture

<table>
<thead>
<tr>
<th>Fractional Urban Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban Type</td>
</tr>
<tr>
<td>Roof level (building height)</td>
</tr>
<tr>
<td>Roof area ratio (Building coverage ratio)</td>
</tr>
<tr>
<td>Wall area ratio</td>
</tr>
<tr>
<td>Road area ratio</td>
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<tr>
<td>Volumetric heat capacity of roof</td>
</tr>
<tr>
<td>Volumetric heat capacity of wall</td>
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<tr>
<td>Volumetric heat capacity of road</td>
</tr>
<tr>
<td>Thermal conductivity of roof</td>
</tr>
<tr>
<td>Thermal conductivity of wall</td>
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<tr>
<td>Thermal conductivity of road</td>
</tr>
<tr>
<td>Sub-layer Stanton number</td>
</tr>
<tr>
<td>Roughness length</td>
</tr>
<tr>
<td>Roughness length above canyon</td>
</tr>
<tr>
<td>Roughness length above roof</td>
</tr>
<tr>
<td>Zero plane displacement height</td>
</tr>
<tr>
<td>Roof surface albedo</td>
</tr>
<tr>
<td>Wall surface albedo</td>
</tr>
<tr>
<td>Road surface albedo</td>
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<tr>
<td>Roof surface emissivity</td>
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<tr>
<td>Wall surface emissivity</td>
</tr>
<tr>
<td>Road surface emissivity</td>
</tr>
<tr>
<td>Moisture availability of roof</td>
</tr>
<tr>
<td>Moisture availability of road</td>
</tr>
</tbody>
</table>
From Real World to UCM

UCM parameter space

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Simple Bulk Scheme vs Urban Canopy Model
2-m Temperature at 1800 LST 26 Aug 2000

Generally lower daytime temp (1-1.5 K) with UCM

2-m T: UCM-WRF

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Simple Bulk Scheme vs Urban Canopy Model
2-m Temperature at 0300 LST 26 Aug 2000

Generally higher nocturnal temp with UCM

2-m T: UCM-WRF

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Simple Bulk Scheme vs Urban Canopy Model

Sensible heat flux at 0300 LST 26 Aug

Positive SHF at 3 am with UCM

Sensible heat flux:
UCM-WRF

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Verification with Sounding
Downtown Houston, 1700 UTC 25 Aug 2000

Mixing Ratio

Temperature

Potential temperature
Simulations with UCM Enhance Strength of Sea Breeze

lowest-model level wind at 21 UTC 25 Aug 2000

With Urban Canopy Model

Simple urban treatment
Summary

- NWP model need to capture urban processes
- New WRF capability of urban-canopy modeling
  - Simple urban bulk parameterization perform adequately
  - More complex UCM provide more details
- Specification of urban landuse and characteristics critical (need to use remote sensing and local data)
- Specify UCM parameters is a challenge
  - Use look-up tables
  - Use spatial and temporal gridded data
  - New urban morphological data set
- Develop new approach to validate UCM
  - PBL structures are integrated
  - Spatial pattern of UHI and circulations