Modelling Urban Sensible Heat Flux at Multiple Spatial Scales: a Demonstration Using Multi-spectral Imagery and a Temperature-Emissivity Separation Approach

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Second Workshop on Earth Observation in Urban Planning and Management:
sub-theme Urban Heat Island/ Urban Climatology
The Hong Kong Polytechnic University, Hong Kong
Objective: Urban Energy Balance from Remote Sensing & Modelling

- Main emphasis is on spatial estimates of turbulent sensible heat flux (transfers heat from land surface to atmosphere)
- Using both airborne and spaceborne data (thermal/optical)
Methodology

Remotely Sensed Data Sources
- Airborne Operative Modular Imaging Spectrometer (OMIS)
- Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)
  - One offers more precision and detail, the other more frequent observations.

Sensible Heat Flux Modelled Spatially
- Local-scale Urban Meteorological Parameterization Scheme (LUMPS)

Atmospheric Correction of RS Imagery
- MODTRAN v4 with atmospheric profile from radiosonde balloons

Surface Kinetic Temperature & Emissivity Determination
- Temperature-emissivity separation (TES) alg. (Gillespie et al., 1998) for ASTER
- Adapted for use with OMIS (different wavebands, more spectral channels)
Test Study Area : London, UK

ASTER Imagery London

- ASTER Spaceborne Data, London
  - 15 m spatial resolution VIS
  - 30 m spatial resolution SWIR
  - 90 m spatial resolution TIR

- Used to test and evaluate our own implementation of ASTER TES alg.
  - to retrieve surface kinetic temp
  - validate against in situ data

- After validation, TES then used on Shanghai OMIS data (more bands)

Measures reflected/emitted radiation at different $\lambda$, after passage through atmos. Use Temperature/Emissivity Separation (TES) alg. for surface kinetic temperature
Temperature/Emissivity (TES) Application

**Figure 1.** Basic design of the TES algorithm. The NEM module estimates normalized emissivities used to estimate reflected sky irradiance, which is removed iteratively, and then estimates the surface temperature \( T \). \( T \) is used in the RATIO module to calculate normalized emissivities, or \( \beta \) values, which measure spectral shape. The MMD module calculates the Min-Max \( \beta \) difference, from which the minimum emissivity \( \epsilon_{\text{min}} \) is found by empirical regression. The \( \beta \) spectrum is scaled by \( \epsilon_{\text{min}} \) to give the TES emissivities, from which the surface temperature is calculated. Accuracies and precisions are calculated from data characteristics and measures of TES performance. A more detailed flow diagram is given in Figure 4.
London TES Evaluation in Urban Areas

- ASTER imagery obtained at times of Thames water temperature 10 – 21°C
- Adjusted TOA radiances to surface leaving radiance (MODTRAN v4)
- Input into TES algorithm to calculate emissivity and kinetic temperature ($T_k$)
- $T_k$ estimate compared to simultaneous measures of Thames water temp.

![7th April 2000](<14 18 22 >23)
![9th September 2004](<24 27 30 >31)

Surface Kinetic Temperature (°C)

**TES-derived $T_k$ vs in situ**

- RMSE = 0.4 °C
- Bias = 0.1 °C

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### OMIS Developed by:
Shanghai Institute of Technical Physics (SITP, Chinese Academy of Sciences)

<table>
<thead>
<tr>
<th>Spectral range (µm)</th>
<th>Spectral Resolution (nm)</th>
<th>Number of Spectral Bands (Total :128)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.46 - 1.10 (VIS)</td>
<td>10</td>
<td>64</td>
</tr>
<tr>
<td>1.06 - 1.70 (NIR)</td>
<td>40</td>
<td>16</td>
</tr>
<tr>
<td>2.00 - 2.50 (SWIR)</td>
<td>15</td>
<td>32</td>
</tr>
<tr>
<td>3.00 - 5.00 (MIR)</td>
<td>250</td>
<td>8</td>
</tr>
<tr>
<td>8.00 - 12.50 (TIR)</td>
<td>500</td>
<td>8</td>
</tr>
</tbody>
</table>

- Detector types: Si, InGaAs, InSb and HgCdTe
- FOV: >70°
- Scan rate (Hz): 5-10-15-20 (selectable)
- Across track pixels no.: 512
- Signal quantization level: 12 bits

OMIS flown on helicopter to give 6 m pixels (overflight time 14:00 hrs)
Main Study Area: Shanghai, China

2 km x 2 km region of central Shanghai, neighboring the Huangpu River

- OMIS Airborne Data, Shanghai
  - 6 m spatial resolution
  - VIS-SWIR-MIR-TIR

- Used to parameterise LUMPS model

Met station provided air temp., wind speed, and relative humidity (and radiosonde)
Local-scale Urban Meteorological Parameterisation Scheme (LUMPS)

- Calculates partitioning of the net all wave radiation ($Q^*$):

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S$$

net all wave radiation + anthropogenic heat = sensible heat + latent heat + heat storage

- LUMPS dependence only on relatively easily identifiable surface characteristics.
- Believed to offer an acceptable level of accuracy (Offerle, 2003).
Shanghai Land Surface Cover Characterisation for LUMPS

OMIS Colour Composite

Empirical Line Method Calibration

Fractional Cover Determination

- **Shadow**
  - OMIS
  - Manual analysis → Mask

- **Water**
  - OMIS
  - Manual analysis → Mask

- **Vegetation**
  - OMIS
  - Aerial photograph (0.67 m)
  - OMIS sub-pixel classification (Small 2001)

- **Buildings**
  - Aerial Photograph
  - Digital Topographic Map

- **Other Impervious**
  - OMIS – (Veg + Roof)

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OMIS-Derived Vegetation Fraction

OMIS-derived Vegetation Fraction vs High Spatial Resolution Aerial Photo

Vegetation Fraction
(Linear Mixture Modelling, Small (2001))
Vegetation Fraction
(OMIS/Linear Mixture Modelling, Small (2001))

Building Fraction
(1:2000 digital topographic map)
Survey Map-Derived Building Fraction

Vegetation Fraction
(OMIS/Linear Mixture Modelling, Small (2001))

Building Fraction
(1:2000 digital topographic map)

Remaining Fraction of Each 6 m Cell Classed as Other Impervious (Road, Pavement etc)
**Shanghai Land Surface Cover Characterisation for LUMPS**

**OMIS Colour Composite**

**Empirical Line Method Calibration & Fractional Cover Classification**

**Landcover Classification**

- **Red:** Roof
- **Purple:** Road
- **Green:** Veg
- **Blue:** River
- **Black:** Shadow

(dominant class threshold of 50%)

**Fractional Cover Determination**

- **Shadow**
  - 18%
  - **OMIS**
  - Manual analysis → Mask

- **Water**
  - 15%
  - **OMIS**
  - Manual analysis → Mask

- **Vegetation**
  - 8%
  - **OMIS**
  - Aerial photograph (0.67 m)
  - OMIS sub-pixel classification (Small 2001)

- **Buildings**
  - 32%
  - Aerial Photograph
  - Digital Topographic Map

- **Other Impervious**
  - 27%
  - OMIS – (Veg + Roof)
• Mean spectral emissivity difference (OMIS to Lib) is 0.005; max difference of 0.02

• Uncertainty of 0.1 in broadband emissivity corresponds to uncertainty of 45 Wm\(^{-2}\) in radiative heat flux 300 K (portion maybe compensated by reflected downwelling)
Summary of OMIS Data Processing & Input into LUMPS

- **8 Thermal IR bands**
  - Processed using 8 band TES implementation to:
    - Surface Kinetic Temperature
    - Surface Spectral Emissivity

- **112 Visible bands**
  - Processed to
    - Spectral Reflectance
    - Albedo & Veg Fraction
RESULTS: OMIS/LUMPS-Derived Fluxes (Net Radiation)

- Net radiation ($Q^*$) distribution similar for the three landcover types.
- Max difference (68 W m$^{-2}$) between pure veg and pure road 6 m pixels.
RESULTS: OMIS/LUMPS-Derived Fluxes (Storage Heat Flux)

• Pure rooftops characterised by lowest storage heat flux (mean ~ 15% $Q^*$)
• Pure roads/pavements have the largest storage heat flux (mean ~ 80% of $Q^*$)
RESULTS: OMIS/LUMPS-Derived Fluxes (Sensible Heat Flux)

- **Rooftops** characterised by highest sensible heat flux (mean ~ 60% $Q^*$)
- **Roads/pavements** have the lowest sensible heat flux (mean ~ 10% $Q^*$)
Influence of Spatial Scale on $Q_H$ ($\text{Wm}^{-2}$)

<table>
<thead>
<tr>
<th>Landcover (6 m)</th>
<th>Mixed Pixels ($Q_H$)</th>
<th>Pure Pixels ($Q_H$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>sd</td>
</tr>
<tr>
<td>Roof Dominated</td>
<td>199</td>
<td>62</td>
</tr>
<tr>
<td>Road Dominated</td>
<td>69</td>
<td>30</td>
</tr>
<tr>
<td>Veg Dominated</td>
<td>104</td>
<td>43</td>
</tr>
<tr>
<td>All</td>
<td>130</td>
<td>81</td>
</tr>
</tbody>
</table>

- Spaceborne sensors have lower spatial detail (but more available data)
  - OMIS 6 m pixels
  - ETM+ 30 - 60 m pixels
  - ASTER 15 - 90 m

- Aggregate OMIS data to lower spatial resolution to determine influence
  - Method 1: resample $Q_H$ results to 30 and 90 m resolution
  - Method 2: resample OMIS imagery to 30 and 90 m resolution prior to classification

- Calculate $Q_H$ via LUMPS approach once more with degraded data – and compare $Q_H$ ($\text{W/m}^2$) to original results obtained at 6 m
Influence of Spatial Scale (30 m)

<table>
<thead>
<tr>
<th>Q_H</th>
<th>Mean</th>
<th>sd</th>
<th>Mean</th>
<th>sd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>185</td>
<td>33</td>
<td>189</td>
<td>32</td>
</tr>
<tr>
<td>Road</td>
<td>83</td>
<td>28</td>
<td>85</td>
<td>28</td>
</tr>
<tr>
<td>Veg</td>
<td>87</td>
<td>21</td>
<td>97</td>
<td>21</td>
</tr>
<tr>
<td>All Pixels</td>
<td>157</td>
<td>56</td>
<td>160</td>
<td>55</td>
</tr>
</tbody>
</table>

← Meth1: Degrade Q_H output

Degradation to 30 m spatial scale.

← Meth2: Degrade LUMPS inputs

Can still identify many dominated class pixels
Influence of Spatial Scale (90 m)

Degradation to 90 m spatial scale.

- Meth1: Degrade $Q_H$ output
- Meth2: Degrade LUMPS inputs

<table>
<thead>
<tr>
<th>Q_H</th>
<th>90m Method 1</th>
<th>90m Method 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>sd</td>
<td>Mean</td>
</tr>
<tr>
<td>All Pixels</td>
<td>123</td>
<td>33</td>
</tr>
</tbody>
</table>

Most pixels now fully mixed classes
Final Comments & Conclusions

- Thermal remote sensing imagery with a GIS-type database provides data to allow calculation of energy fluxes by LUMPS.
- Shanghai changes - land cover detail needs regular updates.
- Using of spaceborne imagery maybe a practical solution for heat flux determination in urban areas where high resolution airborne data is only infrequently available.
- Atm. & emissivity corrections seem ok - but still need 3D info.