Turbulent Fluxes and Air Pollution in Cold Air Pool Events (Meteorology-Chemistry Coupling)

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Key Unanswered Questions

• What role does the boundary layer structure have on PM formation and the chemical processes?

• What role do stratiform clouds have on the atmospheric chemistry and boundary layer mixing?

• Can NWP models simulate near-surface meteorological conditions during stable PBL?

• Is it time to move on from existing dimensionless flux-gradient parameterizations to simulate the PBL mixing?

• Do we have enough turbulence data to make new empirical formulations for the RANS closure?
THE PERSISTENT COLD-AIR POOL STUDY


Utah's Salt Lake valley was the setting for a wintertime study of multiday cold-air pools that affect air quality in urban basins.

- Field Experiment
- Wintertime
- 2 ½ Months
- Salt Lake Valley, Utah
- Multiple Upper Air and Surface Sites

PCAPS field campaign (NSF: 0938397)
C. David Whiteman (U. of Utah)
John Horel (U. of Utah)
Sharon Zhong (Michigan State)

(Figures from: Lareau et al., BAMS 2013)
PCAPS Study Time Period: Winter 2010-2011

- 10 Intensive Observation Periods (IOPs)
- Brief and weak CAPs throughout *Weak CAPs*
- 4 IOPs with *Strong Multiday Persistent CAPs*
- NWP Modeling – IOP3 & IOP5
- Air Quality Modeling – January 2011 (IOP5 – IOP9)
NCAR EOL
Integrated Surface Flux System (ISFS)
Observation period:
Dec 2010 – Feb 2011
Sensor height:
3m or 10m

<table>
<thead>
<tr>
<th>No.</th>
<th>Site</th>
<th>Sensor Height (m)</th>
<th>Land Use (National Land Cover Database, NLCD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Playa</td>
<td>3</td>
<td>Barren land</td>
</tr>
<tr>
<td>2</td>
<td>ABC Urban</td>
<td>10</td>
<td>Developed, high intensity</td>
</tr>
<tr>
<td>3</td>
<td>Highland</td>
<td>10</td>
<td>Developed, medium intensity</td>
</tr>
<tr>
<td>4</td>
<td>West Valley</td>
<td>10</td>
<td>Developed, low intensity</td>
</tr>
<tr>
<td>5</td>
<td>East Slope</td>
<td>10</td>
<td>Developed, low intensity</td>
</tr>
<tr>
<td>6</td>
<td>West Slope</td>
<td>3</td>
<td>Pasture/Hay</td>
</tr>
<tr>
<td>7</td>
<td>Riverton</td>
<td>10</td>
<td>Cultivated Crops</td>
</tr>
</tbody>
</table>

(Map from: Lareau et al. 2013)
Numerical Weather Prediction Model

Weather Research & Forecasting (WRF) v3.7.1

Configurations

- NAM 12-km analysis dataset
- 3 Two-Way Nested Domains (finest: 480m)
- 30 Vertical Levels (10 in first 1,000m AGL)
- Surface and Upper Air Nudging (OBSGRID)
- NLCD Land Use Classification

Common Physics

- Cloud Microphysics: Lin
- Longwave Radiation: Rapid Radiative Transfer Model
- Shortwave Radiation: Dudhia
- Cumulus Parameterizations: Kain-Fritsch
- Cloud Fraction Option: Xu-Randall
Sensitivity Testing: PBL, Surface Layer, LSM

Planetary Boundary Layer, Surface Layer, Land Surface
1. ACM2, Pleim-Xiu, Pleim-Xiu (with soil nudging) [ACM2]
2. YSU, Revised MM5, Noah [YSU]
3. MYJ, Eta Similarity, Noah [MYJ]
4. MYNN, MYNN, Noah [MYNN]
Simulated Net Radiation and Friction Velocity (Strong CAP – IOP5)

Net Radiation (W/m²)

Friction Velocity (m/s)

Sun et al., (in prep)
Simulated Surface Fluxes (Strong CAP - IOP5)

Sensible HF (W/m$^2$)

Latent HF (W/m$^2$)

Sun et al., (*in prep*)
Spatial Variability of Surface Fluxes

Sensible HF (W/m²)

Friction Velocity (m/s)

Sun et al., (in prep)
Spatial Variation of Surface Transfer Coefficient

Sensible Heat Flux Calculation

\[ H = \rho c_p C_h U_a (T_s - T_a) \]

Where:
- \( \rho \) = density
- \( c_p \) = specific heat capacity
- \( C_h \) = surface transfer coefficient
- \( U \) = wind speed
- \( T \) = temperature
- \( s \) = surface
- \( a = 2m \) above surface

\( C_h \) Calculated from Observations

Sun & Holmes, (in review)
Average WRF Simulated Surface Transfer Coefficient

Sun et al., (in prep)
The diagram illustrates the distribution of wave height ($C_h$) across a range of stability parameters ($\zeta$). Different markers and colors represent various simulation runs and observations, with the x-axis indicating stability parameters and the y-axis showing wave heights.

Sun et al., (in prep)
Flux-profile Stability Functions

**Dimensionless Wind Shear**

\[
\phi_M(\zeta) = \frac{\kappa z}{u_*} \frac{\partial U}{\partial z}
\]

**Dimensionless Temp Gradient**

\[
\phi_T(\zeta) = \frac{\kappa z}{\theta_*} \frac{\partial \theta}{\partial z}
\]

(Sun et al. 2019, in prep)

**Graphs:**

- Dimensionless Wind Shear
- Dimensionless Temp Gradient

Legend:
- Green: Cheng and Brutsaert (2005)
- Blue: Lettau (1979)
- Cyan: Holtslag and De Bruin (1988)
- Crosses: OBS

Notes:
- The graphs show the stability functions \( \phi_M(\zeta) \) and \( \phi_T(\zeta) \) as a function of the stability parameter \( \zeta \).
- The data points represent experimental measurements from various sources.
- The stability parameter \( \zeta \) is often used to describe the stability conditions in the atmospheric boundary layer.
In general, WRF performance depends on CAP strength and degrades for strong CAPs.

Surface exchange coefficient is typically overestimated by WRF.

Further investigation of flux-gradient relationship in complex terrain needed to improve surface layer model parameterizations.

Can NWP models simulate near-surface meteorological conditions during stable PBL? **No!**

Is it time to move on from existing dimensionless flux-gradient parameterizations to simulate the PBL mixing? **Yes!**

Do we have enough turbulence data to make new empirical formulations for the RANS closure? **No!**
Field Experiment Wish List

- Surface energy balance; SHF, LHF, $u_*$ @ many locations
- Surface skin temperature and moisture @ many locations
- Vertical profiles of SHF, LHF, and TKE
- Vertical profiles of aerosols and nitrogen chemistry
- Cloud thermodynamics and mixing (entrainment)