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Outline

• Introduction
• Methodology
• 6 – 8 December 2010 NWFS
• ARW-WRF simulations
  – Default
  – No surface sensible heat flux
  – No surface latent heat flux
• Summary and forecasting implications
Introduction
Introduction

Provides most of the background information on the current understanding of Northwest Flow Snowfall (NWFS) events.
Introduction

• “Great Lakes Tap” with NWFS events
  – moistening
  – destabilization
of lower layers
Introduction

• Surface effects closer to the southern Appalachians impacting NWFS events?
  – Mode of convection (diurnal cycle)
    • Ground as source/sink of heat
  – Reverse “seeder feeder” mechanism
    • Ground as source of ice nucleii
  – Moist soil conditions
    • Ground as source of water vapor
Introduction

• **Purpose**
  – to investigate the potential impact of antecedent surface conditions directly upstream of the Southern Appalachian Mountains (SAMs) through experiments using the ARW-WRF mesoscale model
Methodology

Methodology

• Version 3.1.1 of the ARW-WRF mesoscale model
• Four nested model domains centered on a point in the SAMs,
  – horizontal grid spacing varied in ratios of three from 13.5 km of the outermost nest down to 0.5 km of the innermost nest
Study domain

1.5 km

4.5 km
Study domain

Nested domain 2 terrain elevation (km) exceeding 400 m above sea level. Line marked A-B is the orientation of the vertical cross section shown in later figures located upwind of the southern Appalachian Mountains.
Nested domain 3 terrain elevation (km) exceeding 400 m above sea level. Locations of cities in the southern Appalachian Mountains are indicated in by the star symbol and the location of Max Patch is highlighted by the oval. Location of the KAVL ASOS is indicated by the open circle.
Methodology

- 45 model vertical levels extended from the ground to the model top at the 100 hPa level.
- One way nesting; simulated model fields on the innermost grids didn’t feed back to fields on the outer nests.
Methodology

• Specified model physics
  – WRF single-moment 5-class microphysics (WSM5) explicit moisture scheme
  – Monin-Obukhov similarity theory-based surface layer scheme linked with
  – Yonsei University PBL scheme
  – unified Noah land-surface model with four soil layers
Methodology

• Specified model physics
  – Betts-Miller-Janjic convective parameterization scheme switched “on” for only the two outer domains (13.5 and 4.5 km domains)
  – Rapid Radiative Transfer Model (RRTM) longwave
  – Eta Geophysical Fluid Dynamics Laboratory shortwave radiation schemes
Methodology

• 48-h time integration
• initial conditions and lateral boundary conditions were derived from the NCEP-NCAR North American Regional Reanalysis surface and atmospheric fields
Methodology

• The initial conditions were generated using the WRF Environmental Modeling System (EMS) Version 3.1 software
  – model start time at 0000 UTC 6 December 2010
  – lateral boundary conditions for the outermost domain were created via the WRF EMS software and updated every six hours up to and including the model simulation end time at 0000 UTC 8 December 2010 (Table 1).
## Methodology

<table>
<thead>
<tr>
<th>Period</th>
<th>Designator</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000 UTC 6 Dec – 1200 UTC 6 Dec 2010</td>
<td>P1</td>
</tr>
<tr>
<td>1200 UTC 6 Dec – 0000 UTC 7 Dec 2010</td>
<td>P2</td>
</tr>
<tr>
<td>0000 UTC 7 Dec – 0000 UTC 8 Dec 2010</td>
<td>P34</td>
</tr>
</tbody>
</table>

red = daylight hours
Methodology

• ARW-WRF model experiments
  – “SH off” or “LH off”
    • during the first 12-h period of the model simulation (P1),
    • during the middle 12-h period of the model simulation (P2), or
    • during the final 24-h period of the model simulation (P34).
  – The remainder of the model time integration consisted of using either the “default,” “50% SH enhancement,” or “50% LH enhancement” unified Noah land-surface model.
Methodology

• “Enhanced” experiments in this study
  – The enhanced experiments involved multiplying the “default” estimate by 1.5, changing the magnitude of the surface moisture or heat fluxes without modifying their direction

  • “What if” default land-surface model had a low flux magnitude (damped) bias due to
    – imperfect model physics (e.g., transfer coefficient underestimate)
    – poor surface moisture or temperature initialization.
Methodology

• The surface sensible and latent experiment simulations were run separately so that the impacts of surface warming and surface moistening could be assessed in a more straightforward manner.
6 – 8 December 2010

NWFS

Departure from 1971 – 2000 Normal

December 5, 2010 – December 11, 2010

National Climatic Data Center, NOAA
based on data provided by the
Climate Prediction Center, NOAA

6 – 8 December 2010 NWFS

• Why 6 – 8 December 2010 case study?
  – It was the first NWFS event of moderate snow accumulation during the 2010-2011 cool season and was potentially driven, in part, by surface conditions in which the land surface over the central and eastern U.S. had not yet become “winterized” (frozen and covered with snow).
Why 6 – 8 December 2010 case study?

– Its relatively significant impact on the residents of western North Carolina. Accumulations for the event ranged from about two-to-six inches of snow in the valleys of the Tennessee border counties, to ten inches of snow at the high elevations of the Smoky Mountains, to almost 18 inches of snow in the mountains further to the north of the Smokies in NC.
One week earlier…

Observed 24-h accumulated precipitation (inches) analysed by the Advanced Hydrologic Prediction Service valid at 1200 UTC 30 November 2010.
6 – 8 December 2010 NWFS

One week earlier…

Observed 24-h accumulated precipitation (inches) analysed by the Advanced Hydrologic Prediction Service valid at 1200 UTC 1 December 2010.
6 – 8 December 2010 NWFS

Daily Weather Map of mean sea level pressure (solid contours, interval = 60 m), 0°C isotherm (dashed), locations of overcast skies (shading), and surface fronts available from the HPC valid 1200 UTC 7 December 2010. {Courtesy: Hydrometeorological Prediction Center.}
Daily Weather Map of geopotential height (solid contours, interval = 60 m) and temperature (dashed contours, interval = 2°C) at the 500 hPa level available from the HPC valid 1200 UTC 7 December 2010. {Courtesy: Hydrometeorological Prediction Center.}
6 – 8 December 2010 NWFS

• KMRX NEXRAD 0.5° reflectivity loops
  • 1200 UTC 6 – 0000 UTC 7 December 2010
  • 0000 UTC 7 – 0000 UTC 8 December 2010
6 – 8 December 2010 NWFS

GOES-13 visible imagery valid 2032 UTC 6 December 2010.
6 – 8 December 2010 NWFS

Plymouth State Weather Center

Meteogram for KAVL from 0000Z 6 DEC 10 to 2300Z 6 DEC 10

KAVL meteogram valid 6 December 2010.
6 – 8 December 2010 NWFS

Plymouth State Weather Center

Meteogram for KAVL from 0000Z 7 DEC 10 to 2300Z 7 DEC 10

KAVL meteogram valid 7 December 2010.
ARW-WRF simulations

Weekly Temperature Anomaly
Departure from 1971 – 2000 Normal
December 5, 2010 – December 11, 2010

Model simulated 3-h accumulated precipitation (cm) for a location near Max Patch starting at 0000 UTC 6 December 2010. Period designators ‘P1’, ‘P2’, and ‘P34’ are also indicated. Horizontal thick lines indicate the period associated with daylight hours (sunrise; 0725 EST, sunset; 1717 EST).
Model simulated 500 hPa level geopotential height (contoured in dashed lines every 6 dm) and absolute vorticity (shading, x 10^{-5} s^{-1}) valid at 1200 UTC 6 December 2010 [F12].
WRF Default Simulation

Model simulated 500 hPa level geopotential height (contoured in dashed lines every 6 dm) and absolute vorticity (shading, x 10^{-5} s^{-1}) valid at 0000 UTC 7 December 2010 [F24].
Vertical cross section of model simulated potential temperature (contoured in dashed lines every 2 K), section-normal wind speed (contoured in thick solid lines every 5 m s\(^{-1}\), negative values indicate winds directed out of the page) and vapor mixing ratio (shading for values exceeding 1.4 g kg\(^{-1}\)) valid at 2000 UTC 6 December 2010 [F20] located in Kentucky.

Upstream of Cumberland Plateau
WRF Default Simulation

Model simulated skew-T-log $p$ diagram valid at 2000 UTC 6 December 2010 [F20] at the middle point of the upstream vertical cross section.
WRF Default Simulation

Model simulated 850 hPa level liquid and ice mixing ratio (shading, x $10^{-2}$ g kg$^{-1}$) and domain 3 terrain elevation exceeding 0.4 and 1.0 km (contours) valid at 1800 UTC 6 December 2010 [F18]. The star symbol highlights the location of Asheville, NC.
Model simulated 850 hPa level liquid and ice mixing ratio (shading, x $10^{-2}$ g kg$^{-1}$) and domain 3 terrain elevation exceeding 0.4 and 1.0 km (contours) valid at 2100 UTC 6 December 2010 [F21]. The star symbol highlights the location of Asheville, NC.
WRF Default Simulation

Model simulated 850 hPa level liquid and ice mixing ratio (shading, x \(10^{-2} \text{ g kg}^{-1}\)) and domain 3 terrain elevation exceeding 0.4 and 1.0 km (contours) valid at 0000 UTC 7 December 2010 [F24]. The star symbol highlights the location of Asheville, NC.
Model simulated 850 hPa level liquid and ice mixing ratio (shading, $x \times 10^{-2}$ g kg$^{-1}$) and domain 3 terrain elevation exceeding 0.4 and 1.0 km (contours) valid at **0300 UTC 7 December 2010** [F27]. The star symbol highlights the location of Asheville, NC.
Vertical cross section of model simulated equivalent potential temperature (contoured in dashed lines every 2 K) and relative humidity (shading for values exceeding 80%) valid at 0000 UTC 7 December 2010 [F24].

Upstream of NC/TN border
WRF Default Simulation

Model simulated 24-h trajectories (0000 UTC 6 – 7 December 2010) analysed by HYSPLIT for air parcels ending at the end points (AA=▲, BB=■) and middle point (Mid=♦) of the vertical cross section shown in the previous figure at the 850 hPa level (middle of the cloud layer).
Model simulated vertical motion (shading, hPa s\(^{-1}\)), cloud mixing ratio (thick solid contour 1 x 10\(^{-2}\) g kg\(^{-1}\)), and potential temperature (contoured in dashed lines every 2 K) valid at 2100 UTC 6 December 2010 [F21] in a vertical cross section oriented along the cloud band labeled NW-SE in a previous figure. The horizontal distance between vertical motion crests is approximately 10 km.
Model simulated 24-h liquid equivalent accumulated precipitation (cm) for the period ending 0000 UTC 8 December 2010 [period designated ‘P34’] for the experiment having the default SH flux parameterization scheme “on” during the entire model simulation.
Model simulated 24-h liquid equivalent accumulated precipitation (cm) for the period ending 0000 UTC 8 December 2010 [period designated ‘P34’] for the experiment having the default SH flux parameterization scheme “off” during P2.
Model simulated 24-h liquid equivalent accumulated precipitation (cm) for the period ending 0000 UTC 8 December 2010 [period designated ‘P34’] for the experiment having the enhanced SH flux parameterization scheme “on” during the entire model simulation.
WRF SHF experiments

Model simulated 24-h liquid equivalent accumulated precipitation (cm) for the period ending 0000 UTC 8 December 2010 [period designated ‘P34’] for the experiment having the SH fluxes shut “off” during the entire model simulation.
**WRF SHF experiments**

Model simulated 24-h liquid equivalent accumulated precipitation (cm) statistics

<table>
<thead>
<tr>
<th>Surface SH flux parameterization</th>
<th>SH scheme “off”</th>
<th>Exp. mean (cm)</th>
<th>“on” mean (cm)</th>
<th>Exp. σ (cm)</th>
<th>“on” σ (cm)</th>
<th>RMSE (cm)</th>
<th>Bias (cm)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>default</td>
<td></td>
<td>0.188</td>
<td>0.182</td>
<td>0.208</td>
<td>0.202</td>
<td>0.027</td>
<td>+0.006</td>
<td>10949</td>
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<tr>
<td></td>
<td>P2</td>
<td>0.134</td>
<td>0.147</td>
<td>0.156</td>
<td>0.195</td>
<td>0.113</td>
<td>-0.013</td>
<td>13635</td>
</tr>
<tr>
<td></td>
<td>P34</td>
<td>0.201</td>
<td>0.173</td>
<td>0.228</td>
<td>0.201</td>
<td>0.060</td>
<td>+0.028</td>
<td>11531</td>
</tr>
<tr>
<td>50% enhancement</td>
<td>P1</td>
<td>0.148</td>
<td>0.144</td>
<td>0.190</td>
<td>0.184</td>
<td>0.025</td>
<td>+0.004</td>
<td>10716</td>
</tr>
<tr>
<td>50% enhancement</td>
<td>P2</td>
<td>0.125</td>
<td>0.116</td>
<td>0.146</td>
<td>0.175</td>
<td>0.125</td>
<td>+0.009</td>
<td>13331</td>
</tr>
<tr>
<td>50% enhancement</td>
<td>P34</td>
<td>0.167</td>
<td>0.139</td>
<td>0.222</td>
<td>0.182</td>
<td>0.064</td>
<td>+0.028</td>
<td>11174</td>
</tr>
<tr>
<td>N/A</td>
<td>ALL</td>
<td>0.162</td>
<td>0.128/0.098</td>
<td>0.181</td>
<td>0.187/0.166</td>
<td>0.122/0.146</td>
<td>+0.035/+0.064</td>
<td>15767</td>
</tr>
</tbody>
</table>

Only default and experiment grid points having at least one simulation whose 24-h liquid equivalent accumulated precipitation amount exceeding 0.025 cm are included in the statistics.
Model simulated vertical motion (shading, hPa s⁻¹), cloud mixing ratio (thick solid contour 1 x 10⁻² g kg⁻¹), and potential temperature (contoured in dashed lines every 2 K) valid at 2100 UTC 6 December 2010 [F21] for the enhanced SH flux parameterization scheme “on” during the entire model simulation.
Model simulated vertical motion (shading, hPa s$^{-1}$), cloud mixing ratio (thick solid contour $1 \times 10^{-2}$ g kg$^{-1}$), and potential temperature (contoured in dashed lines every 2 K) valid at 2100 UTC 6 December 2010 [F21] for the SH fluxes shut “off” during the entire model simulation.
WRF SHF experiments

Model simulated liquid and ice mixing ratio (shading, $x \times 10^{-2}$ g kg$^{-1}$) and domain 3 terrain elevation exceeding 0.4 and 1.0 km (contours) valid at 2100 UTC 6 December [F21] at the 825 hPa level for the enhanced surface SH flux experiment.
Model simulated liquid and ice mixing ratio (shading, $x \times 10^{-2}$ g kg$^{-1}$) and domain 3 terrain elevation exceeding 0.4 and 1.0 km (contours) valid at 2100 UTC 6 December [F21] at the 900 hPa level for the zero surface SH flux experiment. Line marked CC-DD is the orientation of the vertical cross section shown in an upcoming vertical cross section.
eriments

Model simulated environmental lapse rate (contoured in solid lines every $3^\circ$C km$^{-1}$) and wind shear (contoured in dashed lines; $8$ and $12 \times 10^{-3}$ s$^{-1}$) with steep lapse rates (magnitude exceeding $9^\circ$C km$^{-1}$) shaded valid at 1800 UTC 6 December [F18] for the enhanced surface SH flux experiment. Section is located in Kentucky.

Upstream of Cumberland Plateau
Model simulated environmental lapse rate (contoured in solid lines every $3^\circ \text{C km}^{-1}$) and wind shear (contoured in dashed lines; $8$ and $12 \times 10^{-3}$ s$^{-1}$) with steep lapse rates (magnitude exceeding $9^\circ \text{C km}^{-1}$) shaded valid at 1800 UTC 6 December [F18] for the zero surface SH flux experiment. Section is located in Kentucky.

Upstream of Cumberland Plateau
Model simulated cloud mixing ratio (contoured in thick solid lines; $1, 5, 10,$ and $15 \times 10^{-2}$ g kg$^{-1}$) and divergence of cross-band winds (convergence contoured in dashed lines; -2, -4, and $-6 \times 10^{-4}$ s$^{-1}$, divergence is shaded) valid at 2100 UTC 6 December [F21] for the enhanced surface SH flux experiment.

Section in the Tennessee Valley
Model simulated cloud mixing ratio (contoured in thick solid lines; 1, 5, 10, and 15 x 10^{-2} g kg^{-1}) and divergence of cross-band winds (convergence contoured in dashed lines; -2, -4, and -6 x 10^{-4} s^{-1}, divergence is shaded) valid at 2100 UTC 6 December [F21] for the zero surface SH flux experiment.

Section in the Tennessee Valley
Model simulated 24-h liquid equivalent accumulated precipitation (cm) for the period ending 0000 UTC 8 December 2010 [period designated ‘P34’] for the experiment having the default SH flux parameterization scheme “on” during the entire model simulation.
Model simulated 24-h liquid equivalent accumulated precipitation (cm) for the period ending 0000 UTC 8 December 2010 [period designated ‘P34’] for the experiment having the enhanced LH flux parameterization scheme “on” during the entire model simulation.
Model simulated 24-h liquid equivalent accumulated precipitation (cm) for the period ending 0000 UTC 8 December 2010 [period designated ‘P34’] for the experiment having the default LH flux parameterization scheme “off” during P2.
WRF LHF experiments

Model simulated 24-h liquid equivalent accumulated precipitation (cm) for the period ending 0000 UTC 8 December 2010 [period designated ‘P34’] for the experiment having the LH fluxes shut “off” during the entire model simulation.
WRF LHF experiments

Model simulated 24-h liquid equivalent accumulated precipitation (cm) statistics

<table>
<thead>
<tr>
<th>Surface LH flux parameterization</th>
<th>LH scheme “off”</th>
<th>Exp. mean (cm)</th>
<th>“on” mean (cm)</th>
<th>Exp. σ (cm)</th>
<th>“on” σ (cm)</th>
<th>RMSE (cm)</th>
<th>Bias (cm)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>default</td>
<td>P1</td>
<td>0.174</td>
<td>0.189</td>
<td>0.197</td>
<td>0.204</td>
<td>0.023</td>
<td>-0.015</td>
<td>10488</td>
</tr>
<tr>
<td>default</td>
<td>P2</td>
<td>0.082</td>
<td>0.190</td>
<td>0.131</td>
<td>0.204</td>
<td>0.149</td>
<td>-0.109</td>
<td>10415</td>
</tr>
<tr>
<td>default</td>
<td>P34</td>
<td>0.157</td>
<td>0.190</td>
<td>0.182</td>
<td>0.204</td>
<td>0.048</td>
<td>-0.033</td>
<td>10421</td>
</tr>
<tr>
<td>50% enhancement</td>
<td>P1</td>
<td>0.197</td>
<td>0.207</td>
<td>0.222</td>
<td>0.227</td>
<td>0.027</td>
<td>-0.009</td>
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<tr>
<td>50% enhancement</td>
<td>P2</td>
<td>0.112</td>
<td>0.238</td>
<td>0.164</td>
<td>0.236</td>
<td>0.171</td>
<td>-0.125</td>
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<tr>
<td>50% enhancement</td>
<td>P34</td>
<td>0.178</td>
<td>0.220</td>
<td>0.194</td>
<td>0.231</td>
<td>0.064</td>
<td>-0.042</td>
<td>11559</td>
</tr>
<tr>
<td>N/A</td>
<td>ALL</td>
<td>0.028</td>
<td>0.190/0.238</td>
<td>0.060</td>
<td>0.204/0.236</td>
<td>0.232/0.290</td>
<td>-0.163/-0.210</td>
<td>10415</td>
</tr>
</tbody>
</table>

Only default and experiment grid points having at least one simulation whose 24-h liquid equivalent accumulated precipitation amount exceeding 0.025 cm are included in the statistics.
Summary and forecasting implications
Summary and forecasting implications

• 6 – 8 December 2010 NWFS
  – Cancellation of classes and events on 7 December
  – Surface fluxes potentially play an important role
    • early in winter season
    • heavy rainfall event 30 Nov, 1 Dec
Summary and forecasting implications

• Numerical *simulations* of the *single* event suggest
  – Surface latent heat fluxes
    • Moisture converted to accumulated snow came from the ground over the study domain
    • Trajectory analyses indicated most of the vapor was made available in the PBL during daytime hours
Summary and forecasting implications

• Numerical *simulations* of the *single* event suggest
  – Surface *sensible* heat fluxes
    • Daytime fluxes *oppose* cloud/snow development through resultant heating and thickening of PBL
    • Daytime fluxes *contribute to* cloud/snow development through more efficient transport of moisture from the ground (buoyancy-driven mixing), moistening air parcels in the PBL
Summary and forecasting implications

• Forecast implications
  – Evolution of PBL temperature, moisture, depth, wind profile, and stability
    • determine production of clouds and precipitation at the top of the PBL during NWFS events
  – Cloud and snow production is suppressed if PBL is too warm, too dry, too thin, or too deep
Summary and forecasting implications

• Forecast implications
  – Optimal PBL conditions for maximizing snow production during NWFS event
    • Cool PBL that quickly becomes saturated when vapor is added via upward latent heat fluxes
    • PBL mixing of moderate strength for efficient moistening of the PBL
    • Strongest unidirectional vertical wind shear and dry adiabatic environmental lapse rate collocated next to the ground
Summary and forecasting implications

• Forecast implications
  – Optimal PBL conditions for maximizing snow production during NWFS event
    • Produces intense (deep) longitudinal cloud bands that increases the likelihood of significant snowfall accumulation downstream of the crest of the mountains
  – Optimal PBL conditions are most likely to occur during nighttime, early morning, and late afternoon hours
End of presentation

Weekly Temperature Anomaly
Departure from 1971 – 2000 Normal

December 5, 2010 – December 11, 2010

Methodology

• ARW-WRF model experiments
  – original (“default”) and modified versions of the unified Noah land-surface model having zero surface sensible heat or latent heat, or enhanced surface sensible heat (“50% SH enhancement”) or latent heat (“50% LH enhancement”) fluxes during specific periods.
Summary and forecasting implications

- Numerical *simulations* of the *single* event suggest
  - Unidirectional vertical wind shear
    - Source of constant mixing in the PBL, independent of the time of day
    - Provides enough mixing to sufficiently moisten air parcels in the PBL, resulting in significant snowfall accumulations
Summary and forecasting implications

- Numerical *simulations* of the *single* event suggest
  - Surface sensible heat fluxes “off” during daytime

- Similar total water mass as the default simulation is deposited over a broader area (increase in accumulation over the Cumberland Plateau)
  - change in precipitation banding intensity
Summary and forecasting implications

• Numerical *simulations* of the *single* event suggest
  – Precipitation banding intensity sensitive to the strength and vertical location of the layers of
    • Strongest unidirectional vertical wind shear
    • Weakest (dry adiabatic?) environmental lapse rate
      – Collocated upstream of the mountains next to the ground; precipitation banding intensity is *strongest* (maxima in cloud mixing ratio and magnitude of cross-band convergence)
Summary and forecasting implications

• Numerical *simulations* of the *single* event suggest
  – Precipitation banding intensity
    • Daytime buoyancy-driven mixing “lifts” layer of strongest unidirectional vertical wind shear to the inversion layer capping the PBL
    • In general, a deeper PBL minimizes the overlap of the layers of strongest unidirectional vertical wind shear and weakest stratification
→ weakened banding intensity
Summary and forecasting implications

• Numerical *simulations* of the *single* event suggest
  – Precipitation banding evolution and propagation
    • Closely tied initially to 500 hPa level cyclonic vorticity maximum
    • Intensifies and becomes locked with underlying terrain after vorticity maximum departs from study area, during the midnight hours of 7 December (0300 UTC)
References

Weekly Temperature Anomaly
Departure from 1971 – 2000 Normal
December 5, 2010 – December 11, 2010

National Climatic Data Center, NOAA
based on data provided by the Climate Prediction Center, NOAA

References


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References

References


