Evaluating Climate Models
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Severe Storm Environments

CAPE × Shear (J kg\(^{-1}\) × m s\(^{-1}\))

\(W_{\text{max}} \times \text{Shear} (\text{WmSh, m}^2\text{s}^{-2})\)
<table>
<thead>
<tr>
<th>Model Description</th>
<th>NCEP reanalysis</th>
<th>Community Climate System Model</th>
<th>3rd Generation Coupled Global Climate Model</th>
<th>Hadley Centre Coupled Model, v. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canadian Regional Climate Model (CRCM)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Hadley Regional Model 3 (HRM3)</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Pennsylvania State University/NCAR mesoscale model (MM5I)</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Weather Research and Forecasting model (WRFG)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

NCEP reanalysis abbreviation: NCEP

Community Climate System Model abbreviation: CCSM3

3rd Generation Coupled Global Climate Model abbreviation: CGCM3

Hadley Centre Coupled Model, v. 3 abbreviation: HadCM3

Website links:
- [http://www.narccap.ucar.edu/](http://www.narccap.ucar.edu/)
- [http://www.emc.ncep.noaa.gov/mmb/rreanl/](http://www.emc.ncep.noaa.gov/mmb/rreanl/)
Lingo

WmSh: As before, but set to zero if CAPE < 100 J kg\(^{-1}\)
or \(5 \leq \text{Shear} \leq 50\) ms\(^{-1}\)

q75: Univariate time series giving the upper quartile of
a random variable (CAPE or WmSh) over space at
each time point.

High “field energy”: when q75 > its 90\(^{\text{th}}\) percentile over
time.

\(\kappa\): Frequency of CAPE \(\geq 100\) J kg\(^{-1}\) conditioned on the
presence of high field energy.

\(\omega\): Frequency of WmSh \(\geq 225\) m\(^2\)s\(^{-2}\) conditioned on the
presence of high field energy.
Image Warping

0–energy field

1–energy field

Error Field

RMSE_0 = 0.2665  RMSE_1 = 0.1605

% error reduction ≈ 40%
minimum bending energy = 2.0042

Distance travelled

Deformed 1–energy field

Error Field (after warping)
Image Warping

Pair of thin-plate spline transformations

\[ \Phi(s) = (\Phi_1(s), \Phi_2(s))^T = a + Gs + W^T \Psi(s - p_0) \]

x-coordinate    y-coordinate

affine transformation

\[ \Psi(h) = \|h\|^2 \log \|h\| \]

Columns of coefficients in \( W \) and the sum of products of \( W \) times \( p_0 \) both constrained to sum to 0.
**Image Warping**

Pair of thin-plate spline transformations

\[
\Phi(s) = (\Phi_1(s), \Phi_2(s))^T = a + Gs + W^T \Psi(s - p_0)
\]

\[
LA = \begin{bmatrix}
\Psi & 1_k & p_0 \\
1_k^T & 0 & 0 \\
p_0^T & 0 & 0
\end{bmatrix}
\begin{bmatrix}
w \\
a^T \\
g^T
\end{bmatrix} = \begin{bmatrix}
p_1 \\
0 \\
0
\end{bmatrix}
\]

Want \( L^{-1} \). The upper \( k \times k \) matrix of \( L^{-1} \), call it \( L^{11} \), gives the bending energy matrix. And \( W = L^{11}p_1 \). The bending energy is given by \( \text{trace}( p_1^T L^{11} p_1 ) \).
Image Warping

$k$ parameters of interest are the locations $\mathbf{p}_1$.

Found by numerically optimizing the objective function:

$$Q(\mathbf{p}_1) = \frac{1}{N \sigma^2} \sum_{s=1}^{N} \left( \hat{Z}(W(s)) - Z(s) \right)^2 +$$

$$\beta \left[ \left( \mathbf{p}_{1,x} - \mathbf{p}_0 \right)^T L_{11} \left( \mathbf{p}_{1,x} - \mathbf{p}_0 \right) + \left( \mathbf{p}_{1,y} - \mathbf{p}_0 \right)^T L_{11} \left( \mathbf{p}_{1,y} - \mathbf{p}_0 \right) \right]$$
## Image Warping

<table>
<thead>
<tr>
<th>Model Combination</th>
<th>$\text{RMSE}_0$</th>
<th>$\text{RMSE}_1$</th>
<th>RMSE Reduction</th>
<th>Minimum Bending Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRCM-CCSM3</td>
<td>0.214</td>
<td>0.139</td>
<td>35%</td>
<td>0.96</td>
</tr>
<tr>
<td>CRCM-CGCM3</td>
<td>0.147</td>
<td>0.103</td>
<td>30%</td>
<td>1.07</td>
</tr>
<tr>
<td>HRM3-HadCM3</td>
<td>0.157</td>
<td>0.110</td>
<td>30%</td>
<td>0.25</td>
</tr>
<tr>
<td>MM5I-CCSM3</td>
<td>0.267</td>
<td>0.161</td>
<td>40%</td>
<td>2.00</td>
</tr>
<tr>
<td>MM5I-HadCM3</td>
<td>0.148</td>
<td>0.084</td>
<td>43%</td>
<td>0.69</td>
</tr>
<tr>
<td>WRFG-CCSM3</td>
<td>0.249</td>
<td>0.096</td>
<td>61%</td>
<td>3.27</td>
</tr>
<tr>
<td>WRFG-CGCM3</td>
<td>0.241</td>
<td>0.092</td>
<td>62%</td>
<td>3.32</td>
</tr>
<tr>
<td>CRCM-NCEP</td>
<td>0.214</td>
<td>0.173</td>
<td>19%</td>
<td>0.25</td>
</tr>
<tr>
<td>WRFG-NCEP</td>
<td>0.171</td>
<td>0.092</td>
<td>46%</td>
<td>0.43</td>
</tr>
</tbody>
</table>
Conclusions

• Models generally agree with NARR about spatial location and overall pattern of high severe storm frequencies (κ and ω).
• They tend to under-project the spatial extent of high frequency areas compared to NARR.
• HRM3-HadCM3 is by far the closest to NARR for both κ and ω.
• WRFG configurations not coupled with NCEP (i.e., “observations”) have the least agreement with NARR.
• Climate models should reproduce observed distributional properties for the current-period climate, making spatial forecast verification methods particularly useful, and easy to implement in this context.
• Full analysis including many other spatial methods in G. et al. (submitted to ASCMO, available at http://www.ral.ucar.edu/staff/ericg/GillelandEtAl2016.pdf)