Data Assimilation and Weather Regimes in a Three-Level Quasi-Geostrophic Model

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Outline

• Motivation

• Atmospheric QG model

• Weather regimes classification

• Regime transition properties

• Data assimilation with PSAS
Motivation

- Regime transitions in nonlinear systems can be used to help track and predict.
  - Data assimilation methods can be used to help track and predict.
  - Anomalies => weather regimes.
  - Nonlinearity is the cause of recurrent and persistent atmospheric.
  - They are not red noise => they can be predicted.

Large-scale atmospheric phenomena

-
NH winter observed fields (ECMWF, 1984–1994).

Perpetual-winter simulation.

Observed climatology is represented by the time-averaged equations.

\[
\nabla \psi + (b, \nabla) f = S
\]

\[
S + (\nabla) a \cdot (b, \nabla) f \nabla = \frac{\nabla p}{\partial \psi}
\]

Pv equation:
EOF analysis

• Reduces dimensionality of the model's phase space.

• 18,000 days of 500-mb streamfunction maps in NH, non-filtered

• Signal-to-noise ratio: how many EOFs to use in the analysis?

\[
S = 2 - 5
\]

\[
\left( \frac{C}{\sqrt{\gamma}} \right)^{1/2} \left( \frac{1}{S} \right)^{1/2} = N \parallel x \parallel \quad \text{and} \quad \left( \frac{C}{\sqrt{\gamma}} \right)^{1/2} \left( \frac{S}{S} \right)^{1/2} = S \parallel x \parallel
\]

18,000 days of 200-mb streamfunction maps in NH, non-filtered

Reduces dimensionality of the model's phase space.

EOF analysis
Cluster analysis

- **K-means algorithm** => "hard" clusters, all points are classified.

- **Gaussian mixture model** => "fuzzy" clusters, degree of belonging.

- Applied in a $p$-dimensional subspace of the model’s phase space,
  $d = \text{number of leading EOFs}$.

- Clusters correspond to weather regimes of the QG model.

- How many clusters?


"Fuzzy" clusters: degree of belonging.

*Cluster analysis*
Pattern correlation coefficients between cluster centroid maps of a mixture model on the one hand, and those obtained by the $k$-means algorithm on the other:

(a) For $k = 4$, and $2 \leq d \leq 6$:

<table>
<thead>
<tr>
<th>$d$</th>
<th>5.49</th>
<th>0.994</th>
<th>0.821</th>
<th>0.712</th>
<th>0.956</th>
<th>0.999</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.999</td>
<td>0.999</td>
<td>0.996</td>
<td>0.999</td>
<td>0.997</td>
<td></td>
</tr>
</tbody>
</table>

(b) For $k = 3, 5, 6$ and $d = 5$:

<table>
<thead>
<tr>
<th>$d$</th>
<th>5.7</th>
<th>0.994</th>
<th>0.989</th>
<th>0.961</th>
<th>0.854</th>
<th>0.995</th>
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<tbody>
<tr>
<td>6</td>
<td>0.956</td>
<td>0.912</td>
<td>0.700</td>
<td>0.821</td>
<td>0.994</td>
<td>0.549</td>
</tr>
</tbody>
</table>

Mixture model vs. $k$-means: $k = 4$ is optimal.
The ellipses are spanned by the leading eigenvectors of the Gaussian components' covariance matrices.

PDF of mixture model for $\kappa = 4$, $p = 2$
Covariance ellipses of size $\frac{1}{2}$ are shown.

Cluster membership ($k = 4$, $p = 2$) for the mixture model
Mixture-model anomaly maps for $k = 4$, $p = 2$
Transitions from AO-

Exit-angle PDF for AO-

Transitions from AO-

Probability of 90% significant transitions, and entry points.
Transitions from NAO- Exit-angle PDF for NAO- Probability of 90% significant transitions, and entry points.
Transitions from NAO$^+$ and entry points. Probability of 90% significant transitions from NAO$^+$.
Transitions from AO+ and entry points.

Probability of 90% significant transients from AO+.
A Monte-Carlo simulation for statistical significance test (Vautard, M0, and Ghil, 1990, J. Atmos. Sci., 47, 1926-1931)

- Evaluates conditional probabilities, 90% significant are in bold.

<table>
<thead>
<tr>
<th></th>
<th>AO+</th>
<th>AO-</th>
<th>NAO+</th>
<th>NAO-</th>
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</thead>
<tbody>
<tr>
<td>AO+</td>
<td>0.28</td>
<td>0.01</td>
<td>0.30</td>
<td>0.40</td>
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<tr>
<td>AO-</td>
<td>0.04</td>
<td>0.54</td>
<td>0.04</td>
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<tr>
<td>NAO-</td>
<td>0.36</td>
<td>0.18</td>
<td>0.24</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Markov chain of transitions for $k = 4$, $p = 2$: $z = z$
Physical space Statistical Analysis System (PSAS)
Data assimilation with the QG model

- Identical-twin simulation: observations and forecast data obtained from two model runs with different initial states.
- Observations and forecast data are obtained from two identical-twin simulations.
- Observations simulated with both satellite and radiosonde networks.
- PSAS call every 6 hours.
- RMS (observation-forecast) error for 1-month long assimilation experiment.
RMS convergence for 3-level streamfunction
Observing Locations
Conclusions & Future Work

• More DA experiments for tracking transitions.
• What instabilities are causing the transitions?
• Regime persistence needs to be analyzed further.
• Preferential transitions between regimes do occur.
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