Hemispheric and regional circulation regimes

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Outline

- Introduction: Historical overview on regime theory and modelling
- Detection of regimes in atmospheric and model datasets
- A new look at “hemispheric” and regional regimes using ERA-Interim data
- How to interpret the impact of anomalies in tropical “forcing”
Recurrent flow patterns: examples

A selection of 5-day mean fields of 500 hPa geopotential height during boreal winter...
Regimes as quasi-stationary states

\[ q : \text{barotropic or quasi-geostrophic potential vorticity} \]
\[ \partial_t q = - V_\psi \cdot \text{grad } q - D (q - q^*) \]

steady state for instantaneous flow:
\[ 0 = - V_\psi \cdot \text{grad } q - D (q - q^*) \]

steady state for time-averaged flow:
\[ 0 = - \langle V_\psi \rangle \cdot \text{grad } \langle q \rangle - D (\langle q \rangle - q^*) \]
\[ \quad - \langle V'_\psi \cdot \text{grad } q' \rangle \]
Charney and DeVore 1979

Multiple steady states of low-order barotropic model with wave-shaped bottom topography

Fig. 4. Streamfunction fields of the stable first mode equilibria of a topographically forced flow for $k = 10^{-2}$, $L/a = 1/4$, $n = 2$, $h_u/H = 0.2$ and $\psi = 0.2$: for the spectral model above resonance (a) and slightly below resonance (b); and for the grid-point model above resonance (c) and slightly below resonance (d). The nondimensional topographic heights are shown with light lines; the contour spacing is 0.05 units, with negative regions shaded.
Papers on multiple equilibria and quasi-stationary states

Orographically forced models:

- **Charney and Straus 1980**: Form-grad instability, multiple equilibria and propagating planetary waves in baroclinic, orographically-forced planetary wave systems
- **Charney, Shukla and Mo 1981**: Comparison of barotropic blocking theory with observation
- **Legras and Ghil 1985**: Persistent anomalies, blocking and variations in atmospheric predictability
- **Benzi, Malguzzi, Speranza, Sutera 1986**: The statistical properties of the atmospheric general circulation: observational evidence and a minimal theory of bimodality

Thermally forced models:

- **Mitchell and Derome 1983**: Blocking-like solutions of the potential vorticity equation: their stability at equilibrium and growth at resonance
Reinhold and Pierrehumbert 1983

Hemispheric weather regimes arising from equilibration of large-scale dynamical tendencies and “forcing” from transient baroclinic eddies
Regional weather regimes arising from equilibration of large-scale dynamical tendencies and PV fluxes from transient baroclinic eddies
Looking for bimodality: Hansen and Sutera 1986

Bimodality in the probability density function (PDF) of an index of N. Hem. planetary wave amplitude due to near-resonant wave-numbers (m=2-4)

Fig. 4. MPL probability density estimates of $|Z_{2-4}|$ formed from the 16 winter composite filtered data for (a) $\alpha = 10^5$ and (b) $\alpha = 5 \times 10^5$. 
Multi-dim. PDF estimation and cluster analysis

Searching for densely-populated regions in phase space:

- Mo and Ghil 1988
- Molteni et al. 1990
- Cheng and Wallace 1993
- Kimoto and Ghil 1993a, b
- Michelangeli et al. 1995
- Corti et al. 1999

Kimoto and Ghil 1993a
Regimes from PDF estimation (Corti et al. 1999)
PDF estimation: statistical significance

Fraction of uni/multi-modal PDFs obtained from a gaussian distribution sample size as in Corti et al. 1999
Impact of external forcing in non-linear systems

Lorenz (1963) truncated convection model with additional forcing \( f \) (Molteni et al. 1993; Palmer 1993)

\[
\begin{align*}
\frac{dX}{dt} &= \sigma (Y - X) \\
\frac{dY}{dt} &= -XZ + rX - Y + f \\
\frac{dZ}{dt} &= XY - bZ
\end{align*}
\]

Unstable stationary states (for \( f=0 \))

\[
\begin{align*}
X &= Y = Z = 0 \\
X &= Y = \pm \sqrt{b(r-1)} , Z = r -1
\end{align*}
\]
Impact of external forcing in non-linear systems

The properties of atmospheric flow regimes may be affected by anomalies in boundary forcing in different ways:

- **Weak forcing anomaly**: the number and spatial patterns of regimes remain the same, but their frequency of occurrence is changed (“Lorenz model paradigm”)

- **Strong forcing anomaly**: the number and patterns of regimes are modified as the atmospheric system goes through bifurcation points
Euro-Atlantic regimes and the impact of MJO

Cassou 2008
Pacific – North American regimes

Cluster analysis of low-freq. (T>10 d) Z 200 in NCEP re-analysis and COLA AGCM ensembles (Straus, Corti, Molteni 2007)
Does ENSO affect the number of regimes?

- Ratio of inter-cluster to intra-cluster variance as a function of ENSO indices (Straus and Molteni 2004)

![Graph showing the relationship between Nino3 and variance ratio for 3 clusters.](image)

**Fig. 4.** Scatterplots of (a) the 3-cluster ($k = 3$) variance ratio vs Niño-3, and (b) the 3-cluster variance ratio vs the leading PC of ensemble/seasonal means. The leading PC and SST index time series are standardized.
A re-visitation of Pacific + Atlantic regimes: methodology

- **Data:**
  - 5-day means of 500-hPa height from ERA-Interim

- **Definition of anomalies wrt 34-yr climate (low-pass filtered)**

- **EOF analysis on 3 domains:**
  - Euro-Atlantic (EAT: 80W-40E, 25-85N)
  - Pacific + Atlantic (PAT = PNA + EAT, 160E-40E, 25-85N)

- **Non-hierarchical cluster analysis using k-means algorithm**
  - up to 6 clusters for EAT and PNA, up to 8 clusters for PAT
  - Significance test on signal-to-noise ratio (centroid variance / inter-cluster variance) against 500 red-noise data samples with same variance, skewness and lag-1 autocorrelation as individual PCs

- **Refs.:** Michelangeli et al. 1995, Straus et al. 2007
EOF-1 for the three domains
variance of N EOFs (%) in the three domains
S/N variance ratio and multi-modality

a) 2 regimes in 1 dimension:

\[ P(x) = 0.5 \left[ G(\mu, \sigma) + G(-\mu, \sigma) \right] \]

Total variance = \(\mu^2 + \sigma^2\)

S/N variance ratio = \(\mu^2 / \sigma^2\)

*\(P(x)\) is bimodal if S/N > 1

\(\mu = 0.8, \quad \sigma_x = 0.6: \quad S/N = 1.78\)

\(\mu = 0.71, \quad \sigma_x = 0.71: \quad S/N = 1.00\)

\(\mu = 0.6, \quad \sigma_x = 0.8: \quad S/N = 0.56\)

b) 2 regimes in 2 dimensions

\[ P(x, y) = P(x) \ P(y) \]

\[ P(x) = 0.5 \left[ G(\mu, \sigma_x) + G(-\mu, \sigma_x) \right], \quad P(y) = G(0, \sigma_y) \]

If \(\mu = \sigma_x = \sigma_y = 0.71: \quad S/N = \mu^2 / (\sigma_x^2 + \sigma_y^2) = 0.5\)

For \(N\) regimes, S/N should be > 1 in a subspace of \(N-1\) dimensions

(a lower limit applies to regimes with different population)
## Statistics for N-cluster partitions (%)

<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>E-AT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>var s/n</td>
<td>24.7</td>
<td>42.3</td>
<td>59.3</td>
<td>71.4</td>
<td>81.5</td>
<td></td>
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<tr>
<td></td>
<td>(51.2)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>conf.lev</td>
<td>52.7</td>
<td>86.8</td>
<td><strong>99.8</strong></td>
<td>99.6</td>
<td>99.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>P-NA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>var s/n</td>
<td>24.2</td>
<td>43.8</td>
<td>57.9</td>
<td>69.4</td>
<td>79.1</td>
<td></td>
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<tr>
<td></td>
<td>(49.7)</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>conf.lev</td>
<td>76.0</td>
<td>87.6</td>
<td><strong>98.6</strong></td>
<td>98.8</td>
<td>99.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>P-AT</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>var s/n</td>
<td>15.6</td>
<td>27.3</td>
<td>36.3</td>
<td>43.6</td>
<td>50.0</td>
<td>55.7</td>
<td>61.2</td>
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<td></td>
<td>(54.2)</td>
<td></td>
<td></td>
<td></td>
<td>(54.2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>conf.lev</td>
<td>57.0</td>
<td>76.2</td>
<td>90.4</td>
<td>93.0</td>
<td><strong>97.4</strong></td>
<td>98.0</td>
<td>98.8</td>
</tr>
</tbody>
</table>
Euro-Atlantic 4-cluster centroids

- **NAO+** 31.5%
- **Blocking** 25.0%
- **Atl. Ridge** 22.2%
- **NAO-** 21.3%
Pacific-North American 4-cluster centroids

- Pacific Trough: 27.7%
- PNA+: 24.0%
- Arctic Low: 27.7%
- Alaskan Ridge: 20.6%
Pacific+Atlantic 6-cluster centroids

COWL 18.8%

NAO- 16.5%

E+wn1 15.3%

A+wn3 13.7%

P+wn1 18.0%

P+wn3 17.6%
## Confidence levels for PAT clusters (%)

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<tr>
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</tr>
</thead>
</table>
| Res = 0  
Skw = 0 | 66.6 | **96.0** | 100. | 99.8 | 100. | 100. | 100. |
| Res = 0  
Skw = 1 | 67.4 | 91.0  | **99.6** | 100. | 100. | 100. | 100. |
| Res = 1  
Skw = 0 | 57.2 | 79.2  | 92.8 | **95.6** | 98.6 | 98.6 | 99.0 |
| Res = 1  
Skw = 1 | 57.0 | 76.2  | 90.4 | 93.0 | **97.4** | 98.0 | 98.8 |

Red-noise data: prescribed mean=0, s.dev. and lag-1 autocor. as PC
Res = 1: re-sampling from larger samples (10x)
Skw = 1: prescribed skewness from PC samples
P-AT 3 clusters vs. PDF modes of Corti et al. (1999)
## Partition of PAT cluster frequencies into regional regimes

<table>
<thead>
<tr>
<th>PAT 1</th>
<th>COWL</th>
<th>E-AT 1</th>
<th>E-AT 2</th>
<th>E-AT 3</th>
<th>E-AT 4</th>
<th>P-NA 1</th>
<th>P-NA 2</th>
<th>P-NA 3</th>
<th>P-NA 4</th>
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<tbody>
<tr>
<td>PAT 1</td>
<td>10.05</td>
<td>1.23</td>
<td>6.25</td>
<td>1.23</td>
<td><strong>12.38</strong></td>
<td>4.41</td>
<td>1.84</td>
<td>0.12</td>
<td></td>
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<tr>
<td>PAT 2</td>
<td><strong>13.73</strong></td>
<td>2.21</td>
<td>0.98</td>
<td>1.10</td>
<td>0.25</td>
<td>1.84</td>
<td>6.25</td>
<td><strong>9.68</strong></td>
<td></td>
</tr>
<tr>
<td>PAT 3</td>
<td>6.50</td>
<td><strong>8.33</strong></td>
<td>1.96</td>
<td>0.96</td>
<td>0</td>
<td><strong>14.58</strong></td>
<td>0</td>
<td>3.06</td>
<td></td>
</tr>
<tr>
<td>PAT 4</td>
<td>0.25</td>
<td>0.12</td>
<td>0.86</td>
<td><strong>15.32</strong></td>
<td>2.33</td>
<td>2.94</td>
<td>5.88</td>
<td>5.39</td>
<td></td>
</tr>
<tr>
<td>PAT 5</td>
<td>0.98</td>
<td><strong>12.13</strong></td>
<td>0.74</td>
<td>1.47</td>
<td><strong>9.19</strong></td>
<td>2.21</td>
<td>3.19</td>
<td>0.74</td>
<td></td>
</tr>
<tr>
<td>PAT 6</td>
<td>0</td>
<td>0.98</td>
<td><strong>11.40</strong></td>
<td>1.35</td>
<td>3.55</td>
<td>1.72</td>
<td><strong>6.86</strong></td>
<td>1.59</td>
<td></td>
</tr>
</tbody>
</table>
Examples of regime combinations

PAT cluster 1 = EAT cluster 1 + PNA cluster 1

PAT cluster 6 = EAT cluster 3 + PNA cluster 3
A planetary-wave signal common to different time scales?

Z 500hPa anomaly

| Composite in MJO Phase 3 + 10 days | DJF covariance with Indian Oc. rainfall | Inter-decadal var. in late 20th Century |
Telecon. with DJF W Indian Oc. rainfall: GPCP2.2/ERA-int

![Graph](image1.png)

![Graph](image2.png)

![Graph](image3.png)
Telecon. with DJF W Indian Oc. rainfall: Sys4, m.1
Telecon. with DJF W Indian Oc. rainfall: Sys4, m.2
Impact on Euro-Atl. regime frequencies

Cluster 1: NAO +

Cluster 2: Blocking

Cluster 3: NAO –

Cluster 4: Atl. ridge

NB: clusters 3 and 4 are inverted in this dataset
Conclusions

- Statistically significant regimes can be defined on both “hemispheric” and regional domains as clusters of 5-day mean fields in the post-1979 period.
- Regional regimes (Atlantic & Pacific) are more robust than hemispheric ones, because they can be defined in a lower-dimensional space.
- Hemispheric regimes can be interpreted as the most frequent combinations of Atlantic and Pacific regimes.
- Proper design and use of statistical significance tests is crucial for the detection of regimes in atmospheric and model datasets: significance estimation is by itself subject to uncertainties, therefore “statistical fundamentalism” should be avoided!!
- The impacts of anomalous tropical forcing on regimes are more easily detected on a regional domain. Modifications in the spatial patterns of hemispheric teleconnections/regimes can be due to differences in the strength of such impacts in the Atlantic and Pacific sectors.