Weather regimes

Franco Molteni

European Centre for Medium-Range Weather Forecasts

Outline

- Introduction:
  - Dynamical concepts
  - Examples of recurrent flow patterns
- Historical overview
- Detection of regimes in atmospheric and model datasets
  - Time filtering
  - PDF estimation and statistical significance
- Applications to extended-range predictions
  - Impact of external/boundary forcing on atmospheric regimes
  - Predictability of regime frequencies
  - Non-linear impact of ENSO on regime properties
  - MJO and Euro-Atlantic regimes

Weather regimes and related dynamical concepts

Weather regime:

A persistent and/or recurrent large-scale atmospheric circulation pattern which is associated with specific weather conditions on a regional scale

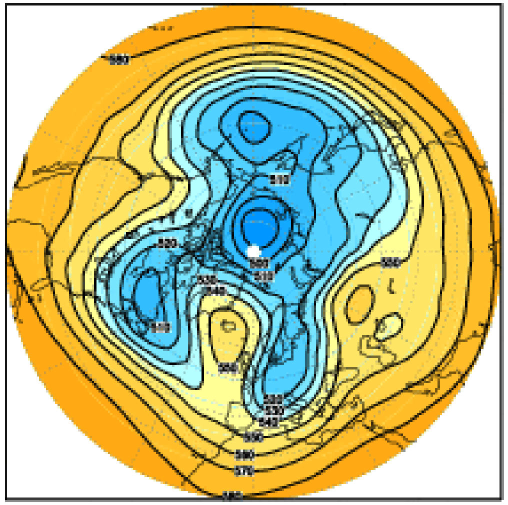
Flow regime:

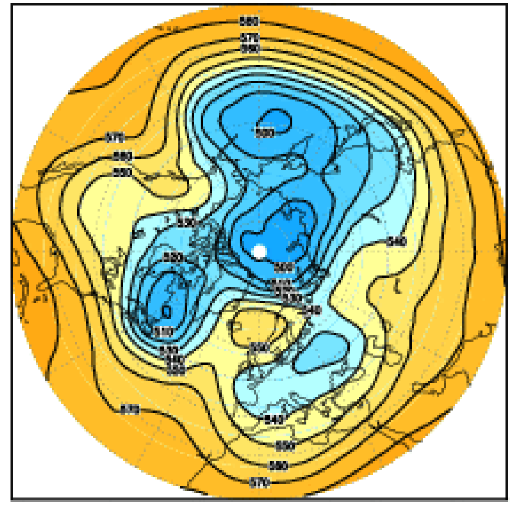
A persistent and/or recurrent large-scale flow pattern in a (geophysical) fluid-dynamical system

Multiple equilibria:

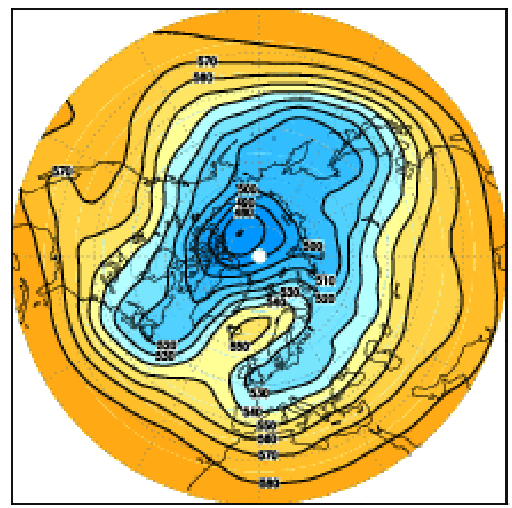
Multiple stationary solutions of a non-linear dynamical system

Recurrent flow patterns: examples



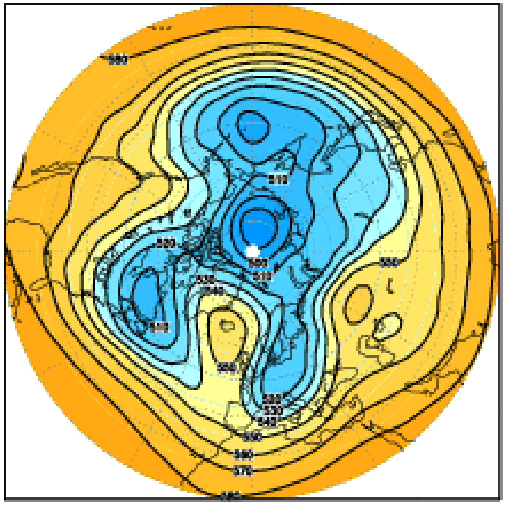


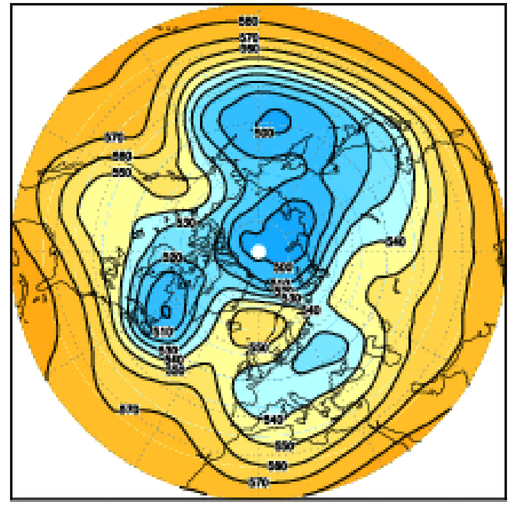
A sequence of 5-day mean fields of 500 hPa geopotential height during boreal winter …



Recurrent flow patterns: examples

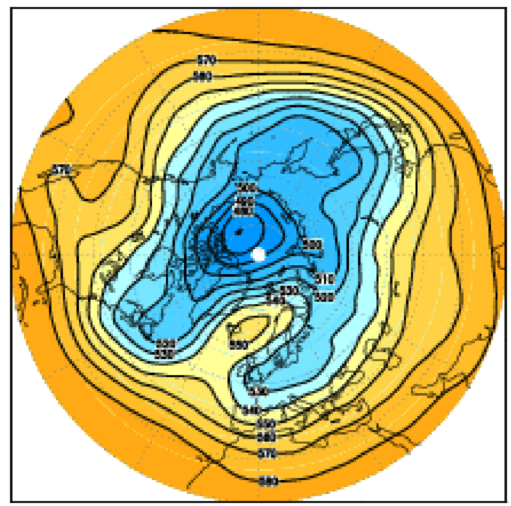
5-9 Jan
1985





4-8 Feb
1986

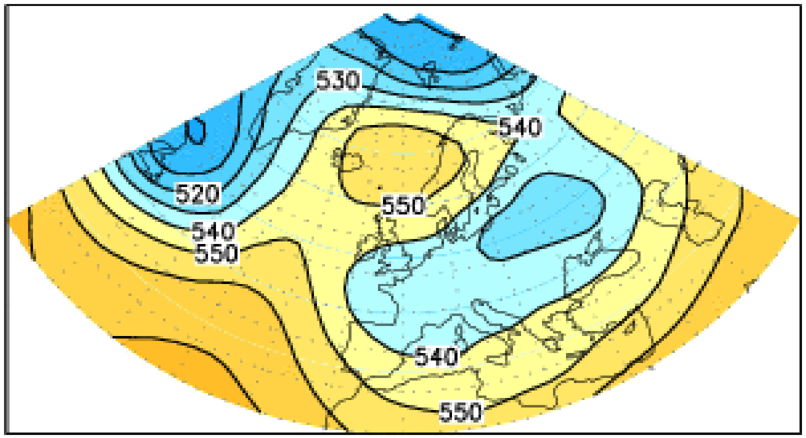
… but each one occurred in a different winter !



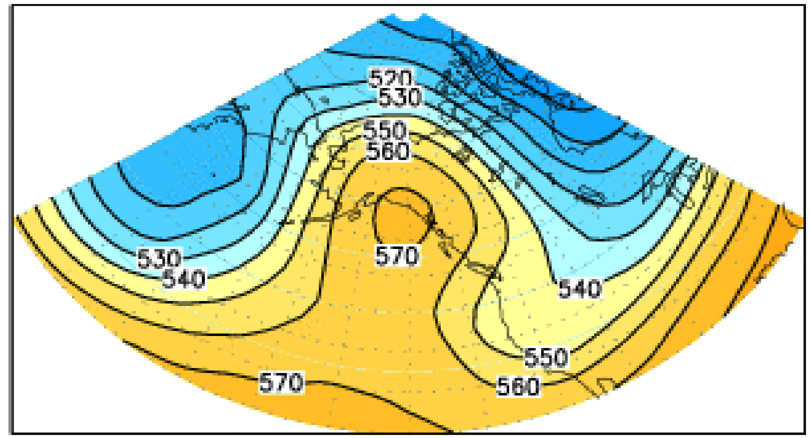
10-14 Jan
1987

500 hPa geop. height

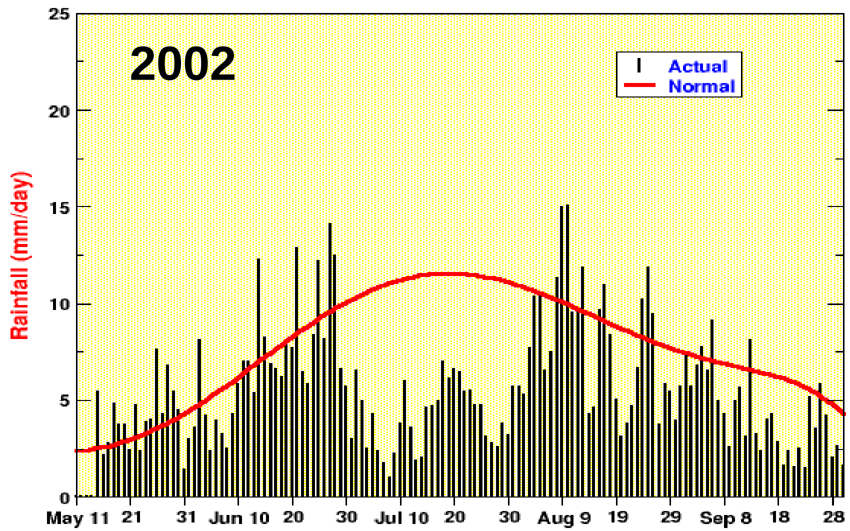
4–8 Feb. 1986



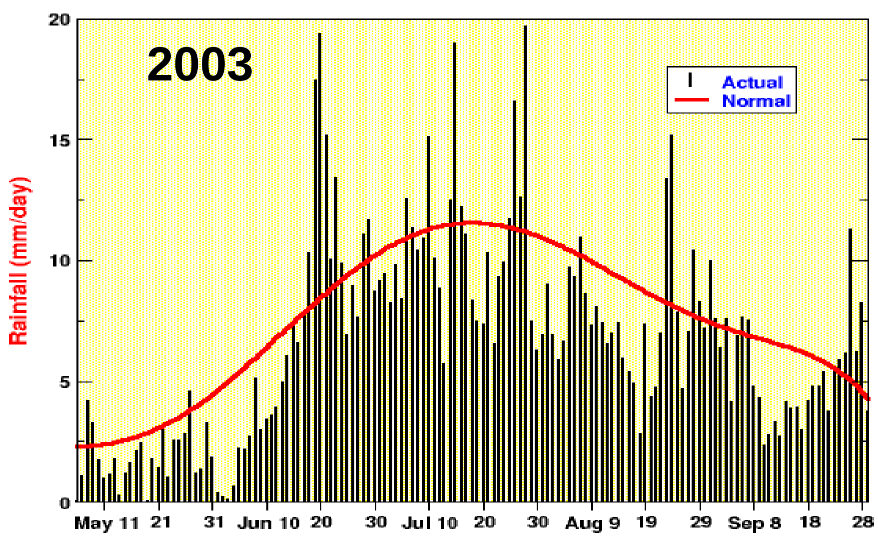
4–8 Feb. 1989

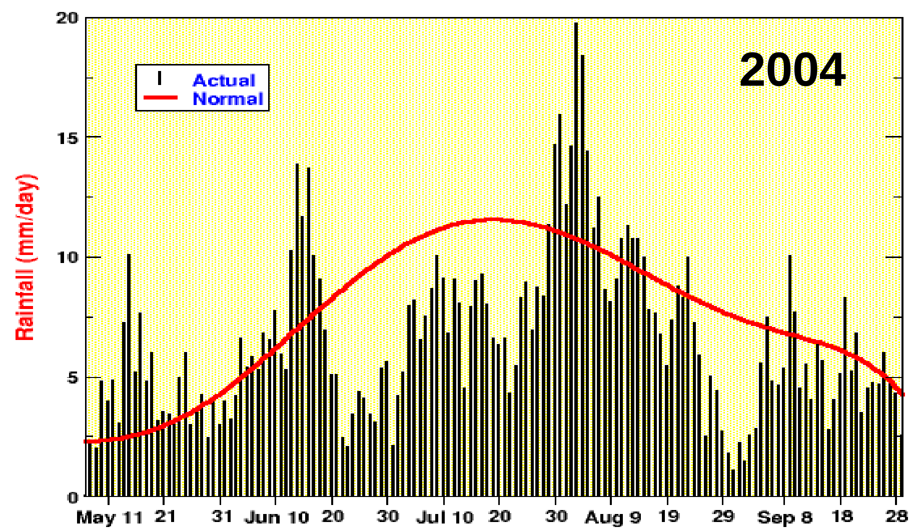


Regional regime behaviour: monsoon active/brake phases



All-India Rainfall time-series (May-September)





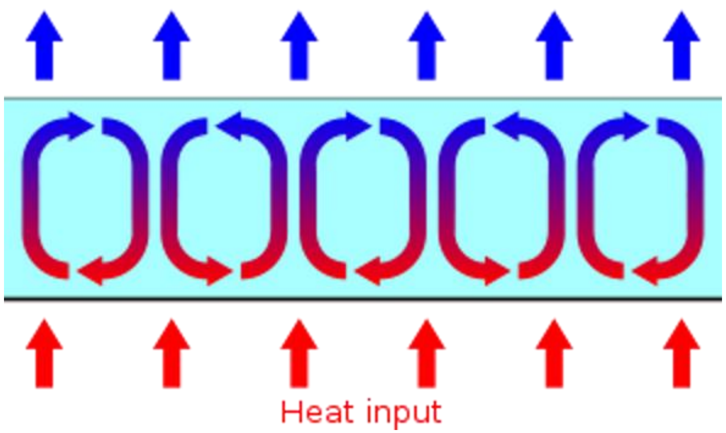
Flow regimes in non-linear systems

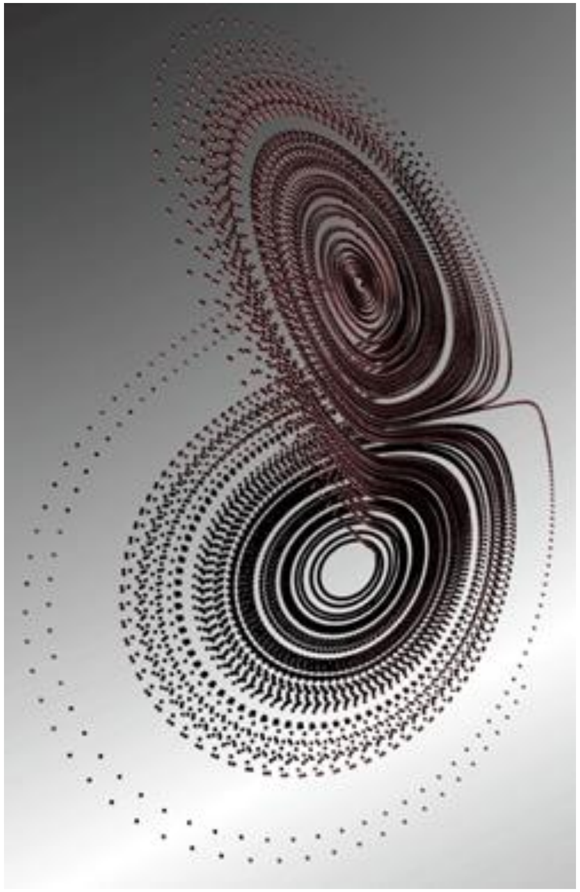
3-variable model of Rayleigh-Benard convection ***(Lorenz 1963)***

- $dX/dt = \sigma (Y - X)$
- $dY/dt = - X Z + \mathbf{r} X - Y$
- $dZ/dt = X Y - b Z$

Unstable stationary states

- $X = Y = Z = 0$
- $X = Y = \pm [b (\mathbf{r} - 1)]^{1/2}$, $Z = \mathbf{r} - 1$





Regimes as quasi-stationary states

q : barotropic or quasi-geostrophic potential vorticity

$$\partial_t q = - V_\psi \cdot \mathit{grad}\, q - D\,(q - q^*)$$

steady state for instantaneous flow:

$$0 = - V_\psi \cdot \mathit{grad}\, q - D\,(q - q^*)$$

steady state for time-averaged flow:

$$0 = - \langle V_\psi \rangle \cdot \mathit{grad} \langle q \rangle - D\,(\langle q \rangle - q^*)$$

$$- \langle V'_\psi \cdot \mathit{grad}\, q' \rangle$$

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

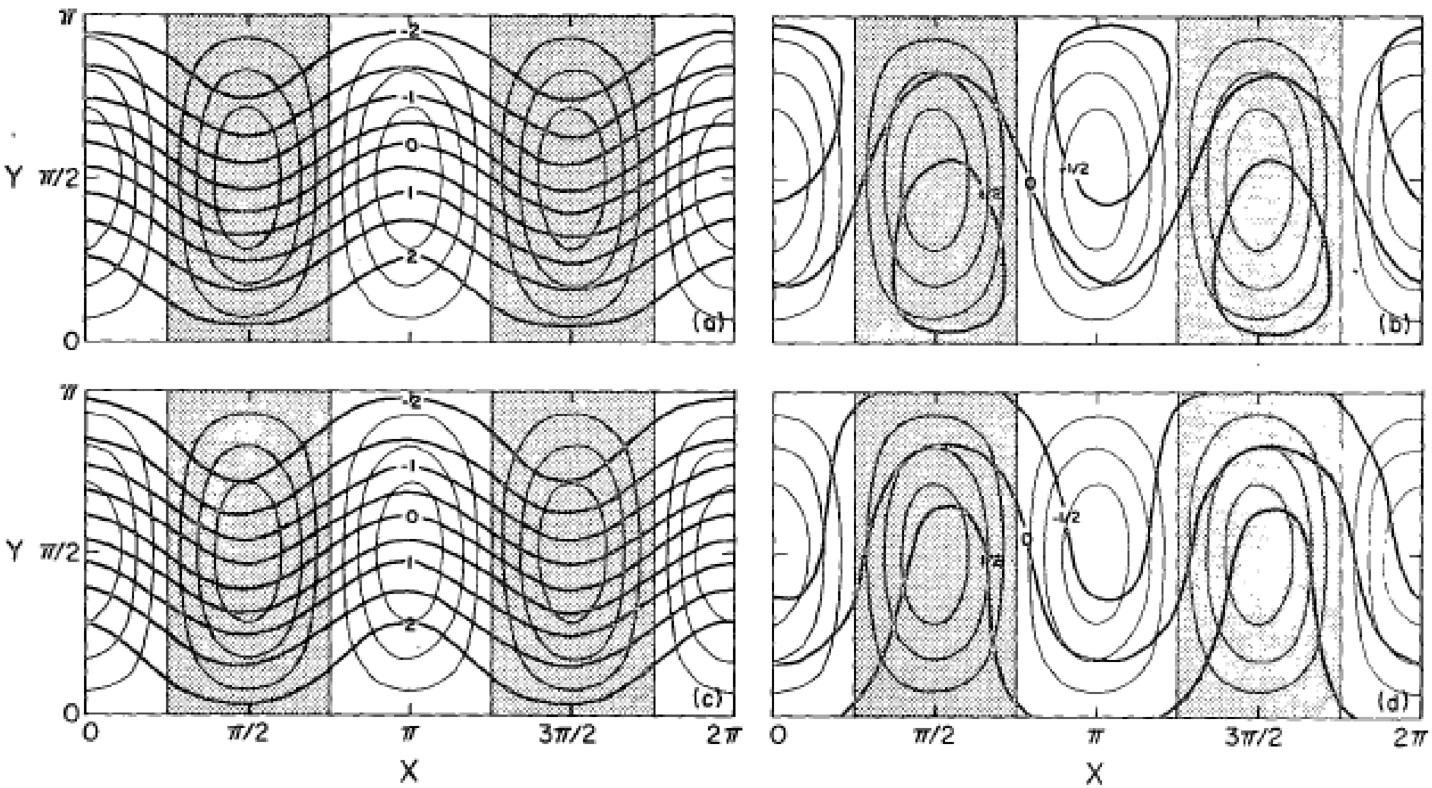


FIG. 4. Streamfunction fields of the stable first mode equilibria of a topographically forced flow for $k = 10^{-2}$, $L/a = ¼$, $n = 2$, $h_0/H = 0.2$ and $\psi_1^* = 0.2$: for the spectral model above resonance (a) and slightly below resonance (b); and for the grid-point model above resonance (c) and 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:

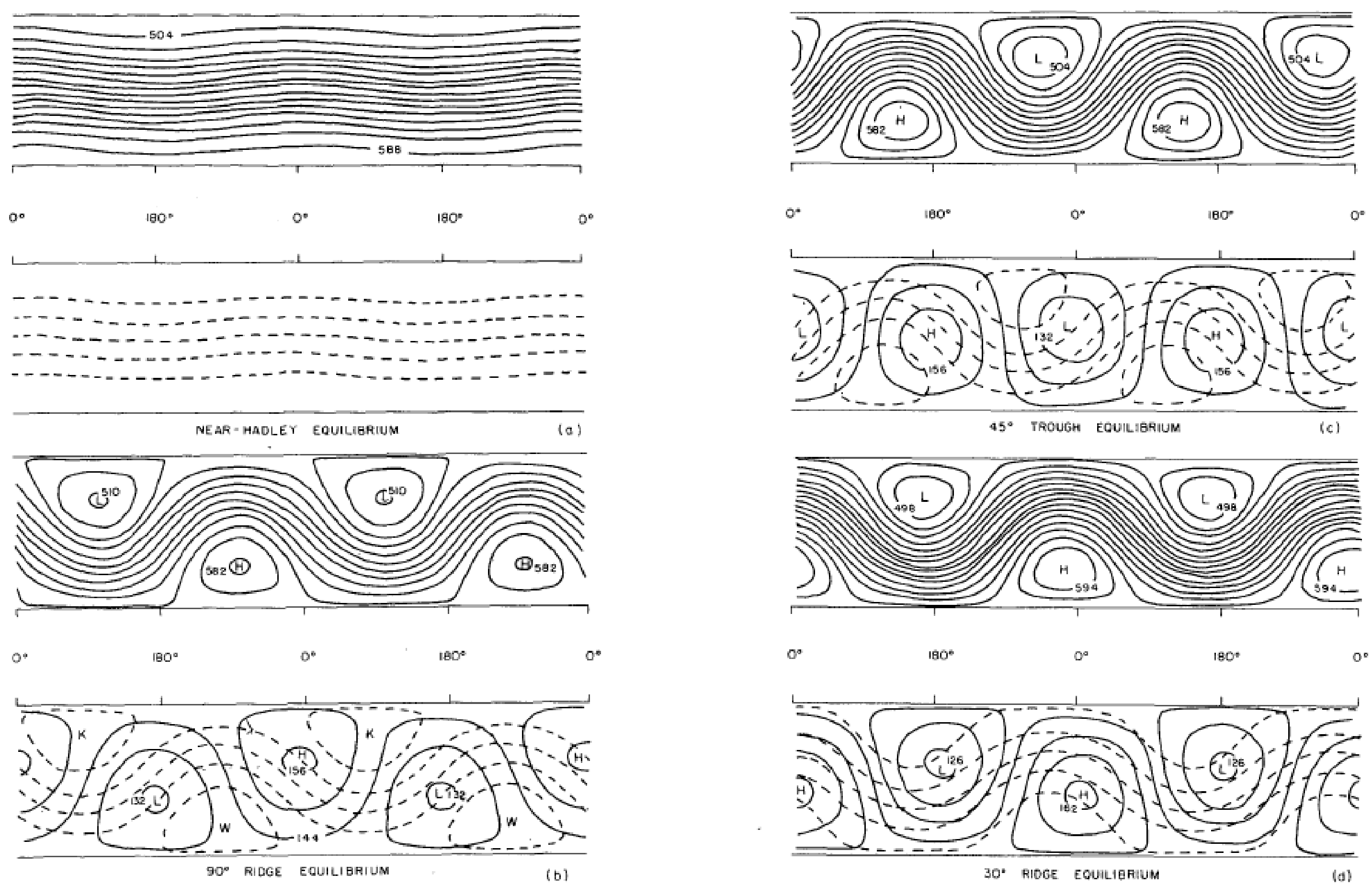
- **Charney and Straus 1980**: *Form-grad instability, multiple equilibria and propagating planetary waves in baroclinic, orographically-forced planetary wave systems*
- **Charney, Shukla and Mo 1981**: *Comparison of barotropic blocking theory with observation*
- **Legras and Ghil 1985**: *Persistent 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*

Seminal papers: Reinhold and Pierrehumbert 1982

Hemispheric weather regimes arising from equilibration of large-scale dynamical tendencies and “forcing” from transient baroclinic eddies



Eddy "forcing" of blocking: the Imperial College school

- **Green 1977**: *The weather during July 1976: some dynamical consideration of the drought*

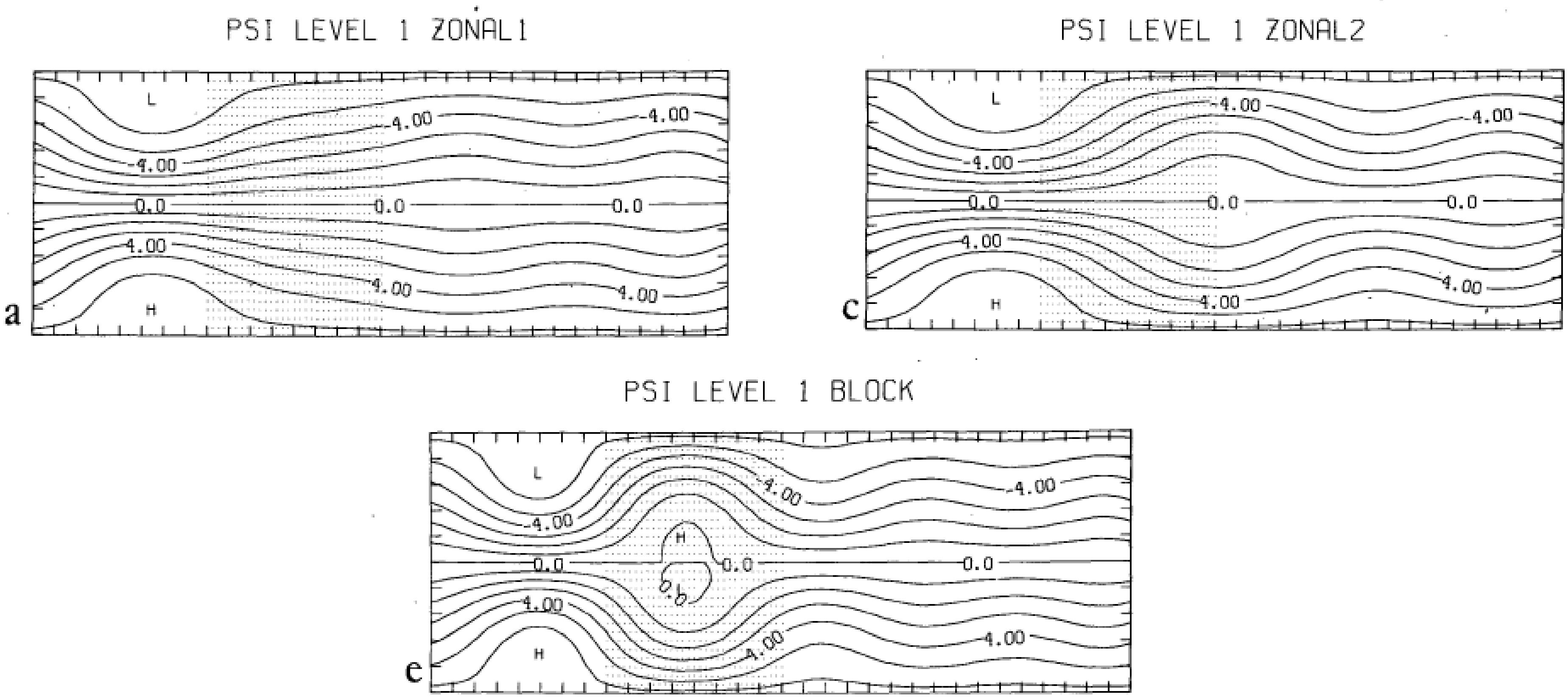
- **Illari and Marshall 1983**: *On the interpretation of eddy fluxes during a blocking episode*

- **Shutts 1986**: *A case study of eddy forcing during an Atlantic blocking episode*

- **Haines and Marshall 1987:** *Eddy-forced coherent structures as a propotype of atmospheric blocking*

Seminal papers: Vautard and Legras 1988

Regional weather regimes arising from equilibration of large-scale dynamical tendencies and PV fluxes from transient baroclinic eddies



Seminal papers: 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)

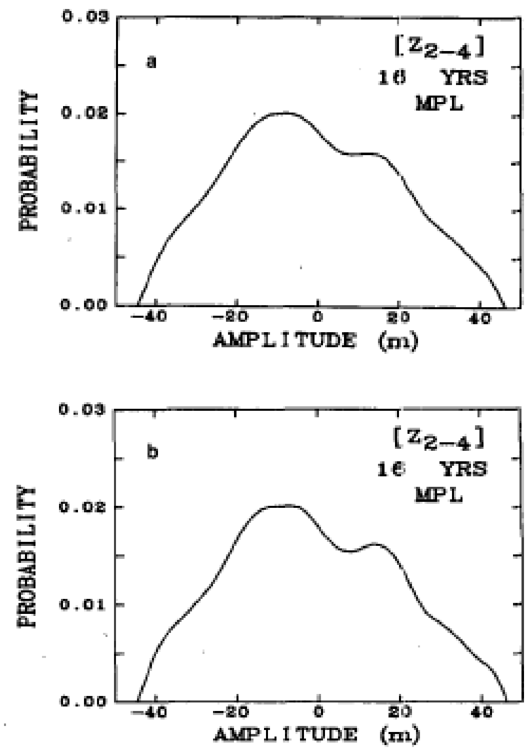
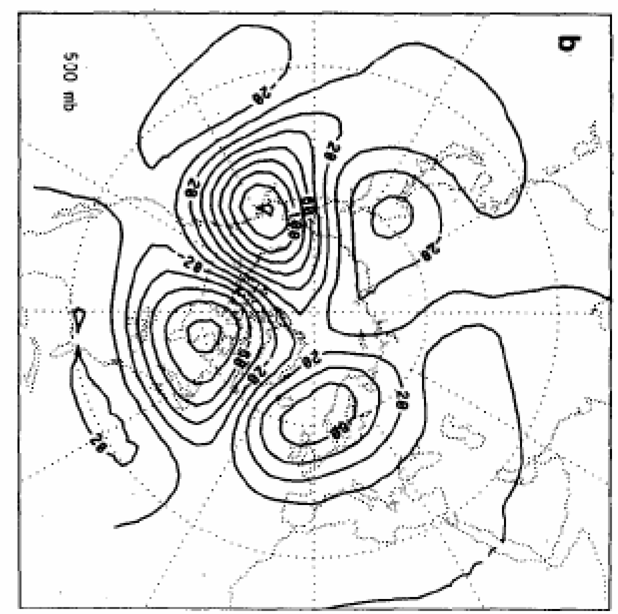


FIG. 4. MPL probability density estimates of $[Z_{2-4}]$ formed from the 16 winter composite filtered data for (a) $\alpha = 10^7$ and (b) $\alpha = 5 \times 10^6$.



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 →

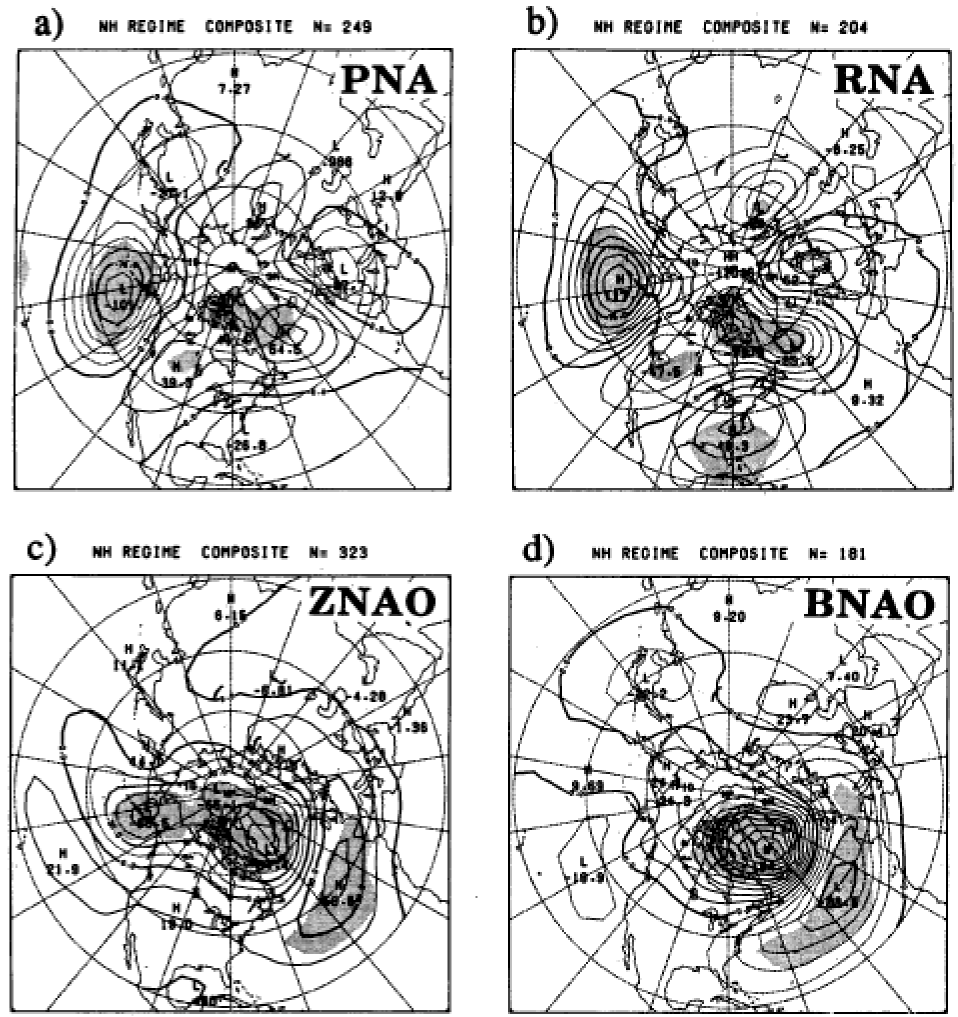
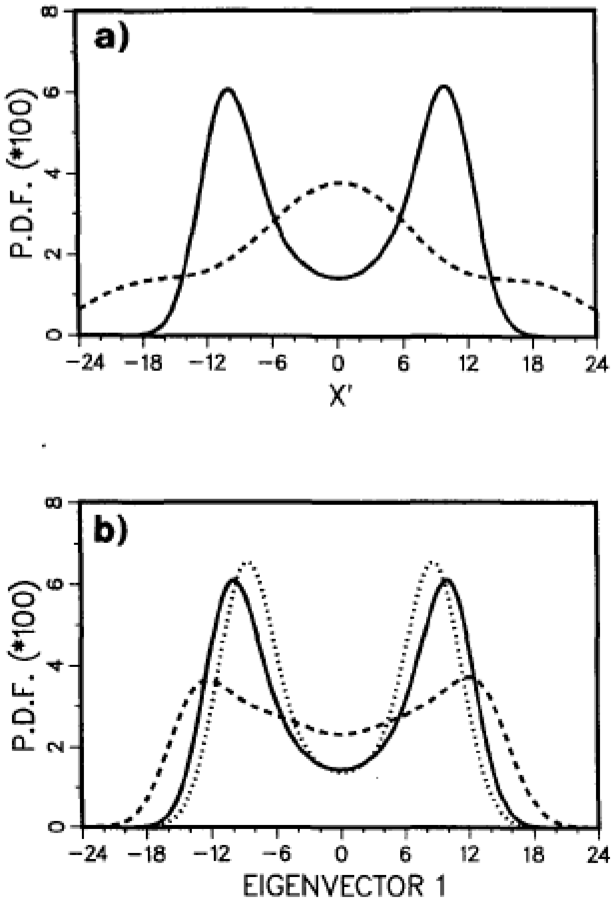


FIG. 14. Composite maps of unfiltered anomalies for the four NH regimes. Those samples falling in either of the four rectangles in Fig. 11a are collected for (a) PNA, (b) RNA, (c) ZNAO, and (d) BNAO. Numbers of collected daily maps are (a) 249, (b) 204, (c) 323, and (d) 181, respectively. Contour interval is 15 meters; shaded regions are significantly different from zero at a 99% level judged by a pointwise t-test.

Regime detection: time filtering



-------- : unfiltered data

______ : running means δt = 0.6

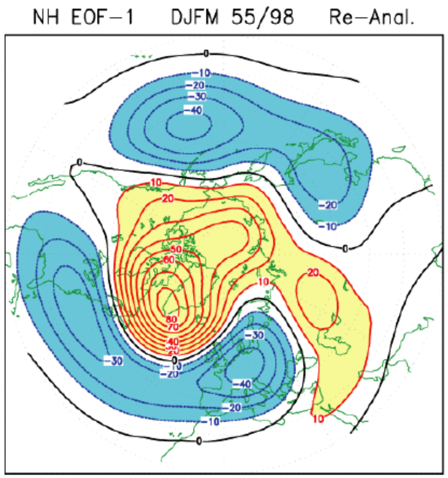
-------- : running means δt = 0.4

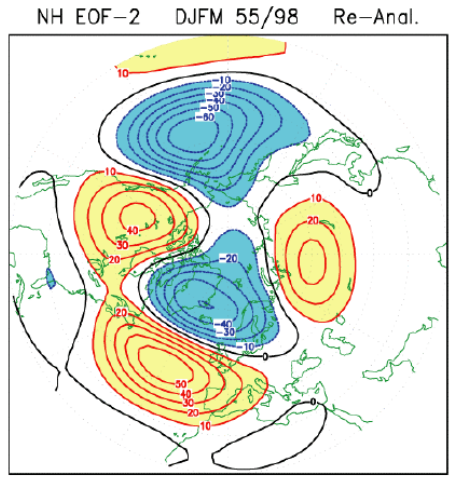
______ : running means δt = 0.6

.... : running means δt = 0.8

PDFs along the axis connecting the two unstable steady states in the 1963 Lorenz system (Marshall and Molteni 1993)

PDF estimation with the Gaussian kernel method

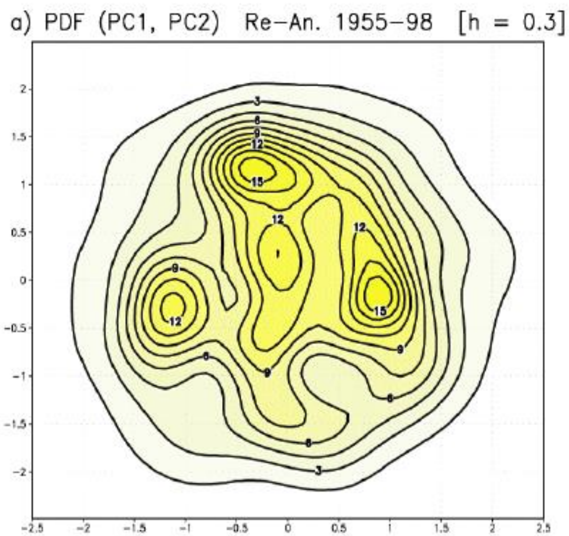




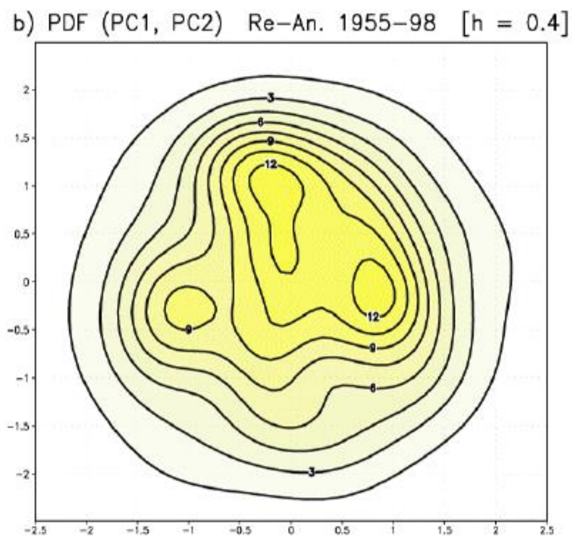
EOFs/PCs of monthly-mean 500 hPa height

$$P(x) = N^{-1} \Sigma_i\, G\,(x_i\, ,\, h\, \sigma\,)$$

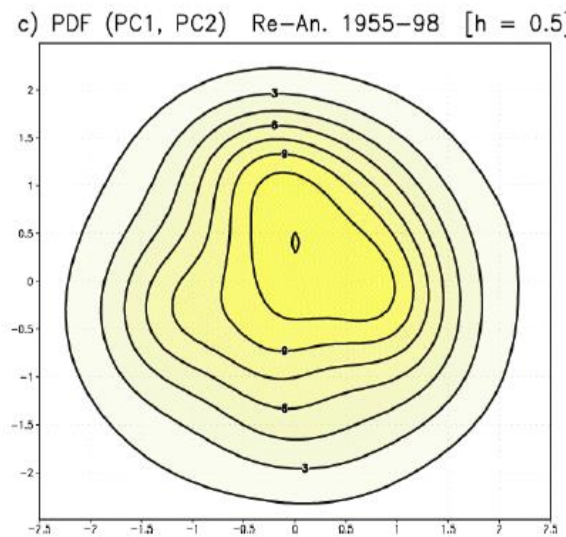
h : kernel width



h = 0.3

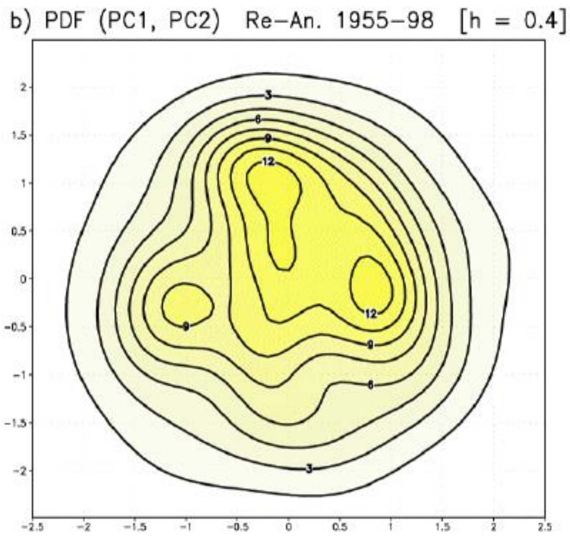


h = 0.4

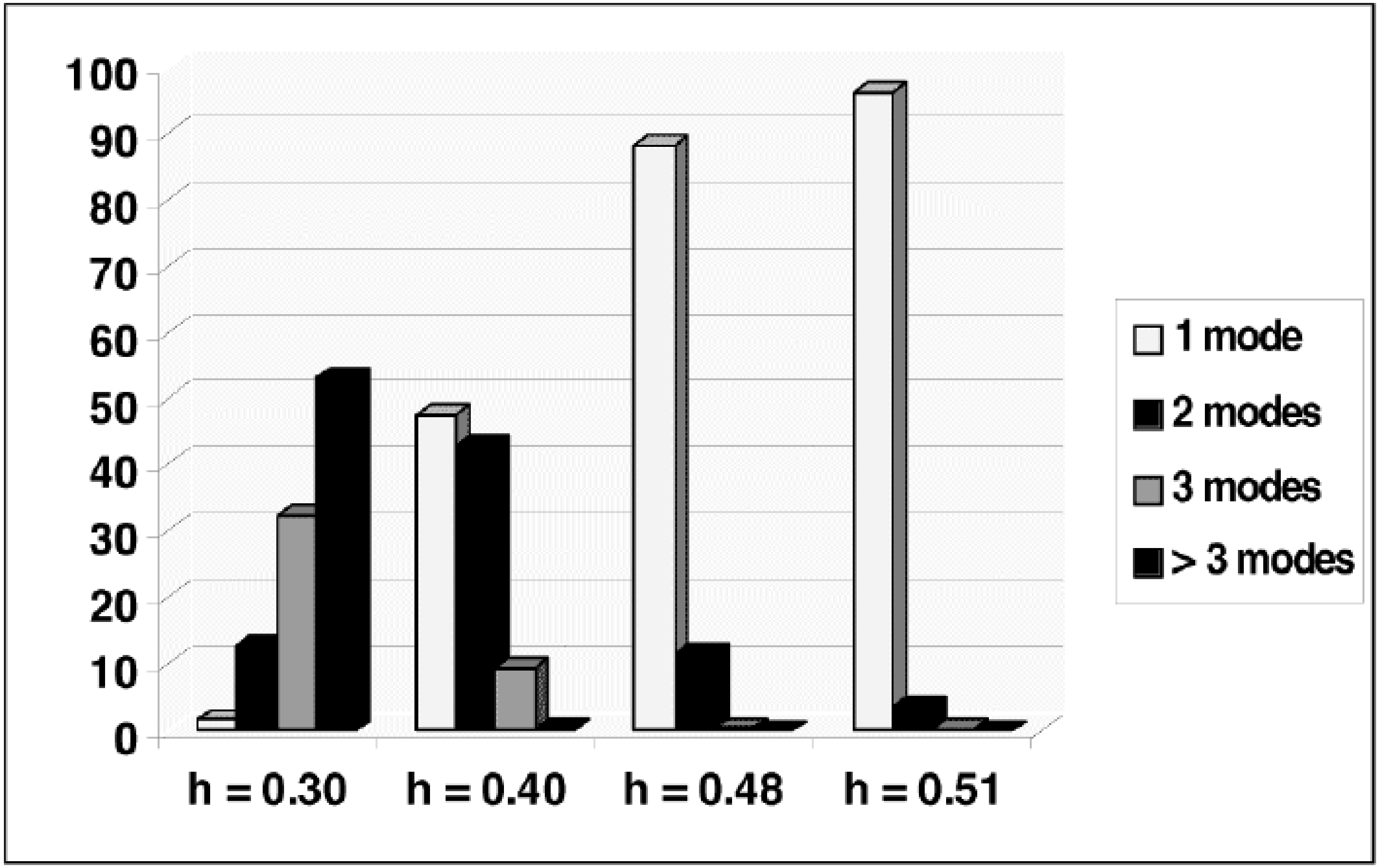


h = 0.5

Regimes from PDF estimation (Corti et al. 1999)



PDF estimation: statistical significance



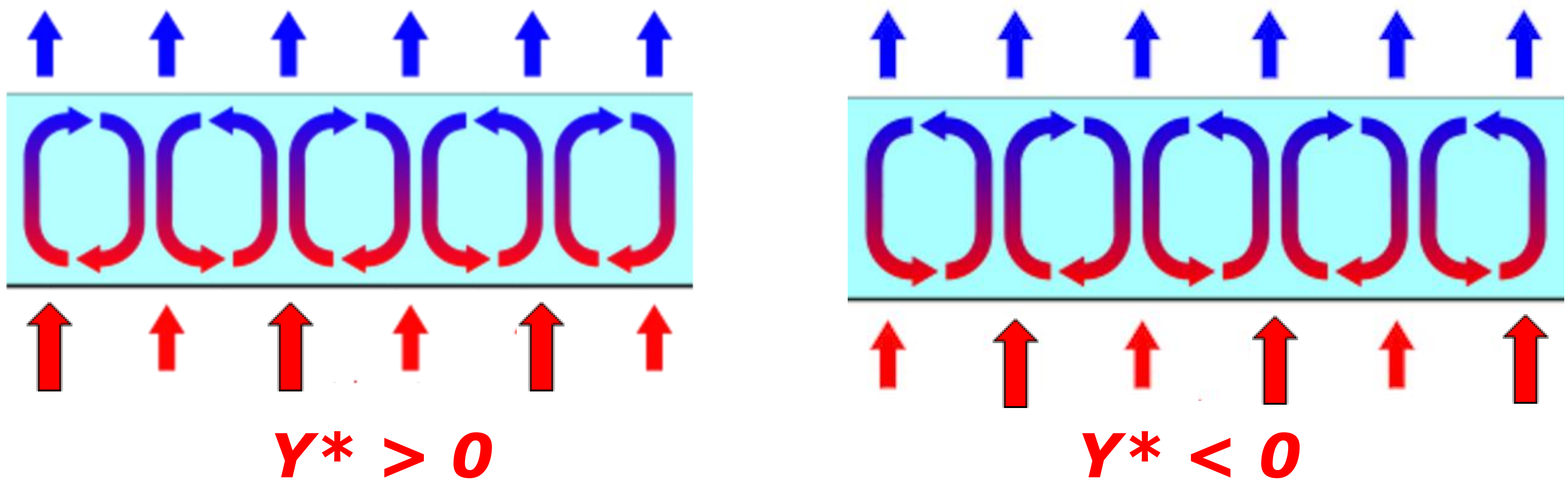
Fraction of uni/multi-modal PDFs obtained from a gaussian distribution

sample size as in Corti et al. 1999

Regime behaviour and anomalous forcing

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

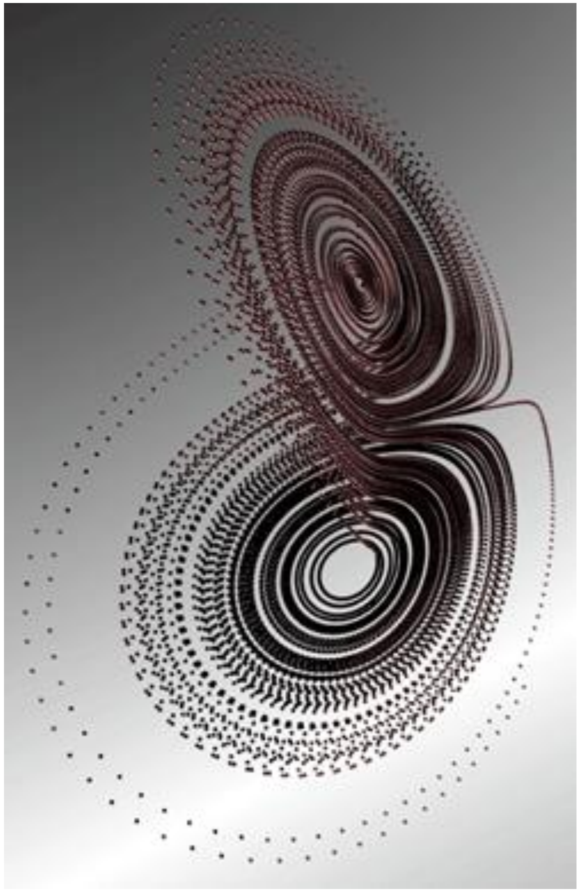
- $dX/dt = \sigma\,(Y - X)$
- $dY/dt = -\,X\,Z + r\,X - (Y - Y^*)$
- $dZ/dt = X\,Y - b\,Z$



Impact of “external” forcing in non-linear systems

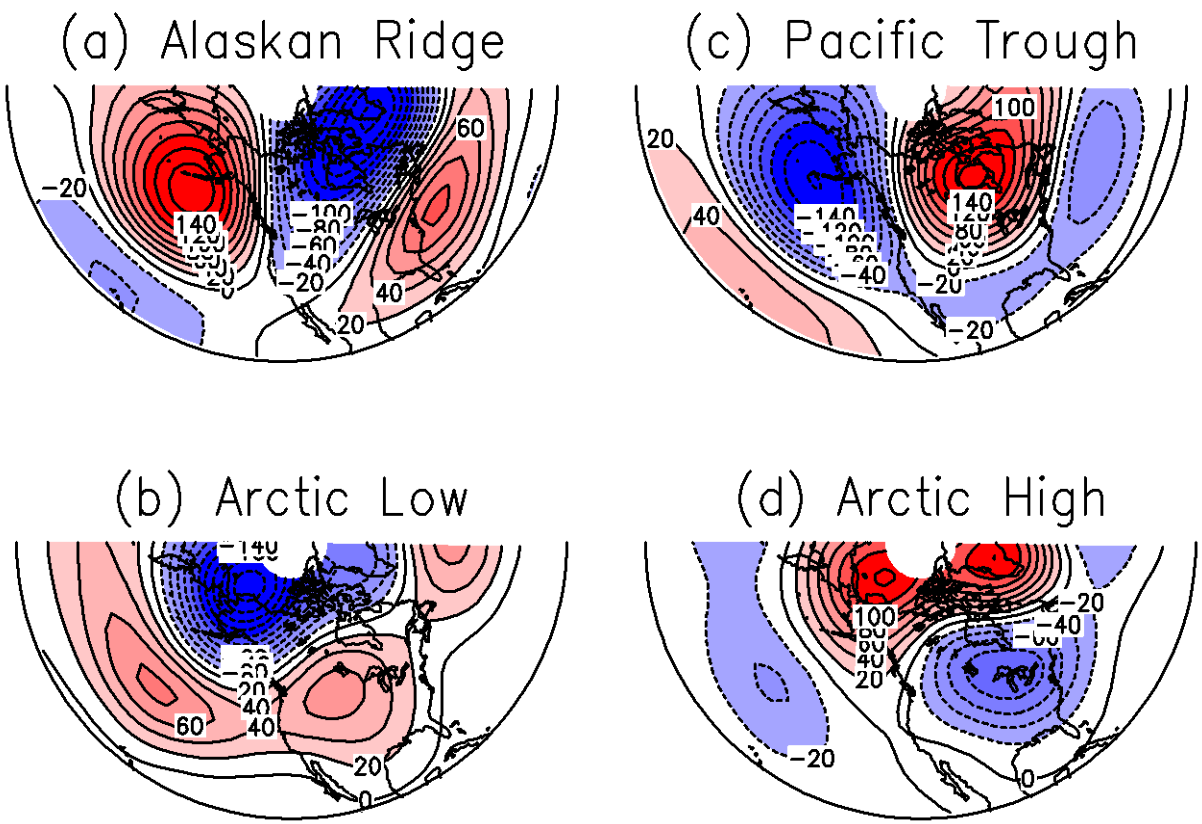
The properties of flow regimes may be affected by anomalous forcing in two different ways:

- **Weak forcing anomaly**: the number and spatial patterns of regimes remain the same, but their frequency of occurrence is changed
- **Strong forcing anomaly**: the number and patterns of regimes are modified as the atmospheric system goes through bifurcation points



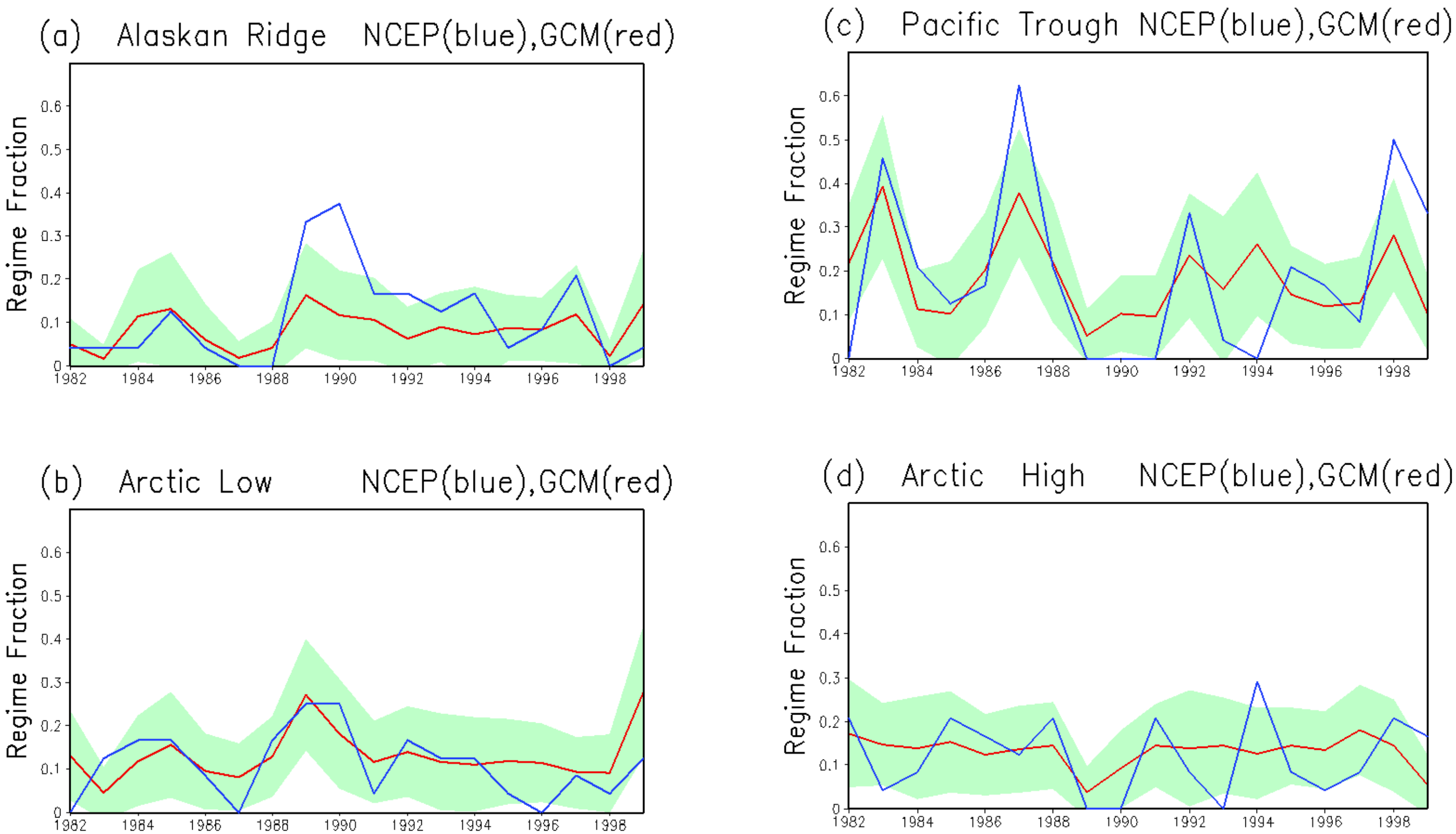
A regime approach to seasonal predictions

Cluster analysis of low-freq. (T>10 d) Z 200 in NCEP re-analysis and COLA AGCM ensembles (Straus, Corti, Molteni 2007)



A regime approach to seasonal predictions

Predictability of cluster frequencies (SCM 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)

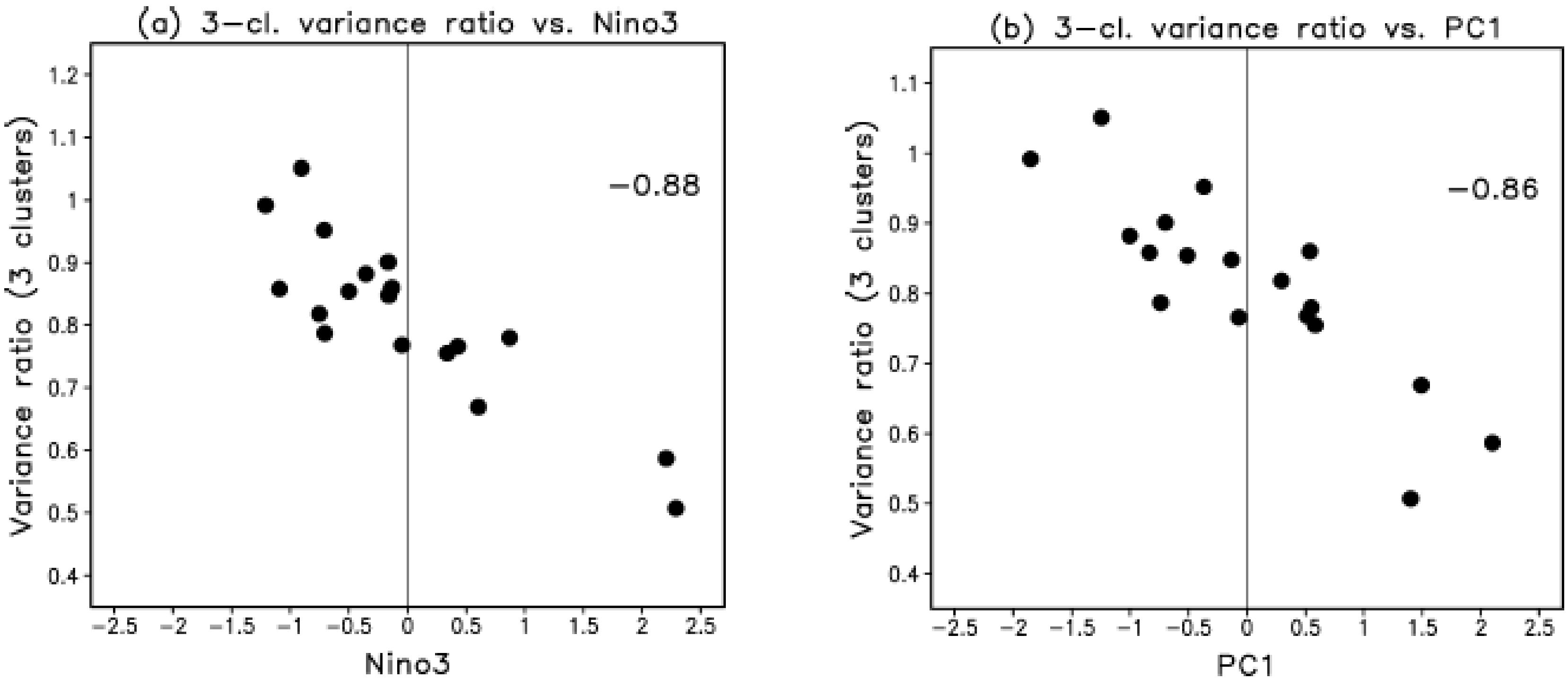
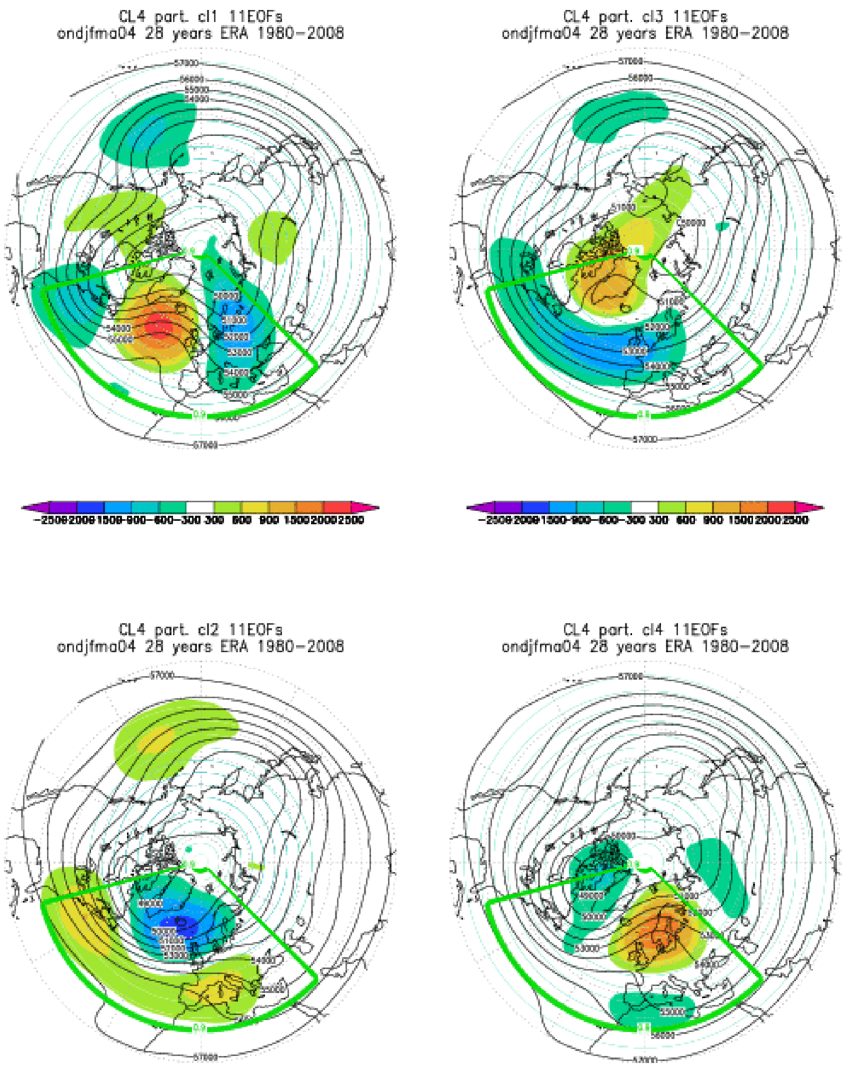
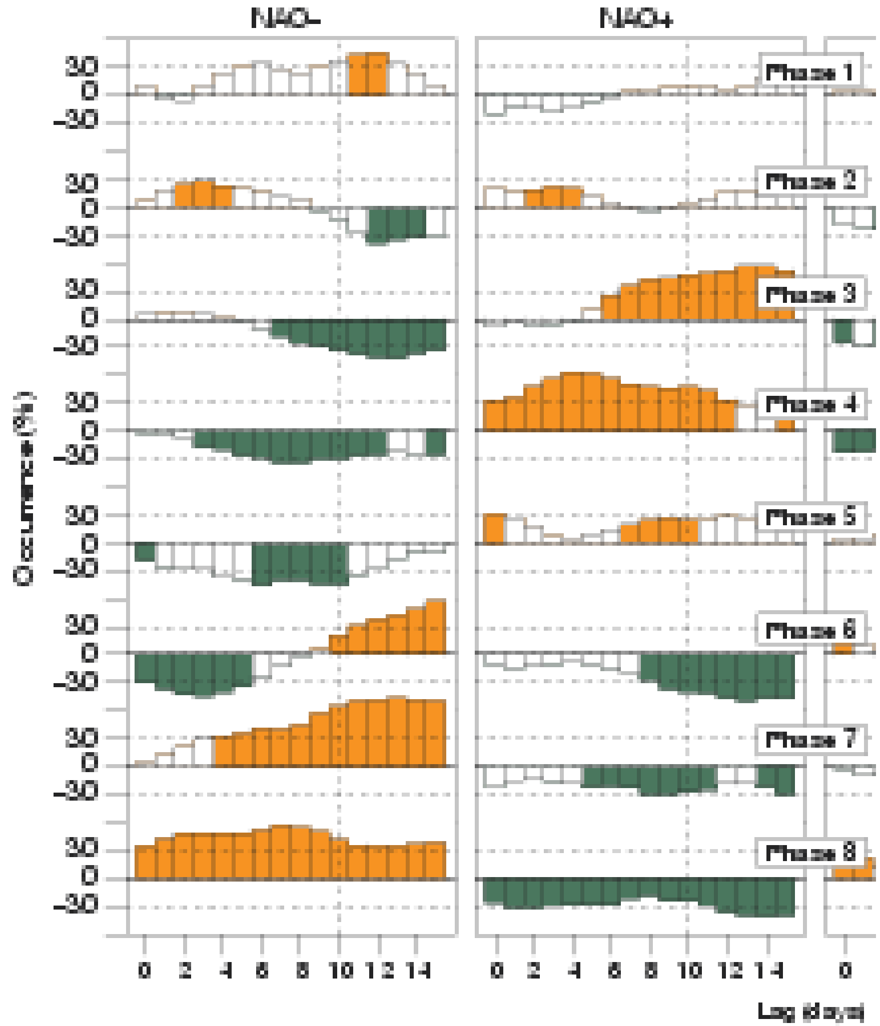


FIG. 4. Scatterplots of (a) the 3-cluster ($k = 3$) variance ratio vs Niño-3, and (b) the 3-cluster variance ratio vs the leading PC of ensemble/seasonal means. The leading PC and SST index time series are standardized.

Impact of MJO on Euro-Atlantic regimes *(see lecture on MJO)*





Cassou 2008

Conclusions

- Flow regime behaviour can be reproduced in a variety of dynamical models of different complexity.
- Atmospheric flow regimes may be defined on a hemispheric or regional domain.
- Detection of regimes in atmospheric and model datasets is usually performed by PDF estimation or cluster analysis; results are dependent on adequate time-filtering and proper use/interpretation of statistical significance tests.
- The impact of forcing anomalies on regime properties may occur through changes in regime frequencies or bifurcation effects.
- Predictability of regime frequencies and variations in the number of regimes as a function of the ENSO and MJO phases have been detected in ensembles of GCM simulations, and offer an alternative approach to long-range prediction.

References

- Benzi, R., P. Malguzzi, A. Speranza and A. Sutera, 1986: The statistical properties of general atmospheric circulation: Observational evidence and a minimal theory of bimodality. *Q. J. R. Meteorol. Soc,* **112**, 661-674.
- Cassou, C., 2008: Intraseasonal interaction between the Madden-Julian Oscillation and the North Atlantic Oscillation. *Nature,* **255,** 523-527.
- Charney, J.G. and J.G. DeVore. 1979: Multiple flow equilibria in the atmosphere and blocking. *J. Atmos. Sci*., **36,** 1205-1216
- Charney J. G. and D. M. Straus, 1980: Form-drag instability, multiple equilibria, and propagating planetary waves in baroclinic, orographically forced, planetary wave systems. *J. Atmos. Sci.,* **37**, 1157-1176.
- Charney J.G., J. Shukla and K. Mo, 1981: Comparison of barotropic blocking theory with observations. *J. Atmos. Sci.,* **38**, 762-779.
- Cheng, X. and J.M. Wallace, 1993: Cluster analysis of the Northern Hemisphere wintertime 500-hPa height field: Spatial patterns. *J. Atmos. Sci.,* **50**, 2674-2696.
- Corti, S., F. Molteni and T.N. Palmer, 1999: Signature of recent climate change in frequencies of natural atmospheric circulation regimes. *Nature*, **398,** 799-802.
- Green, J.S.A., 1977: The weather during July 1976: some dynamical consideration of the drought. *Weather* **32**, 120-128.
- Haines, K. and J. Marshall, 1987: Eddy-forced coherent structures as a prototype of atmospheric blocking. *Q. J. R. Meteorol. Soc* **113**, 681-704.
- Hansen, A.R., and A. Sutera, 1986: On the probability density distribution of large-scale atmospheric wave amplitude. *J. Atmos. Sci*., **43,** 3250-3265.
- Illari, L. and J. Marshall, 1983: On the interpretation of eddy fluxes during a blocking episode. *J. Atmos. Sci*., **40**, 2232-2242.
- Kimoto M. and M. Ghil, 1993a: Multiple flow regimes in the northern hemisphere winter. Part I: methodology and hemispheric regimes. *J. Atmos. Sci*., **50**, 2625-2643.
- Kimoto, M., and M. Ghil, 1993b: Multiple flow regimes in the Northern Hemisphere winter. Part II: Sectorial regimes and preferred transitions. *J. Atmos. Sci*., **50,** 2645-2673.

References (2)

- Legras, B., and M. Ghil, 1985: Persistent anomalies, blocking and variations in atmospheric predictability, *J. Atmos. Sci.*, **42**, 433-471
- Lorenz, E.N, 1963: Deterministic nonperiodic flow. *J. Atmos. Sci*. **20,** 130-141.
- Marshall J. and F. Molteni, 1993: Toward a dynamical understanding of planetary-scale flow regimes. *J. Atmos. Sci*., **50,** 1792-1818.
- Michelangeli, P.-A., R. Vautard, and B. Legras, 1995: Weather regimes: Recurrence and quasi-stationarity. *J. Atmos. Sci.,* **52**, 1237-1256.
- Mitchell, H.L. and J. Derome, 1983: Blocking-like solutions of the potential vorticity equation: their stability at equilibrium and growth at resonance. *J. Atmos. Sci.,* **40**, 2522-2536.
- Mo, K., and M. Ghil, 1988: Cluster analysis of multiple planetary flow regimes, *J. Geophys. Res*., **93D,** 10927-10952.
- Molteni, F., S Tibaldi, and T.N. Palmer, 1990: Regimes in the wintertime circulation over northern extratropics. I: Observational evidence. *Q. J. R. Meteorol. Soc*., **116**, 31-67.
- Molteni, F., L. Ferranti, T.N. Palmer and P. Viterbo, 1993: A dynamic interpretation of the global response to equatorial Pacific SST anomalies. *J. Climate,* **6**, 777-795.
- Palmer, T.N., 1993: Extended-range atmospheric predictions and the Lorenz model. *Bull. Amer. Met. Soc*., **74**, 49-65.
- Shutts, G.J. 1986: A case study of eddy forcing during an Atlantic blocking episode. *Adv. Geophys*. **29,** 135-161.
- Reinhold, B., and R. T. Pierrehumbert, 1982: Dynamics of weather regimes: Quasi-stationary waves and blocking. *Mon. Wea. Rev*., **121,** 2355-1272.
- Straus.D. M., and F. Molteni, 2004: Circulation regimes and SST forcing: Results from large GCM ensembles. *J. Climate*, **17,** 1641-1656.
- Straus, D. M., S. Corti and F. Molteni, 2007: Circulation regimes: Chaotic variability versus SST-forced predictability. *J. Climate*, **20,** 2251–2272.
- Vautard, R., and B. Legras, 1988: On the source of midlatitude low-frequency variability. Part II: nonlinear equilibration of weather regimes. *J. Atmos. Sci*., **45,** 2845-2867.