An Introduction to Circulation Regimes and Weather Types: Bridging Weather and Climate

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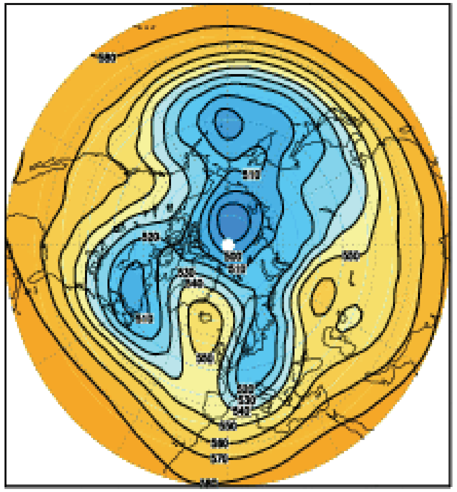
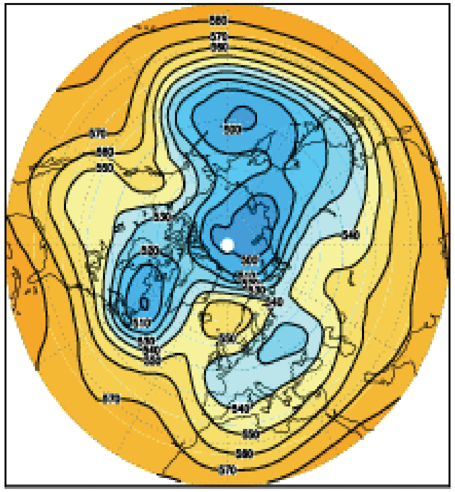
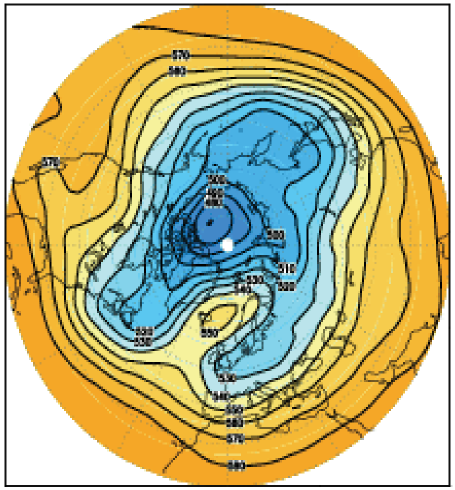
Courtesy Franco Molteni, ECMWF

Recurrent flow patterns: examples





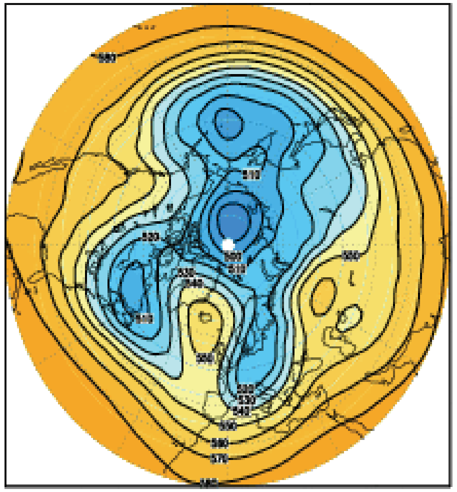
A sequence of 5-day mean fields of 500 hPa geopotential height during boreal winter …

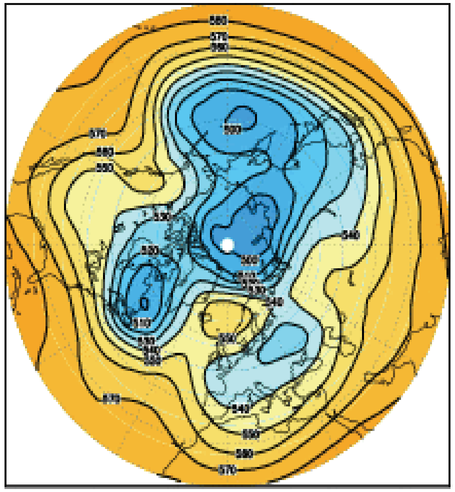


Courtesy Franco Molteni, ECMWF

Recurrent flow patterns: examples

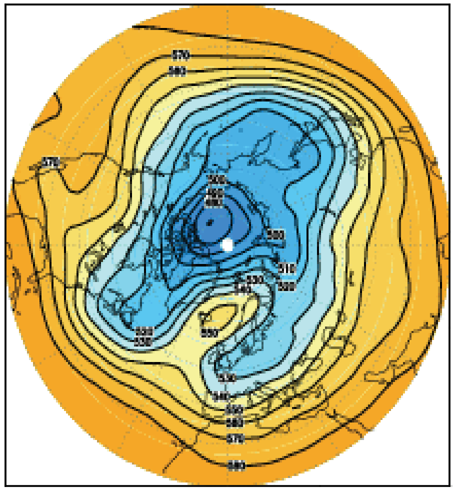
5-9 Jan
1985





4-8 Feb
1986

... but each one occurred in a
different winter !



10-14 Jan
1987

"An important question in the study of atmospheric low-frequency variability in the extratropics is **whether multiple atmospheric regimes exist**. The answer to this question may have far-reaching consequences for our understanding of the climate system and for the detection and interpretation of climate change…"*

* Christiansen, 2005: Bimodality of the Planetary-Scale Atmospheric Wave Amplitude Index. J. Atmos. Sci., 62, 2528-2541.

Circulation Regimes:

(1) Multiple maxima in the probability of occurrence of planetary scale properties

(2) Characterizing a few distinct large scale patterns from departures of the probability distribution from a multivariate Gaussian distribution.

Weather Types:

Recognition that weather (and climate) states on the regional or even local scale can be usefully classified from a broad range of states.

One-dimensional probability function

Planetary-Scale Wave Amplitude Index*:

Is its pdf bimodal?

WAI = measure of integrated PW strength across mid-latitudes:

(a) Daily 500-hPa Z averaged 45- 70 N
(b) Zonal wavenumber 2-4 retained
(c) Remove annual harmonic and $\tau < 5$ d
(d) rms take for NH winter

Daily Data ($\tau > 5$ days)

Daily Data ($\tau > 4$ days)

Daily Data →

Slow variation in WAI →

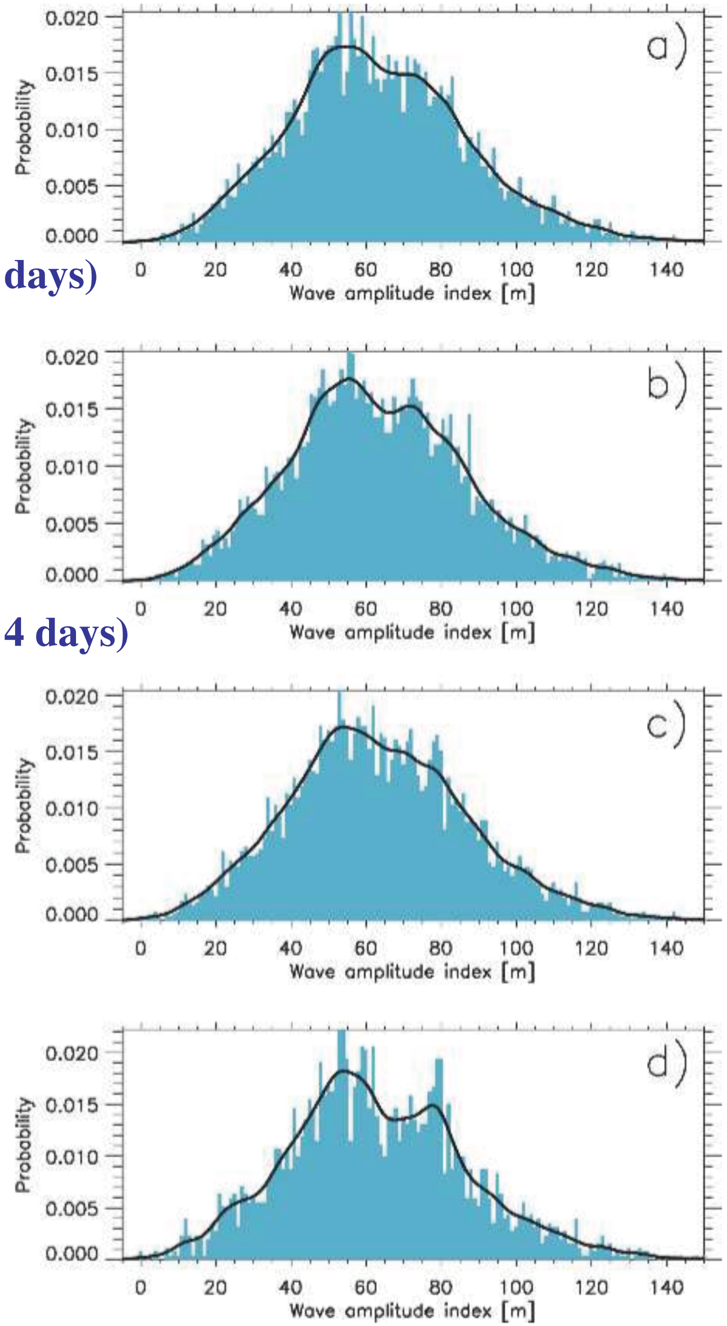


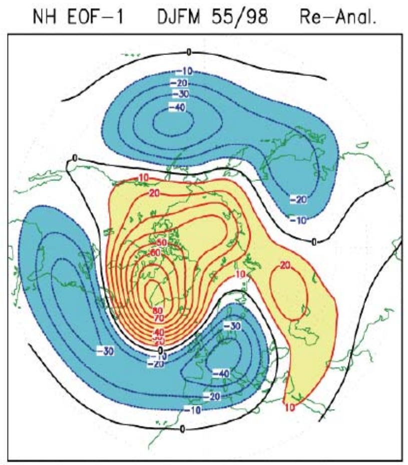
FIG. 1. Probability density of the WAI for the winter days in the period 1948–2003 calculated as a kernel density estimator with a

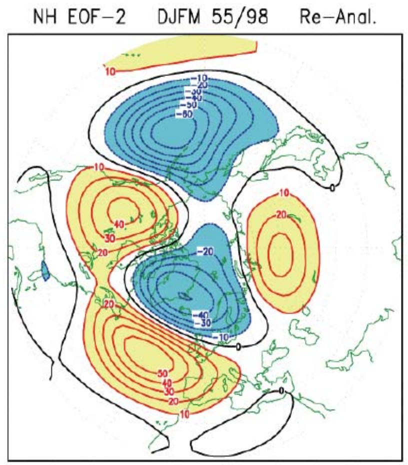
pdf is bi-modal if only time periods in which WAI varies slowly are kept!

* Christiansen, 2005: Bimodality of the Planetary-Scale Atmospheric Wave Amplitude Index. J. Atmos. Sci., 62, 2528-2541.

Two-Dimensional probability function

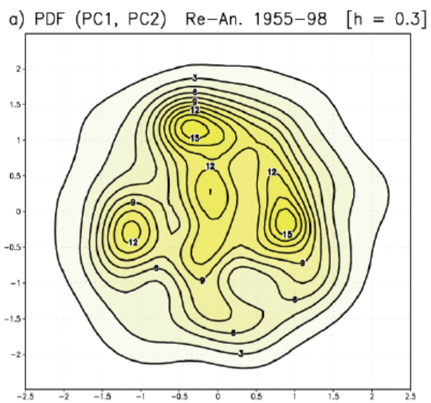
PDF estimation with the Gaussian kernel method

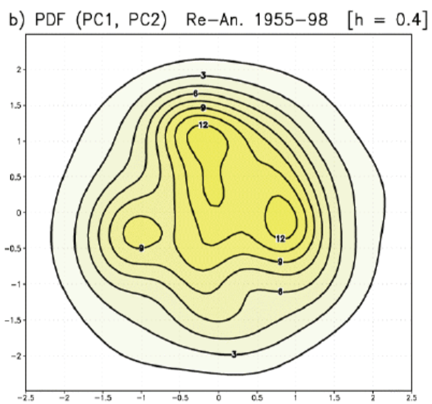


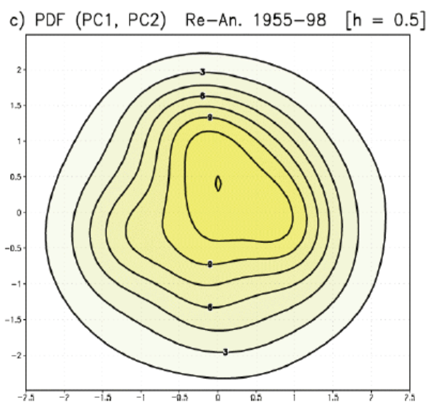


EOFs / PCs monthly-mean Z500

- Plot each month as a point in a 2d space of PC1/PC2
- Smooth the points into a pattern
- Smoothing parameter h







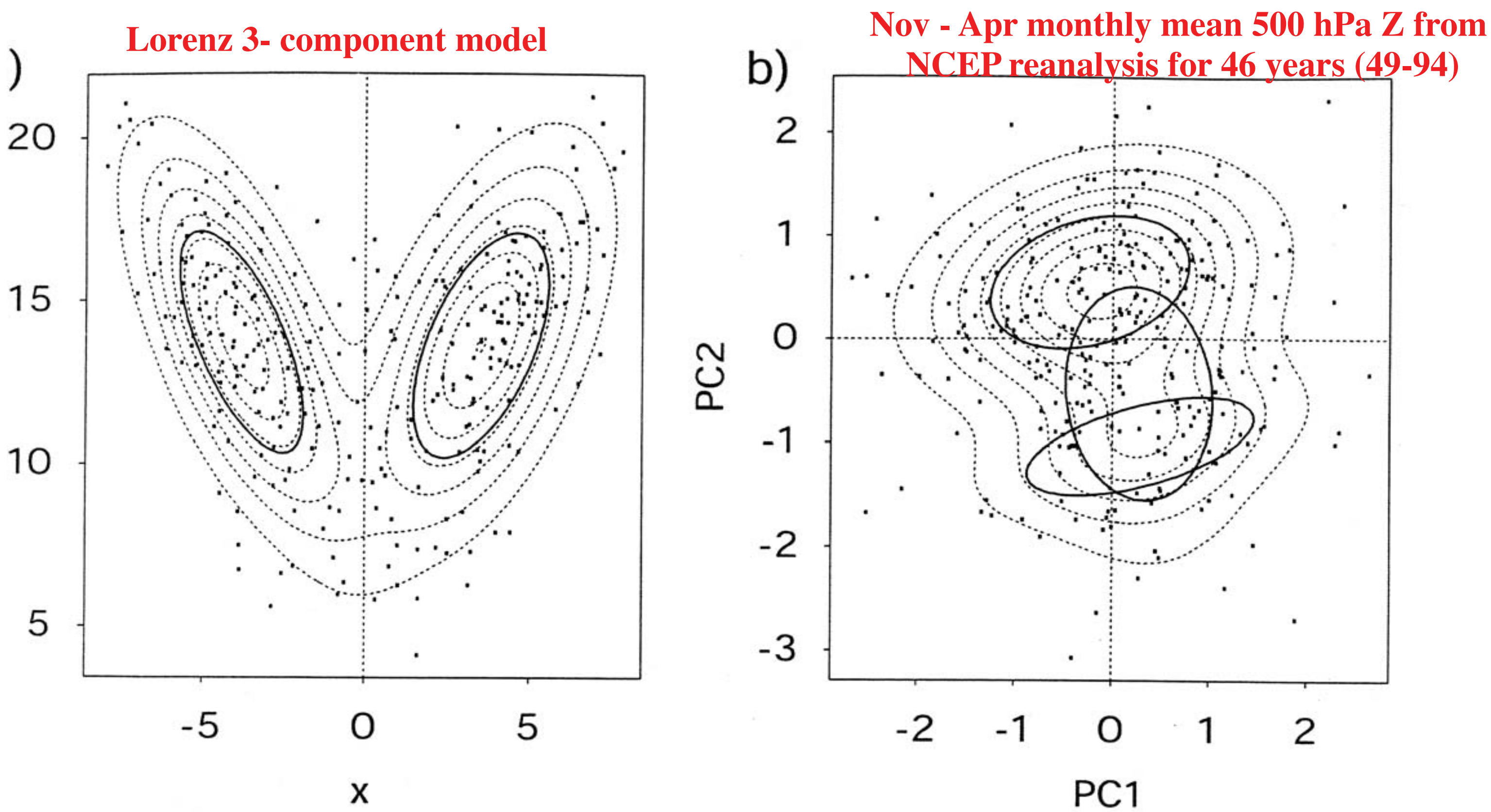
Note 4 maxima !!

h = 0.3 h = 0.4 h = 0.5

Corti, Palmer and Molteni, 1999: Signature of Recent Climate Change in Frequencies of Natural Atmospheric Circulations, *Nature*, 398, 799-802

Circulation Regimes

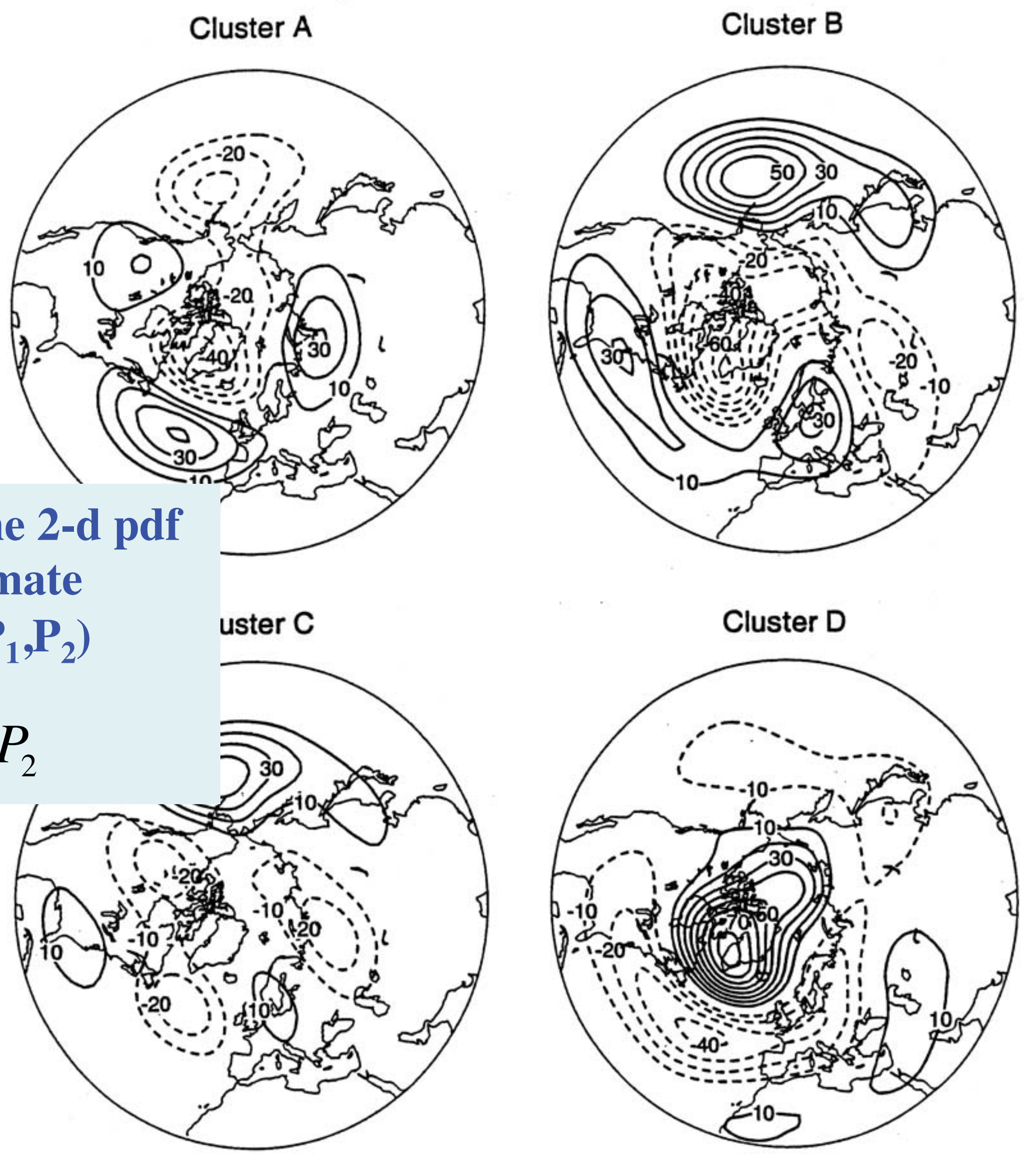
Corti, Palmer and Molteni, 1999: Signature of Recent Climate Change in Frequencies of Natural Atmospheric Circulations, *Nature*, **398**, 799-8



“Cold Ocean Warm Land” (COWL) pattern

Each maximum in the 2-d pdf corresponds to a climate pattern. The point (P_1,P_2) gives:

$$Z_{(i,j)} = E^{(1)}_{i,j} P_1 + E^{(2)}_{i,j} P_2$$

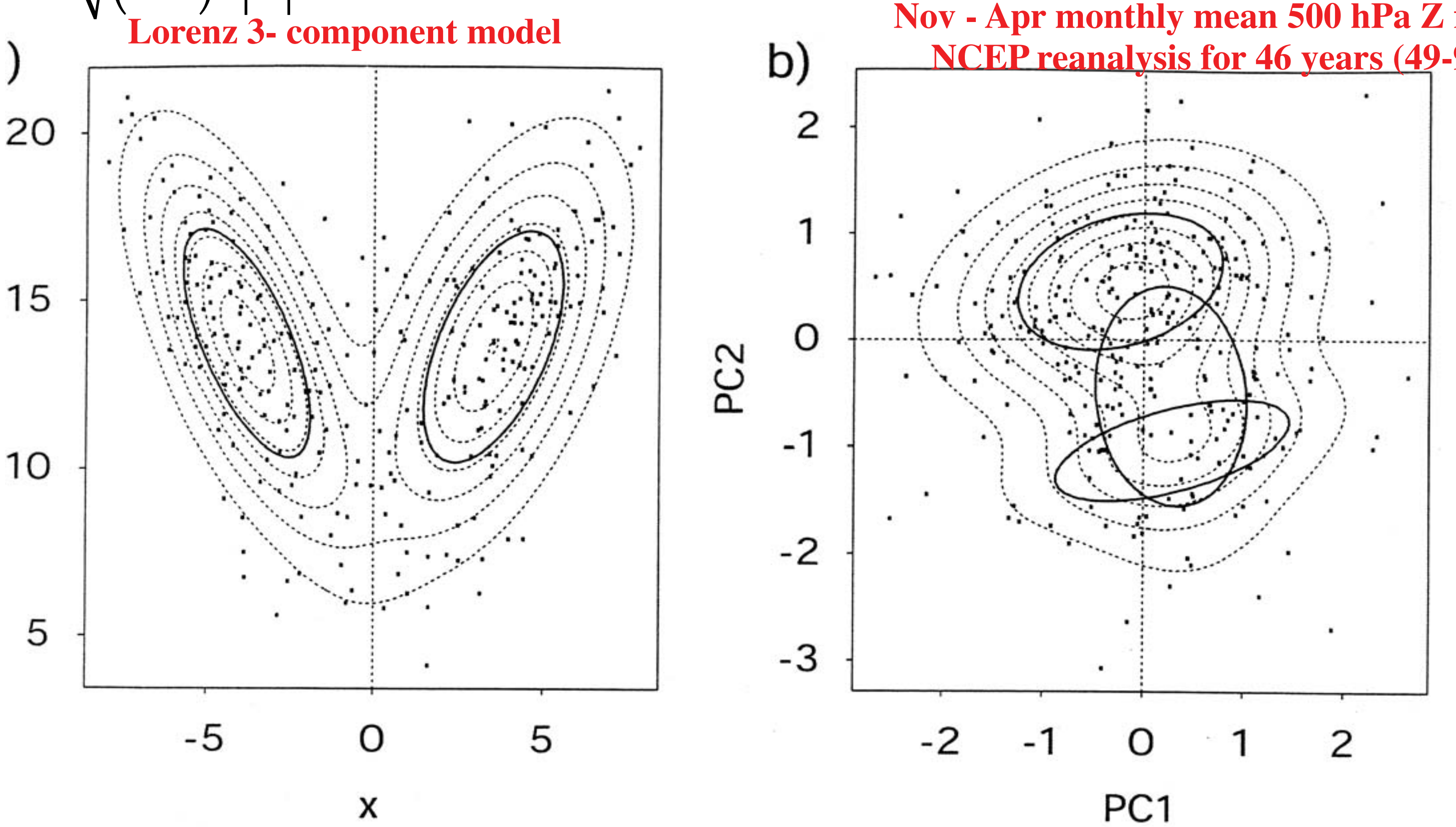


AO / NAO

Figure 3 Geographical patterns of the four atmospheric regimes. Shown is the geographical distribution of 500-hPa geopotential height anomaly associated with clusters A (The “cold ocean warm land” regime) B, C and D (the “Arctic Oscillation” regime). Contour interval, 10 m.

Rigorous fit of pdf to a *sum* of two-dimensional Gaussian distributions ?? (Mixture model method)

$$f(x_1,x_2)=\frac{1}{\sqrt{(2\pi)^2|\Sigma|}}\exp\left(-\frac{1}{2}(\vec{x}-\vec{\mu})\cdot\overleftrightarrow{\Sigma}^{-1}\cdot(\vec{x}-\vec{\mu})\right) \qquad \Sigma_{i,j}=\left\langle (x_i-\mu_i)(x_j-\mu_j)\right\rangle$$



But perhaps we shouldn't expect to be able to reject the null hypothesis of multi-normal behavior using hemisphere monthly means:

-Statistical reason: Short data record

-Physical reason: **Weather regimes** are ***intermittent*** and ***local***

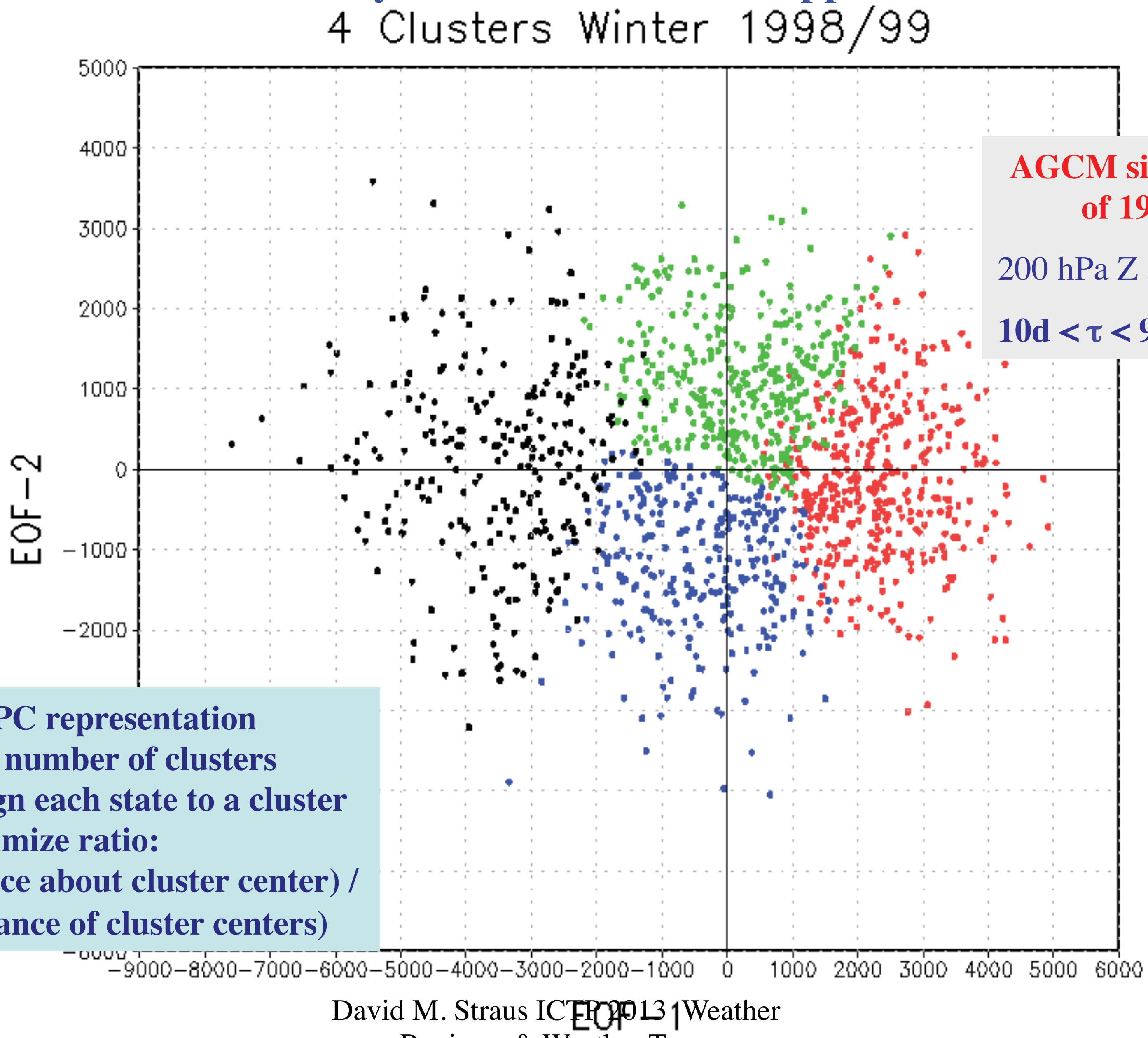
Suggestions:

Look regionally

Use only periods of "quasi-stationary" behavior of large scales

A large number of studies have found **circulation regimes** in observations and models using this strategy

Cluster Analysis : A less ambitious approach !



AGCM simulations of 1998/99

200 hPa Z 55 winters

10d < τ < 90d

PC representation

(1) Pick number of clusters

(2) Assign each state to a cluster

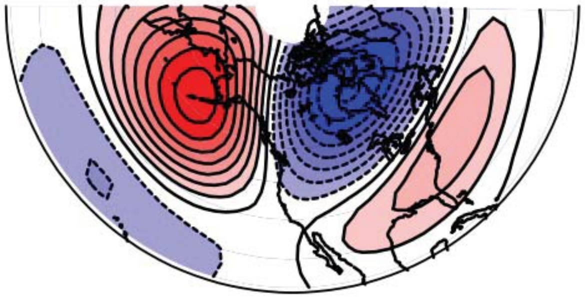
(3) Minimize ratio:

(Variance about cluster center) /

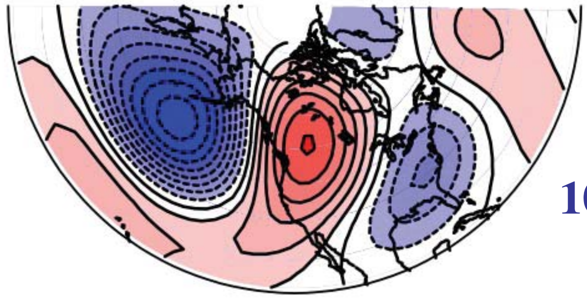
(Variance of cluster centers)

Straus, Corti and Molteni
***Journal of Climate* 2007**

(a) Alaskan Ridge



(c) Pacific Trough



$10d < \tau < 90d$

Regimes in 200 hPa Z from 54 NCEP winters (contour interval = 20 m)

(a) Only quasi-stationary time periods used

(b) H0 can be rejected at the 90% level using partitioning method

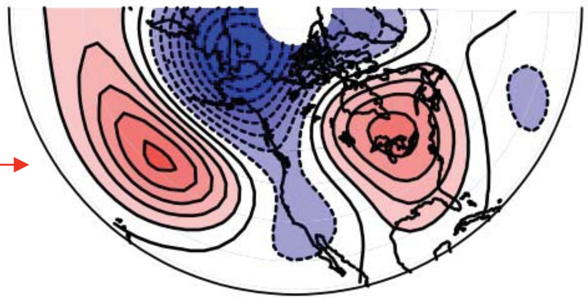
(c) Can not say whether 3 or 4 clusters is optimal

(d) Patterns reproducible using randomly drawn half length samples (always from same winter !!!!)

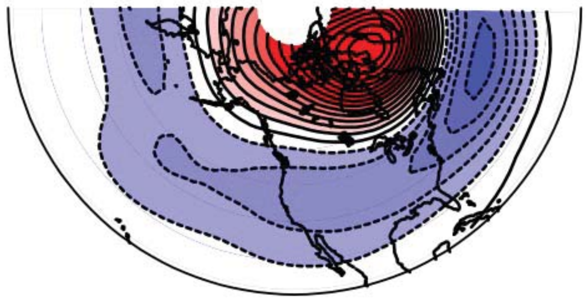
(e) Clusters are due to true “clumping” of states in PC-space, and not just skewness

(b) Arctic Low

least well-defined →



(d) Arctic High



Physical Motivation for Regimes, or Non-Linear Behavior

Existence of extended periods of one type of (possible extreme) weather has been recognized for many years (papers going back to the 1950s at least) - Examples: droughts, stormy periods, cold periods

These periods occur intermittently, and must be related to persistence in the “large-scale” flow

Classification of regional weather patterns into a discrete number of types - e.g. the grosswetterlagen

These are (collectively) called “weather regimes” and provided the original (and still the best) motivation for finding equivalent regimes in the large-scale circulation

Grosswetterlagen = Weather Regimes

- "It has been noticed that weather patterns over certain areas and over the entire Northern Hemisphere tend to repeat themselves from time to time. Using this property of the atmosphere, classification of the *macroweather* situations over Europe was made by…." (Radinovic, 1975)

- "The *grosswetterlagen* defined by Baur …provide a valuable classification of the extended (duration longer than three days) weather types observed in Central Europe...*28 large-scale weather types* derived from about 70 years of observations." (Egger, 1980).

Weather Regimes : Self Organizing Maps

(Polo et al 2011)*

A Weather Regime can be defined as a recurrent and persistent atmospheric state

Low-frequency variability can then be interpreted as a change in the amplitude of these WRs or in the *preferred transitions* between them

Weather regimes have been defined over the Euro-Mediterranean region (15°–70°N, 60°W–60°E) from May to October using the daily SLP, Z 700-hPa and q 700 (specific humidity) from the (ERA)-Interim reanalyses

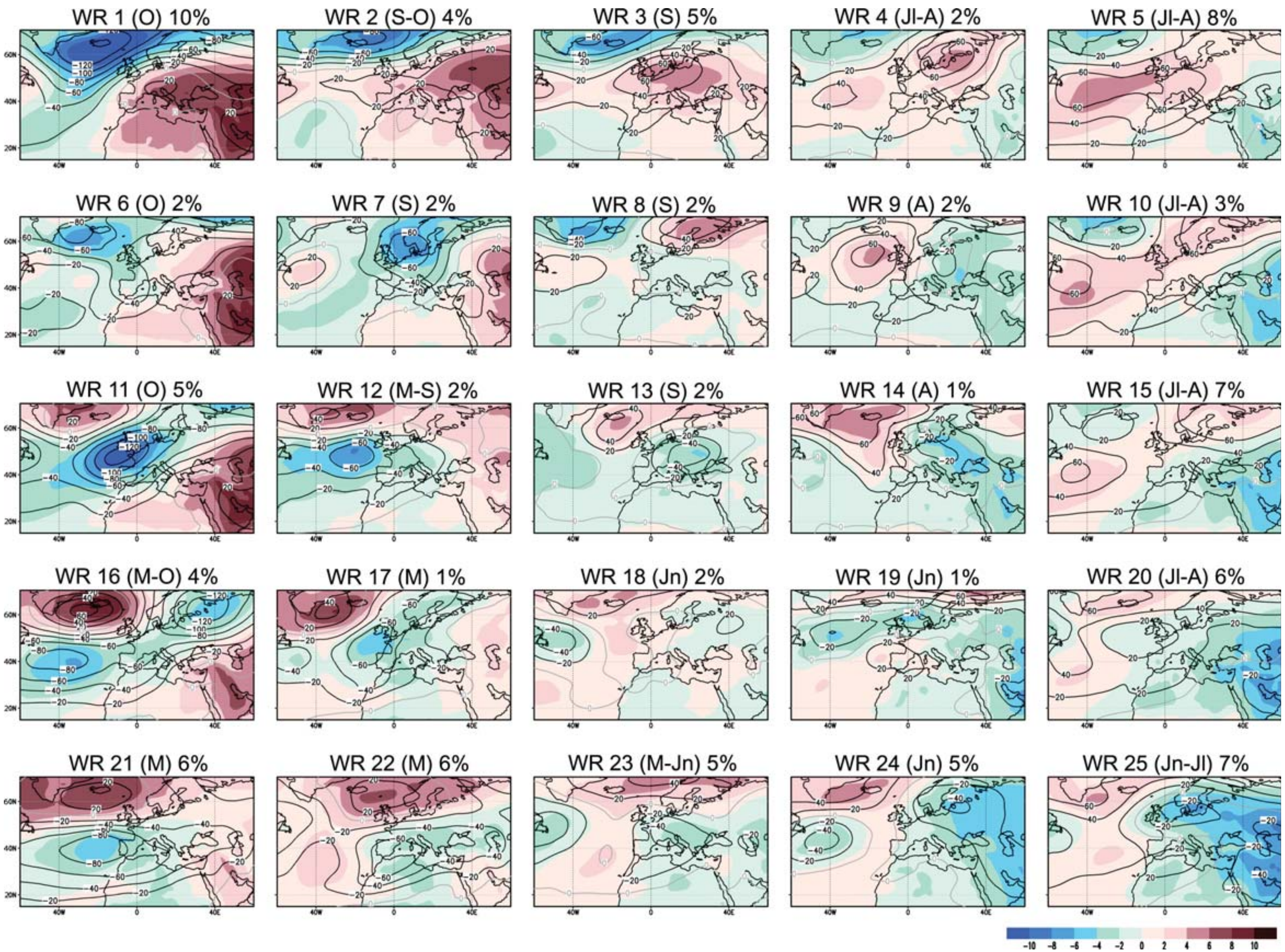
Can we relate changes in frequency of the Weather Regimes over the North Atlantic/Mediterranean sector to subtropical–tropical convection variability over West Africa?

*Polo, Irene, Albin Ullmann, Pascal Roucou, Bernard Fontaine, 2011: Weather Regimes in the Euro-Atlantic and Mediterranean Sector, and Relationship with West African Rainfall over the 1989–2008 Period from a Self-Organizing Maps Approach. *J. Climate*, **24**, 3423–3432.

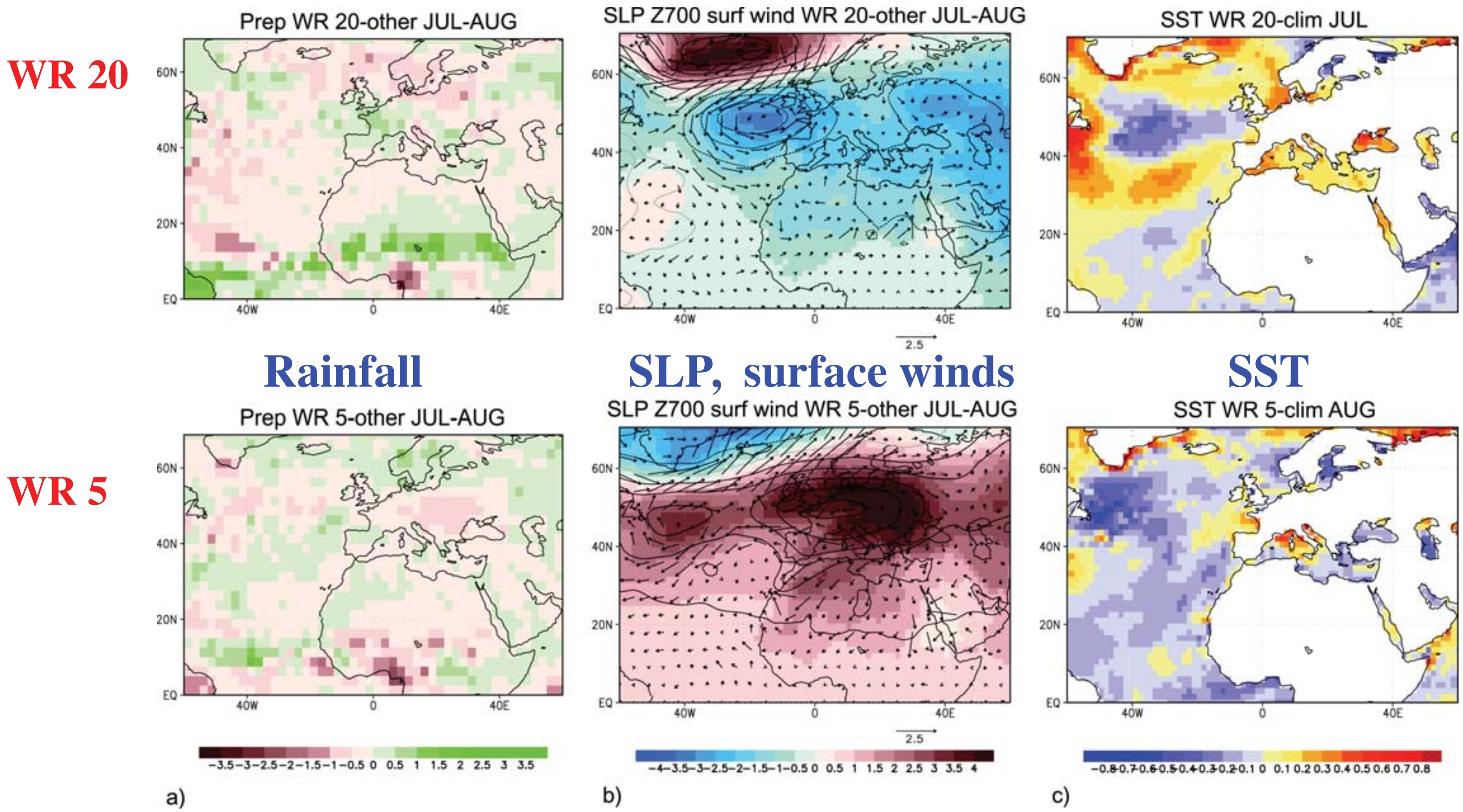
Representation of Weather Regimes using Daily data

May–October (MJJASO) WRs (composite anomalies with respect to the long-term seasonal mean of:
SLP [shaded areas; contour interval (CI) = 2 hPa]
geopotential height at 700 hPa (contour lines; CI = 20 m; zero line in gray)

Percentage at the top right of each map gives the global population of a given WR. Parentheses list the months when each WR is likely to occur.



The continuity in the SOM structures provides an efficient way to identify easily the large-scale atmospheric slow motions.



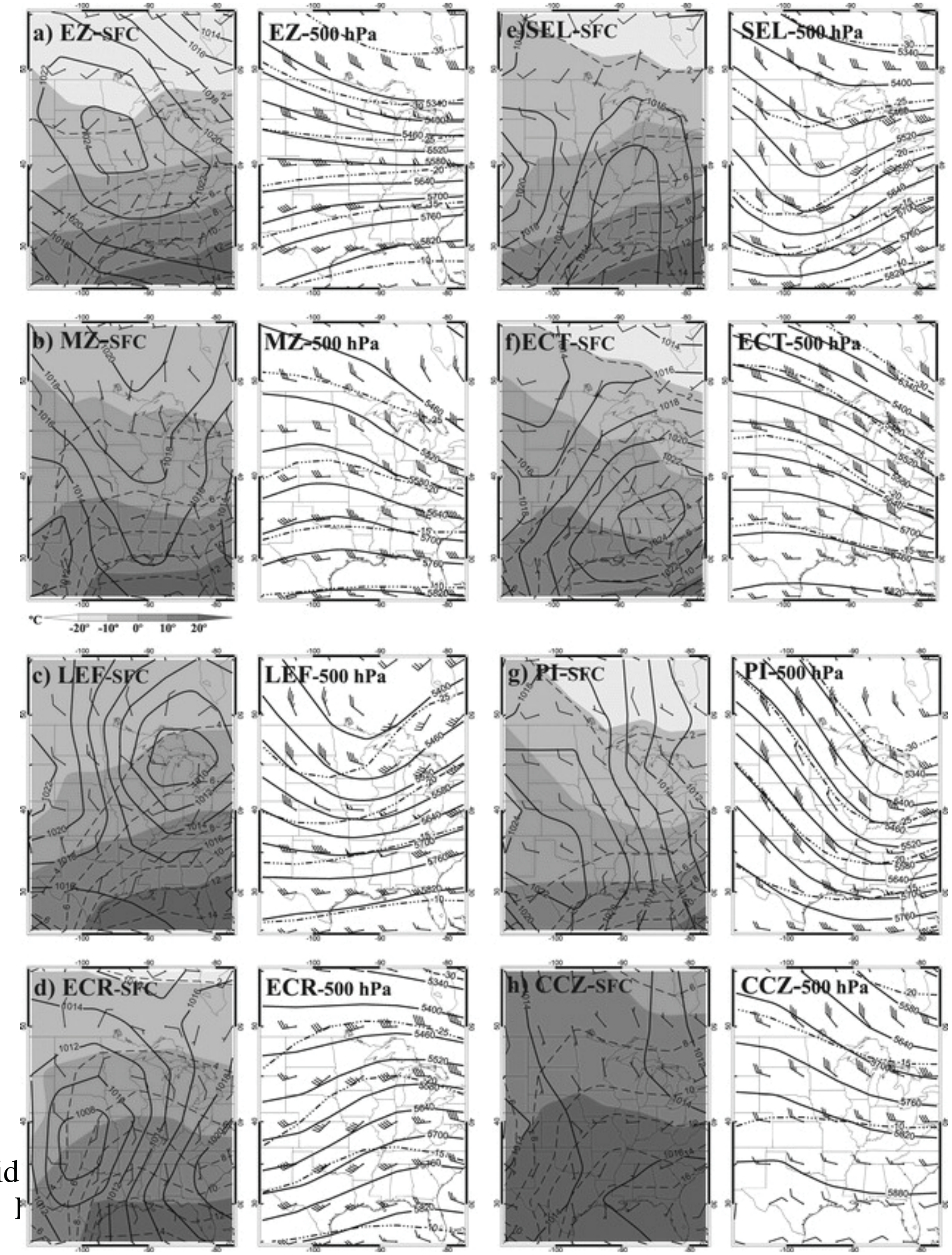
Anomalies of rainfall, SLP, Z700, surface wind, and SST for two weather regimes, compared to periods not in these regimes

Coleman, Jill S. M., Jeffrey C. Rogers, 2007: A Synoptic Climatology of the Central United States and Associations with Pacific Teleconnection Pattern Frequency. *J. Climate*, **20,** 3485–3497.

"A synoptic climatological weather classification scheme incorporating both surface and upper-air data is developed for the central United States based on an automated two-step cluster analysis. It employs daily NCEP–NCAR reanalysis data over all seasons of 57 yr (1948–2004) in creating synoptic types from surface and upper-air (925, 850, 700, and 500 hPa) temperature and humidity data as well as sea level pressure, geopotential heights, and winds aloft. The cluster analysis creates 10 synoptic types …"

.

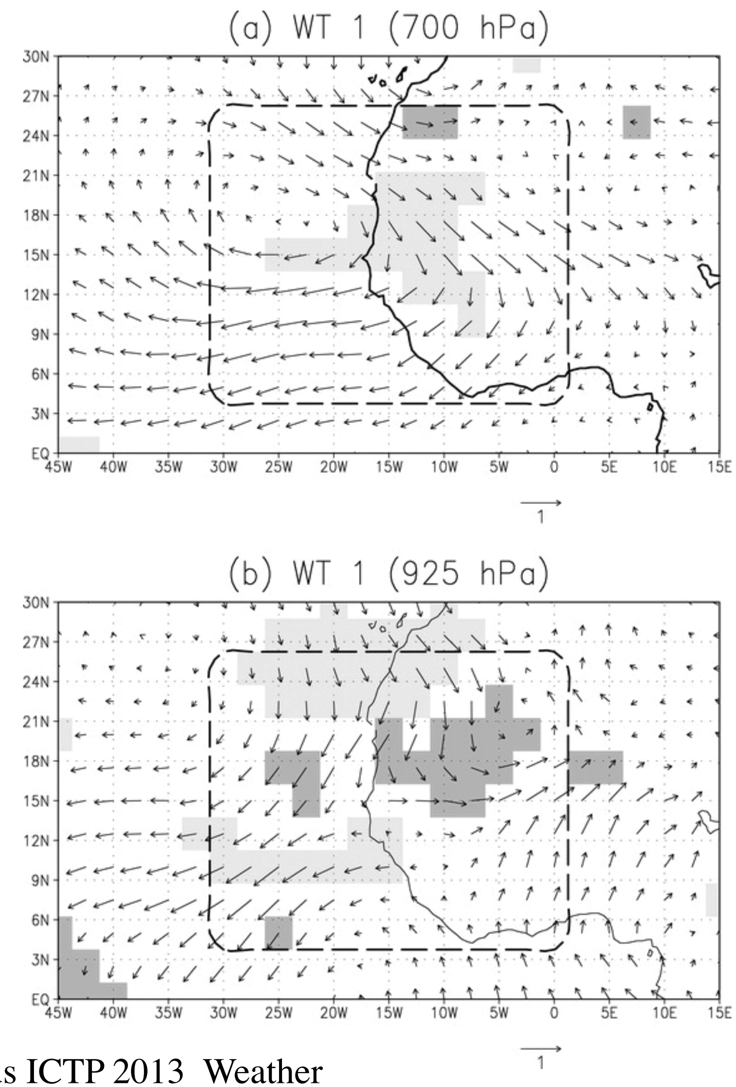
Mean meteorological conditions for each synoptic situation at the surface (sfc) and 500 hPa. Mean temperature (°C) are shown either as shaded contours in 10°C intervals on the surface plots or as dashed–dotted lines (5°C) intervals on the 500-hPa plots. Single dashed lines on surface plots are mean specific humidity (g kg−1). Solid lines indicate mean SLP in hPa for the surface plot or mean geopotential height in m for the 500-hPa level. Mean wind direction and speed, given in kt, are shown as wind barbs at each grid point

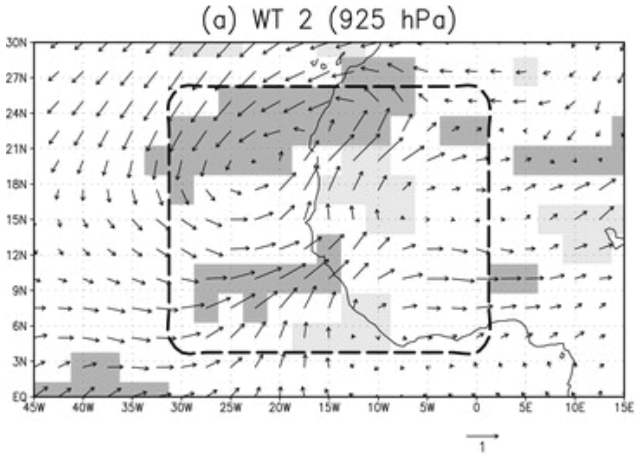


David

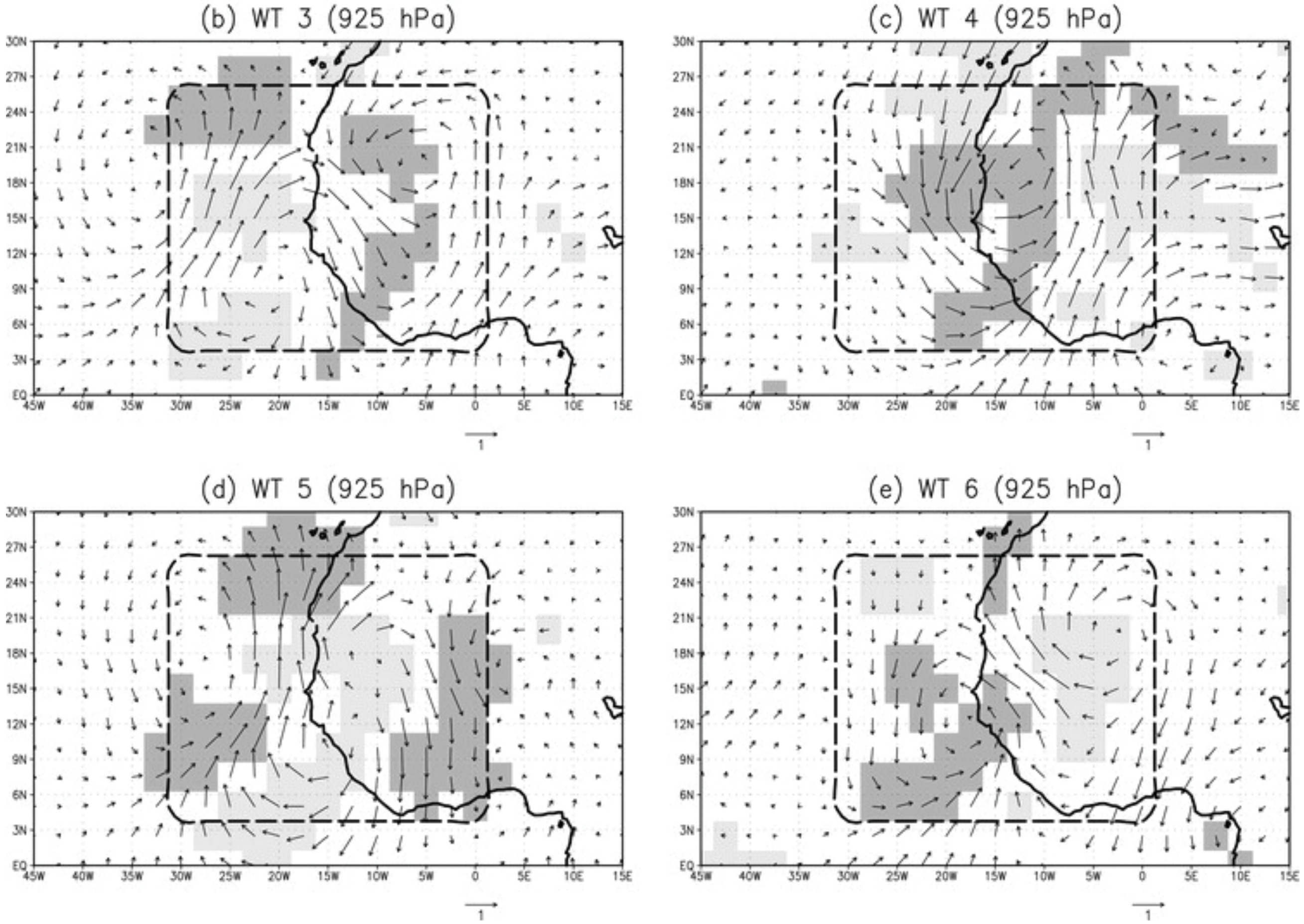
Moron, Vincent, Andrew W. Robertson, M. Neil Ward, Ousmane Ndiaye, 2008: Weather Types and Rainfall over Senegal. Part I: Observational Analysis. *J. Climate*, **21**, 266–287.

Composite maps of (a) 700- and (b) 925-hPa anomaly winds of weather type 1. Shading indicates composite anomalies of divergence greater than 0.25 (light) and less than –0.25 (dark) Positive (negative) values indicate anomalous divergence (convergence). The weather types are computed from wind data in 2.5°–27.5°N, 30°W–0° delineated by a dashed black box.





Composite maps of 925-hPa anomaly winds for (a) WT 2, (b) WT 3, (c) WT 4, (d), WT 5, and (e) WT 6. Shading indicates composite anomalies of divergence greater than 0.25 (light) and less than −0.25 (dark).



Are regimes a useful concept? - Yes!

- In characterizing North Atlantic Ultra-High Frequency (storm-related) variability in preparation for FASTEX*, Aryrault et al (2005) found that "The concept of weather regime is central to any statistical approach of European weather systems." Here weather regimes were identified by a cluster analysis of 700 hPa height in the Atlantic reigon (similar to that of Vautard, 1990).

- Joly et al (1999) found that regimes were useful in discussing the organization of the large scale flow during FASTEX*

- In assessing basic measures of skill for ECMWF ensemble winter forecasts, Chessa and Lalaurette (2001) found the same clusters to be useful in categorizing forecast skill

- Two other examples presented below in detail

FASTEX* = Fronts and Atlantic Storm-Track EXperiment

References:

Ayrault, F., F. Lalauretter, A. Joly and C. Loo, 1995: North Atlantic ultra high frequency variability. *Tellus*, **47A**, 671-696.

Chessa, P. A. and F. Lalaurette, 2001: Verification of the ECMWF Ensemble Prediction System Forecasts: A Study of Large-Scale Patterns. *Weather and Forecasting*, **16**, 611-619.

Joly, A., and co-authors. Overview of the field phase of the Fronts and Atlantic Storm-Track EXperiment (FASTEX) project. *Quart. J. Royal Meteor. Soc.,* **125**, 3131-3164

Interaction of Circulation Regimes and Weather Regimes

(or)

Interaction of Large Scale Flow and Extreme Weather

European Heat Wave Summer 2003*

Responsible for massive over-mortality and tremendous socioeconomic impacts in many European countries

General Relationship of Summer Atlantic Regions Circulation Regimes to surface temperature anomalies over France

Correspondence between two waves of European Summer 2003 Heat Wave and Circulation Regimes

*Cassou, Christophe, Laurent Terray, Adam S. Phillips, 2005: Tropical Atlantic Influence on European Heat Waves. *J. Climate*, **18**, 2805–2811.
doi: http://dx.doi.org/10.1175/JCLI3506.1

Cassou and Terray, 2005: J Clim, 18, 2805-2811

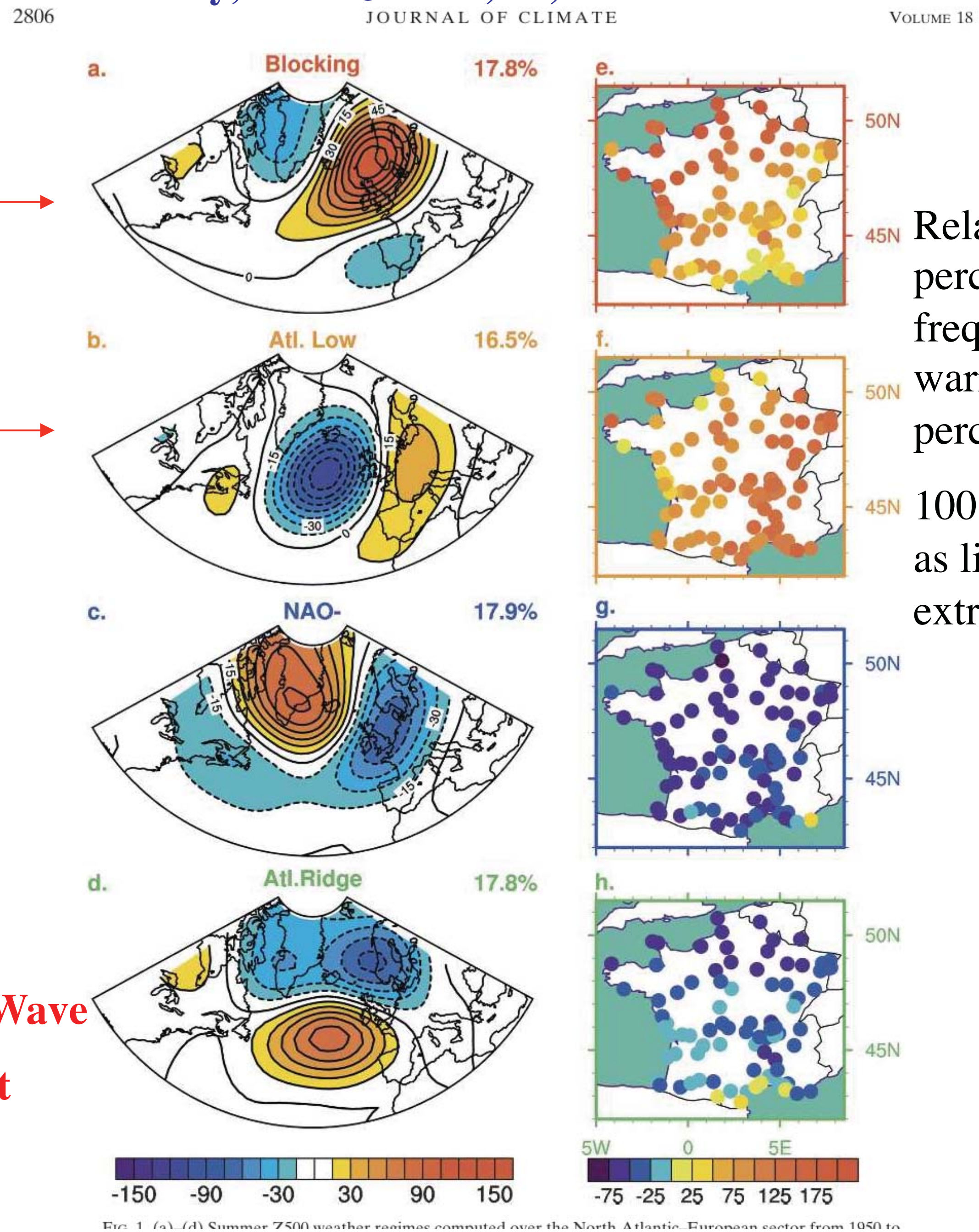
Early Aug 2003 - Blocking

June 2003 - Atl. Low

Clusters (regimes) of *daily* 500 Z from 1950-2003 JJA (CI=15m)

2003 European Heat Wave

June and early August extreme T



Relative changes (in percent) in the frequency of extreme warm days (95% percentile):

100% means twice as likely to have extreme warm day

The Role of High- and Low-Frequency Dynamics in Blocking Formation

Hisashi Nakamura, Mototaka Nakamura, Jeffrey L. Anderson
Monthly Weather Review
Volume **125**, Issue 9 (September 1997) pp. 2074-2093

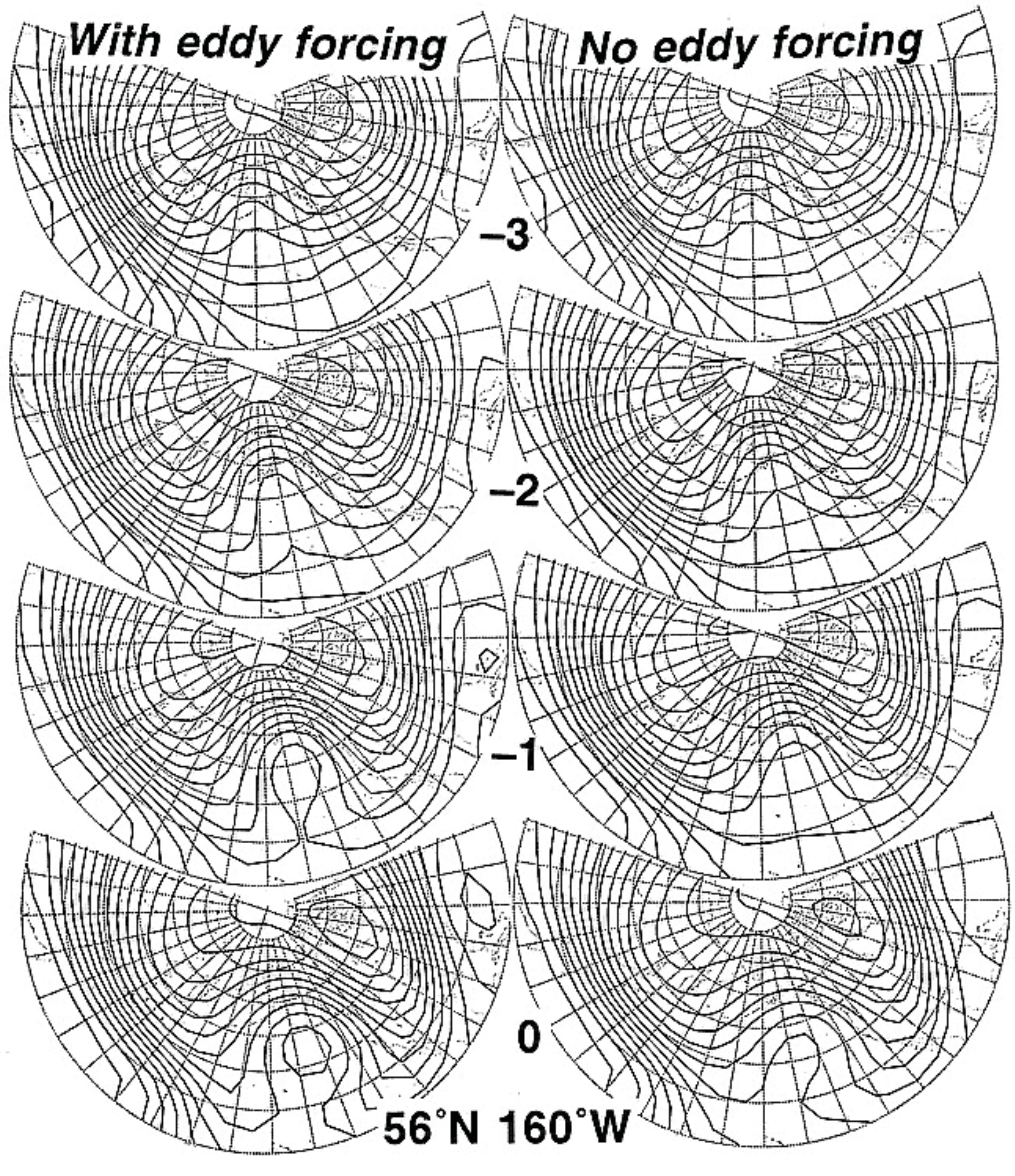
High Frequency Forcing of Blocking Events:

$$\left(\frac{\partial Z_{250}}{\partial t}\right)_{HFT} = \frac{f_0}{g}\nabla^{-2}\left[-\vec{\nabla}\bullet\left(\overline{v'\zeta'} + \overline{\bar{v}\zeta'} + \overline{v'\bar{\zeta}}\right)\right]$$

$\bar{v}$ = 8 – day running mean of meridional wind (Low Frequency)

v' = deviation from 8-day running mean (High-Frequency)

- Strong blocking episodes for locations of interest were identified from reanalysis. - 15 strongest blocking events were composited
-- E1: Use the composites of PV250 at day –4 to initialize the PV contours and then advected them by the geostrophic wind derived from composite Z250
-- E2: Same initial PV field, but the advecting geostrophic wind was derived from the hypothetical Z250 composites from which the transient feedback had been removed.


With eddy forcing
No eddy forcing
–3
–2
–1
0
56°N 160°W

Circulation Regimes – Diagnostic Analysis

"Baroclinic Eddy Mediated Cluster Analysis"

[Straus, D., 2010: Synoptic-Eddy Feedbacks and Circulation Regime Analysis, ***Mon. Wea. Rev.*** Volume 138, Issue 11 (November 2010) pp. 4026-4034]

- Explicit (statistical) linking of low frequency fluctuations and the low frequency *modulation* of baroclinic eddies ("storm tracks")

- Low frequency fluctuations ($\tau > 10$ days): filtered 200 Z fields

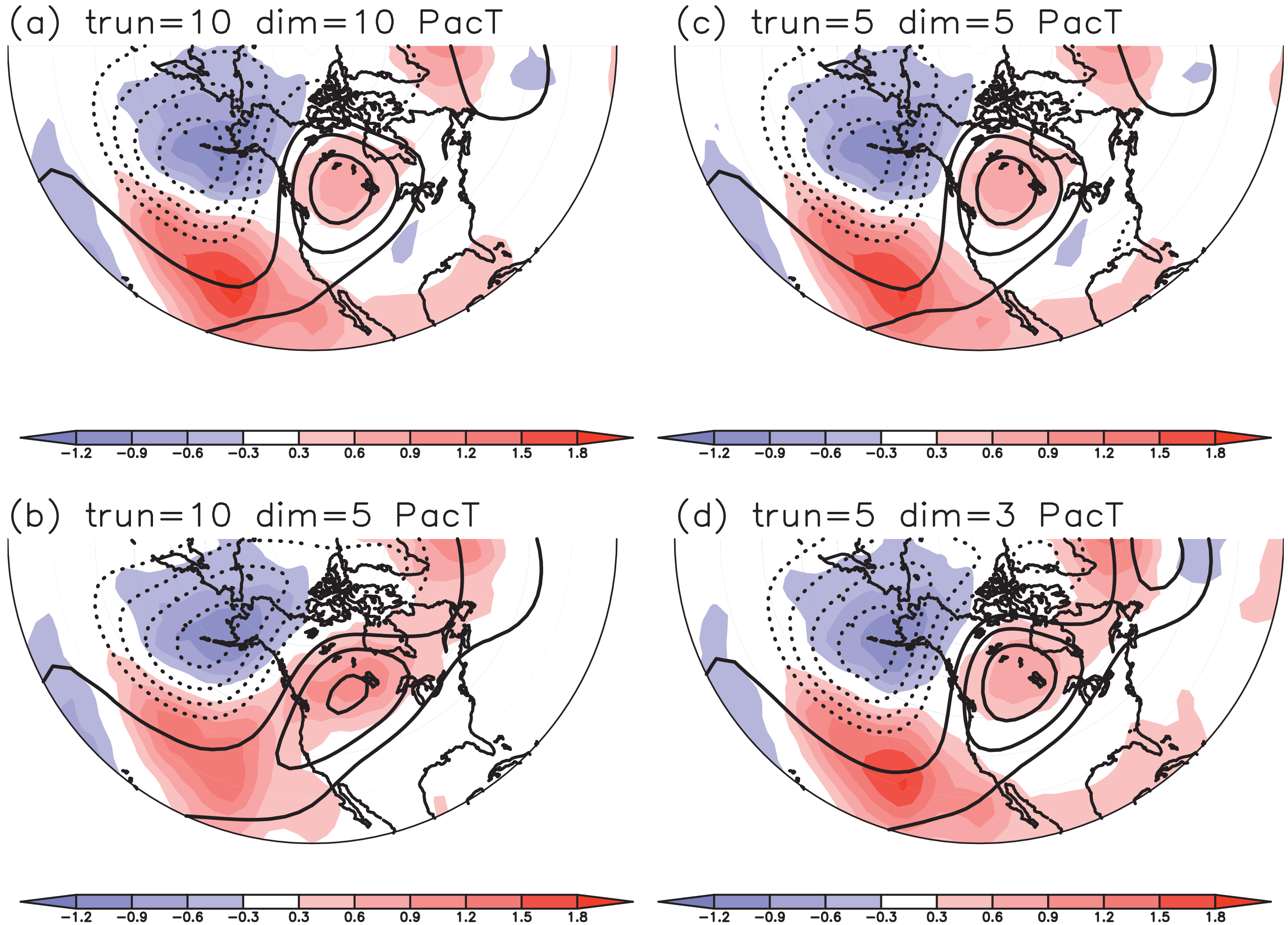
- Baroclinic eddy measure is 200 hPa filtered ($\tau < 10$ days) meridional velocity v (emphasizes– higher wavenumbers)

- Low frequency modulation of baroclinic eddies obtained by "envelope function" of $v_{rms} = (v^2)^{(1/2)}$

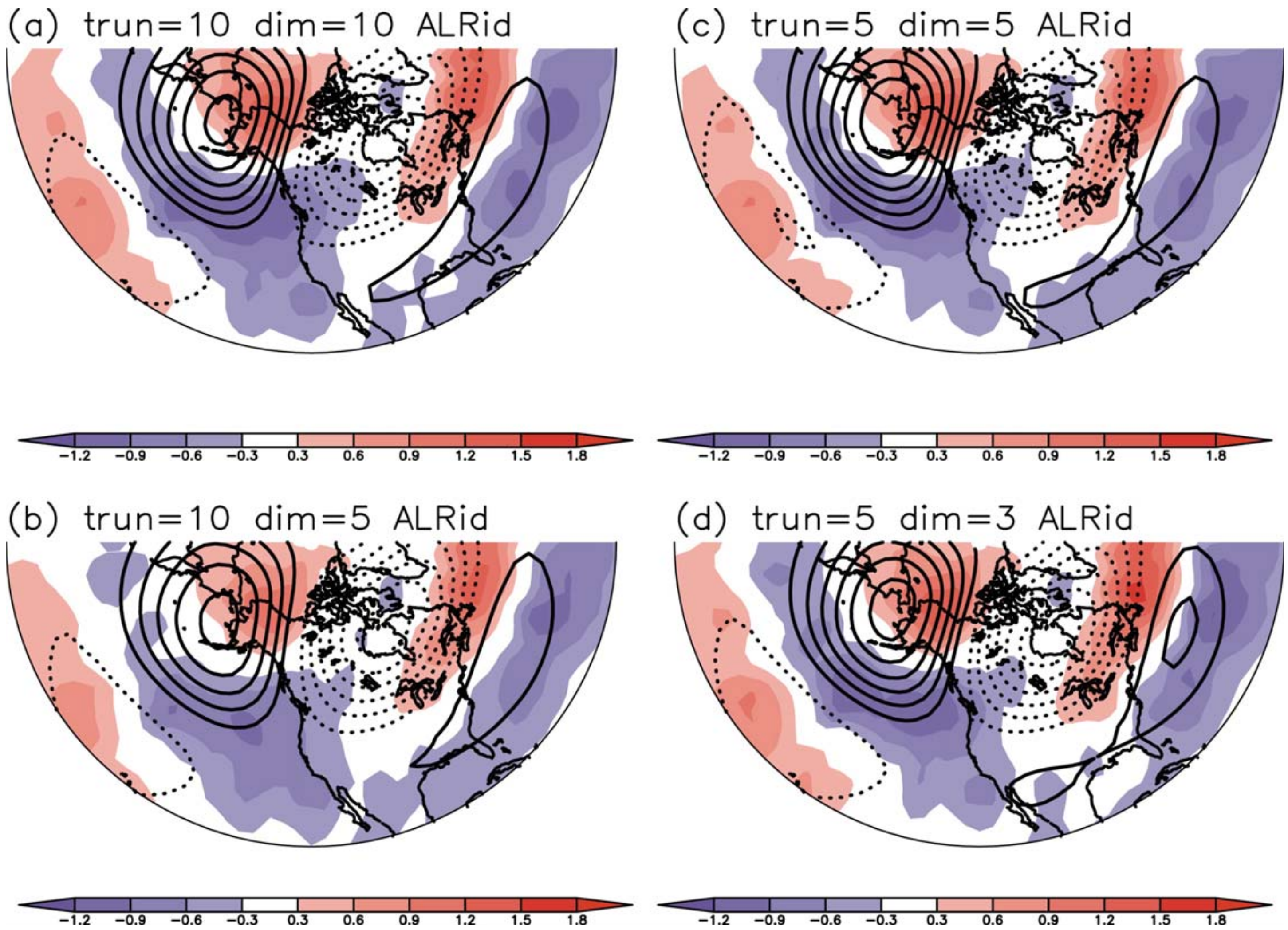
- Linkage between baroclinic eddy envelope function and low frequency takes the form of maximum covariance (singular vector) analysis

- Coefficients subject to cluster analysis to obtain the regimes

First of four cluster patterns "Pacific Trough" obtained by compositing fields in one cluster
Contours = Z 200 (CI = 30 m) ; shading = envelope v field = $(v^2)^{(1/2)}$



"trun" = number of PCs in SVD; "dim" = number of SVDs in clustering


(a) trun=10 dim=10 ALRid
(c) trun=5 dim=5 ALRid
−1.2 −0.9 −0.6 −0.3 0.3 0.6 0.9 1.2 1.5 1.8
(b) trun=10 dim=5 ALRid
(d) trun=5 dim=3 ALRid