Circulation Regimes
Bridging Weather and Climate Predictability
Promises and Challenges

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Mid-Latitude Low Frequency Variability

in terms of Regimes = "Preferred Large Scale States"

(1) Assumptions of linear pattern analysis

(2) Any evidence for strong non-linear behavior?

(3) Low-Order Dynamical Systems (bit of history)

(3) Circulation Regimes - a useful concept for relating climate to weather

(4) Often not enough observed data (!) - need GCMs

(5) Relationship to Boundary Forcing - SST

(6) Regime Behavior and Error Growth in the CFS IE

Linear Approach to Intra-Seasonal Variability (τ = 10-90 days)

Simple Pattern Techniques:

Teleconnection Patterns

Empirical Orthogonal Functions

Rotated Empirical Orthogonal Functions

Empirical (Orthogonal) Teleconnection Patterns

all part of a continuum? (Franzke and Feldstein, 2005)

Propagating Pattern Techiques:

Complex Empirical Orthogonal Functions

Extended Empirical Orthogonal Functions (Multi-Channel Singular Spectrum Analysis)

Principal Oscillation Patterns

Empirical Normal Modes

Properties of Linear Approach

All patterns symmetric about climate mean

Each phase occurs with equal probability

No intrinsic time information in teleconnection patterns

A simple null hypothesis for the pdf - the mean state is the most probable state

Gives rise to (slightly ridiculous) debates, such as NAO vs. AO.

Planetary-Scale Wave Amplitude Index:

An old problem re-examined*:

Is its pdf bimodal?

WAI = measure of integrated PW strength across mid-latitudes

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

Daily Data →

Slow variation in WAI →

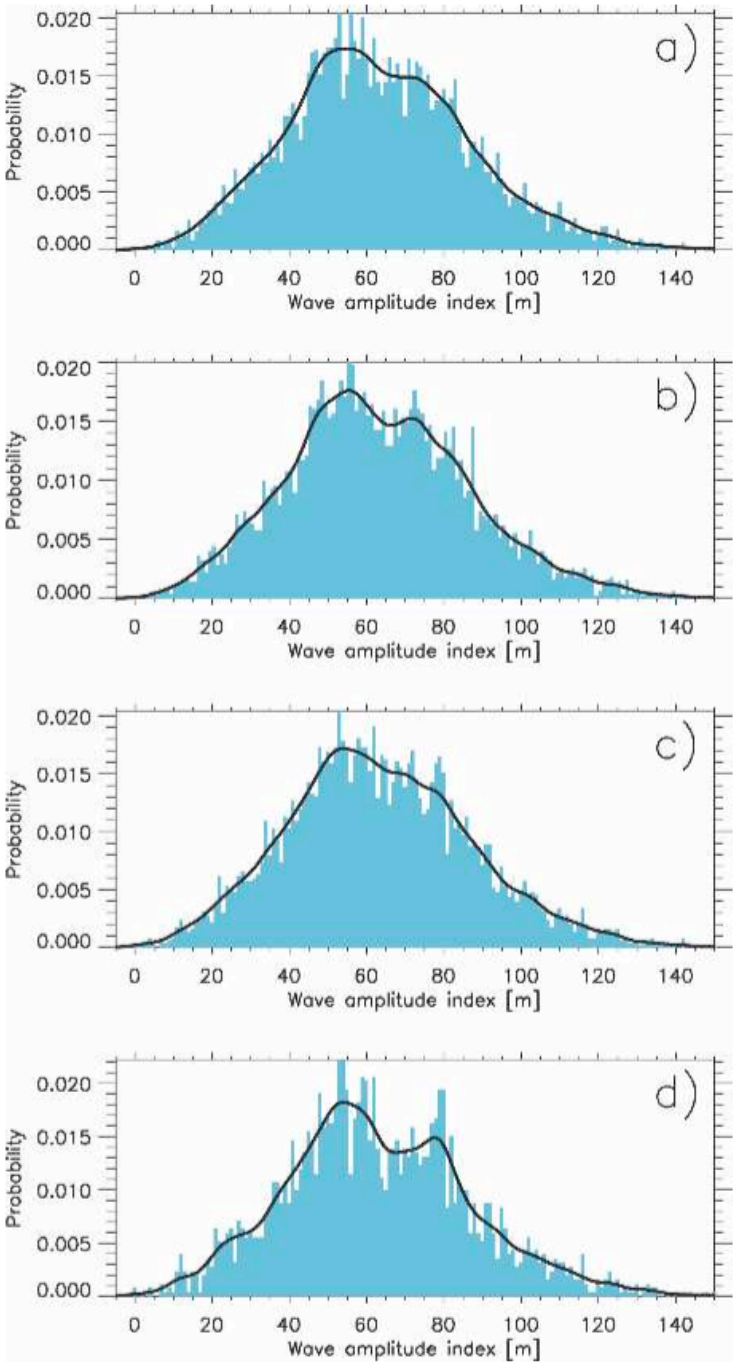

FIG. 1. Probability density of the WAI for the winter days in the period 1948–2003 calculated as a kernel density estimator with a

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

Physical Motivation for Regime, 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
(Synoptic 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).**

Multiple Flow Equilibria in the Atmosphere and Blocking[1]

Regimes in low-order models (dynamical systems) motivated by Grosswetterlagen

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ABSTRACT

A barotropic channel model is used to study the planetary-scale motions of an atmosphere whose zonal flow is externally driven. Perturbations are induced by topography and by a barotropic analogue of thermal driving. The use of highly truncated spectral expansions shows that there may exist a multiplicity of equilibrium states for a given driving, of which two or more may be stable. In the case of topographical forcing, two stable equilibrium states of very different character may be produced by the same forcing: one is a "low-index" flow with a strong wave component and a relatively weaker zonal component which is locked close to linear resonance; the other is a "high-index" flow with a weak wave component and a relatively stronger zonal component which is much farther from linear resonance. It is suggested that the phenomenon of blocking is a metastable equilibrium state of the low-index, near-resonant character. The existence of the two types of equilibria has been confirmed by numerical integration of a grid-point model with many more degrees of freedom than the spectral model.

It has also been found spectrally and for a grid-point model that oscillations may occur when one of the equilibrium states is stable for the lowest order spectral components but unstable for the next higher order components. The oscillation apparently is due to a barotropic instability of the topographic wave of the kind discussed by Lorenz and Gill.

Thermal forcing also produces multiple, stable equilibria in a spectral model but confirmation with a grid-point model has so far not been obtained.

1. Introduction

It is common to regard the flow of the atmosphere as a quasi-stationary circulation of large scale on which are superimposed transient wave and vortex disturbances of smaller scale originating as instabilities of the mean flow and interacting with it. The mean or equilibrium state is often thought of as a Hadley circulation perturbed by fixed topographic and thermal asymmetries of the lower boundary. But this description, while it has permitted a qualitative explanation of many of the observed features of the global circulation, has left others entirely unexplained. In particular it has not accounted for the persistence of large amplitude flow anomalies such as blocking. Nor has it explained the existence, well-known to synoptic meteorologists, of the persistent or recurrent regional weather patterns or types exemplified by the *grosswetterlage* of Baur (1951).[4] Do such patterns originate from the interaction of smaller scale instabilities with a single large-scale equilibrium flow?

We wish to answer this question in the negative by presenting evidence that suggests that there is a *multiplicity* of stationary or oscillatory states, each presumably with its own class of smaller scale instabilities and each presumably capable of undergoing transition with the aid of these instabilities from one to another. We do so by analyzing a simple model of a barotropic atmosphere in which an externally forced zonal flow interacts nonlinearly with topography and with externally forced wave perturbations. We show that in each case there is a

Circulation Regimes

Notion that weather regimes involve mutual feed-back between the (quasi-stationary) large scales waves and the smaller-scale baroclinic, synoptic disturbances was developed theoretically by Reinhold and Pierrehumbert (1982) and Vautard and Legras (1988).

The feedback from the baroclinic waves to the planetary waves can be parameterized:

Purely dynamically (RP)

Semi-empirically (VL)

Completely statistically (multiplicative noise: Sura, Newman, Penland and Sardeshmukh, 2004: J. Atmos. Sci., 62, 1391-1409)

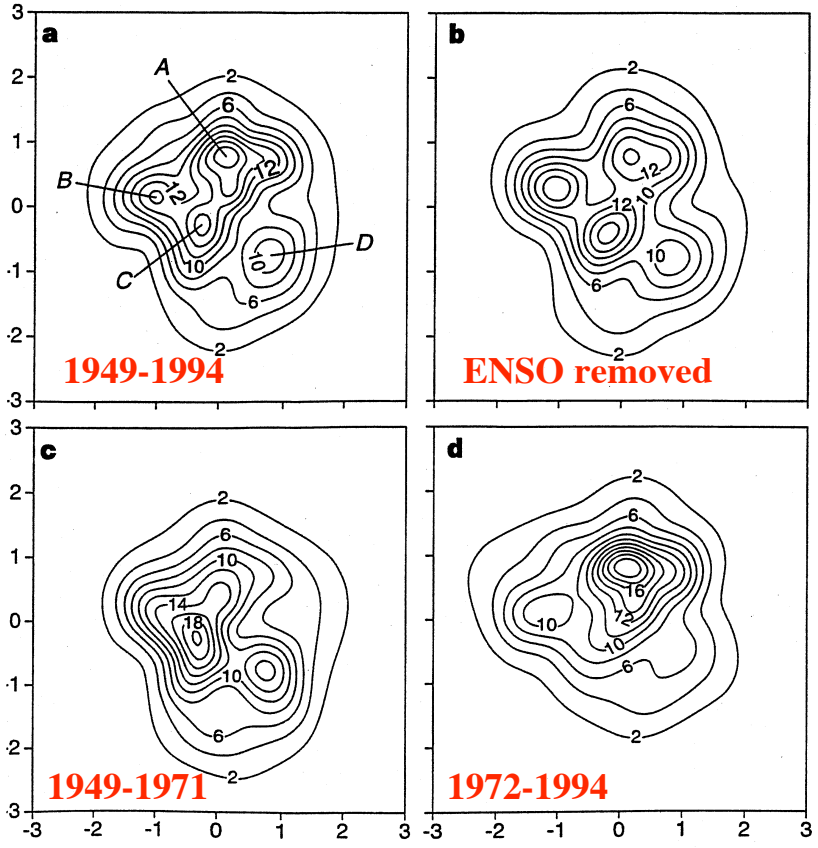
Circulation Regimes

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

Data:

Nov - Apr monthly mean 500 hPa Z from NCEP reanalysis for 46 years (49-94)

(detrended)



Plots:

2-d pdf of leading PCs

Illustration of Palmer (1997) hypothesis: Climate change seen only as difference in population of fixed regimes.

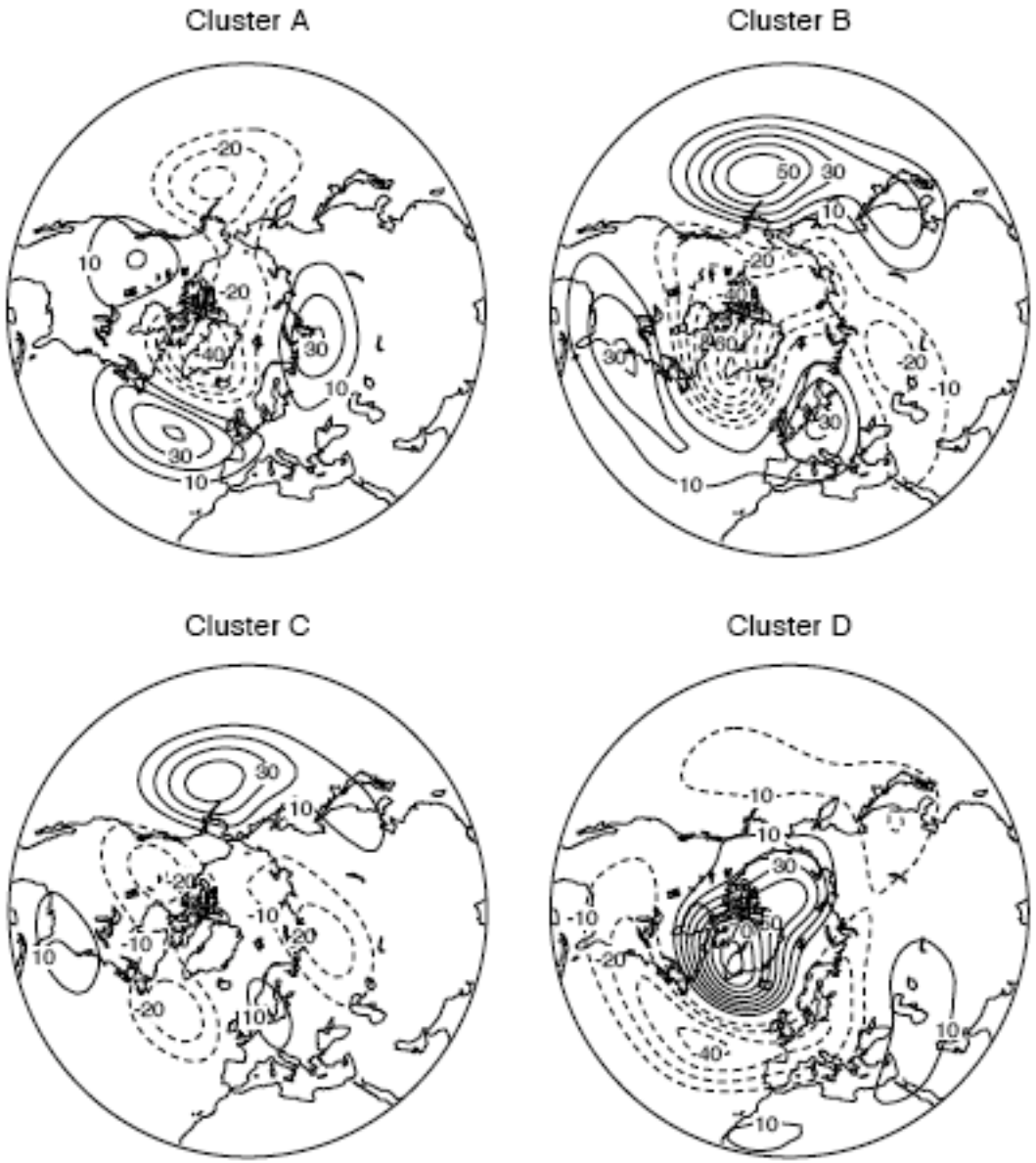
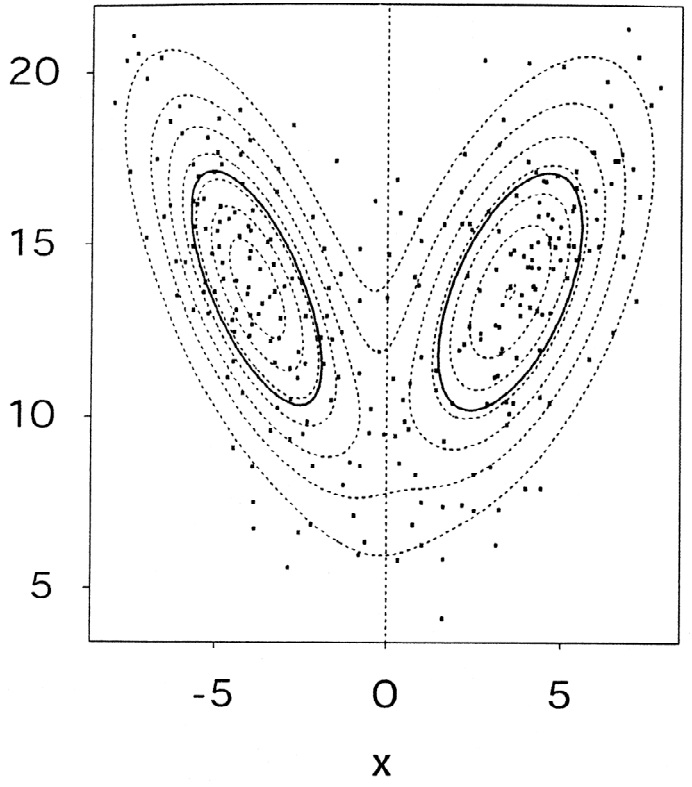


Figure 3 Geographical patterns of the four atmospheric regimes. Shown is the geographical distribution of 500-hPa geopotential height anomaly associated with clusters A (The ''cold ocean warm land'' regime) B, C and D (the "Arctic Oscillation'' regime). Contour interval, 10 m.

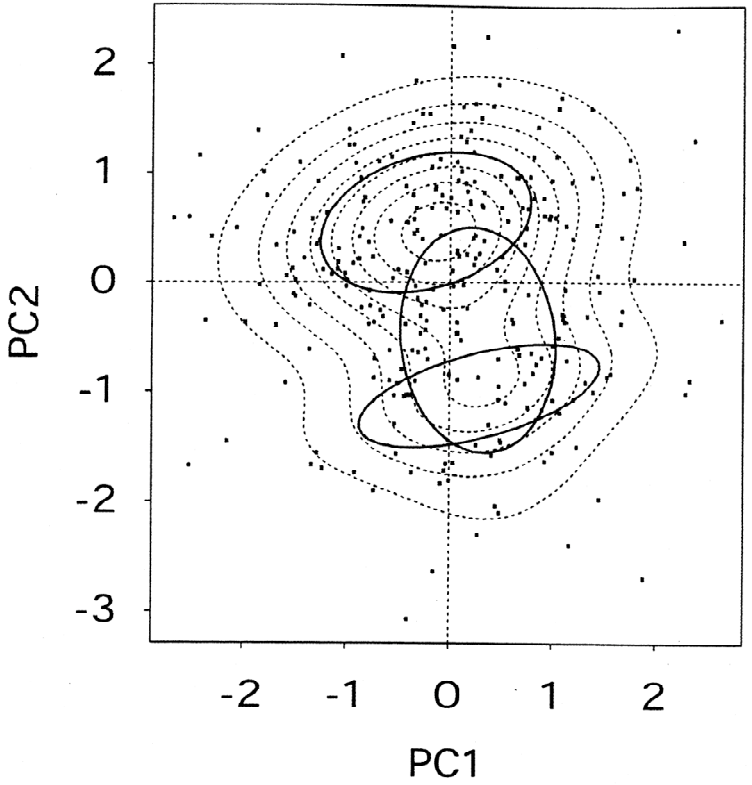
Rigorous Statistical Tests Needed to Reject a Null Hypothesis of Multi-Normal (multi-variate Gaussian) pdf

(Stephenson, Hannachi, and O'Neill, 2004: *QRMS*, **130**, 583-605)

Lorenz 3-component model: Passes the Test!



Monthly means from Obs: Fails the Test!



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

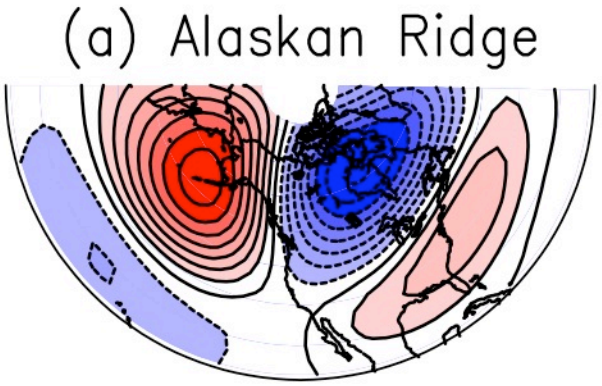
Global Significance of Circulation Regimes

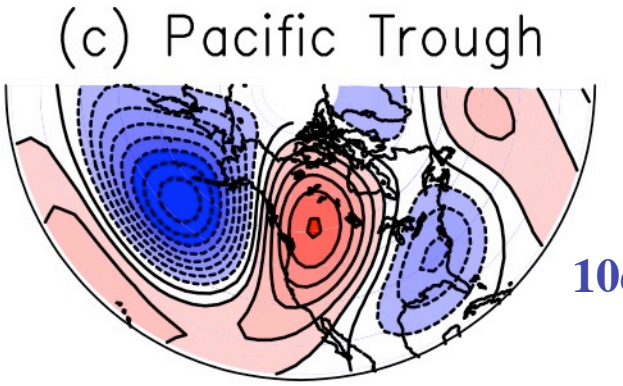
- **Oft-quoted paper by Toth in early 1990s shows that the distribution of daily 700 hPa Northern Hemisphere states from analyses is NOT significantly different from a multivariate normal distribution if the probability distribution is averaged over all angles, that is, considered as a function of the distance from the origin (or climate).**

- **Blue part of statement is often quoted- Green part is forgotten!**

- **In fact Toth (1993) found regions of the multi-dimensional pdf which are locally significantly different from a multi-normal pdf. (Quasi-stationary periods only were considered).**

Straus, Corti and Molteni, 2007 J. Climate





$10d < \tau < 90d$

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

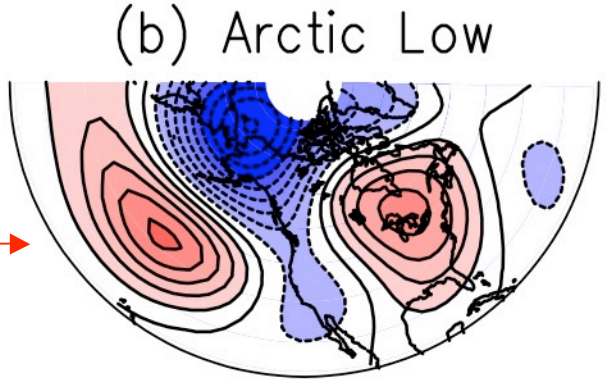
(a) Only quasi-stationary time periods used

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

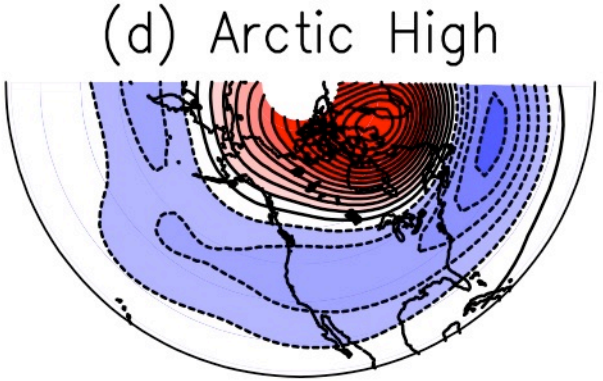
(c) Can not say whether 3 or 4 clusters is optimal

(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



least well-defined →



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

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

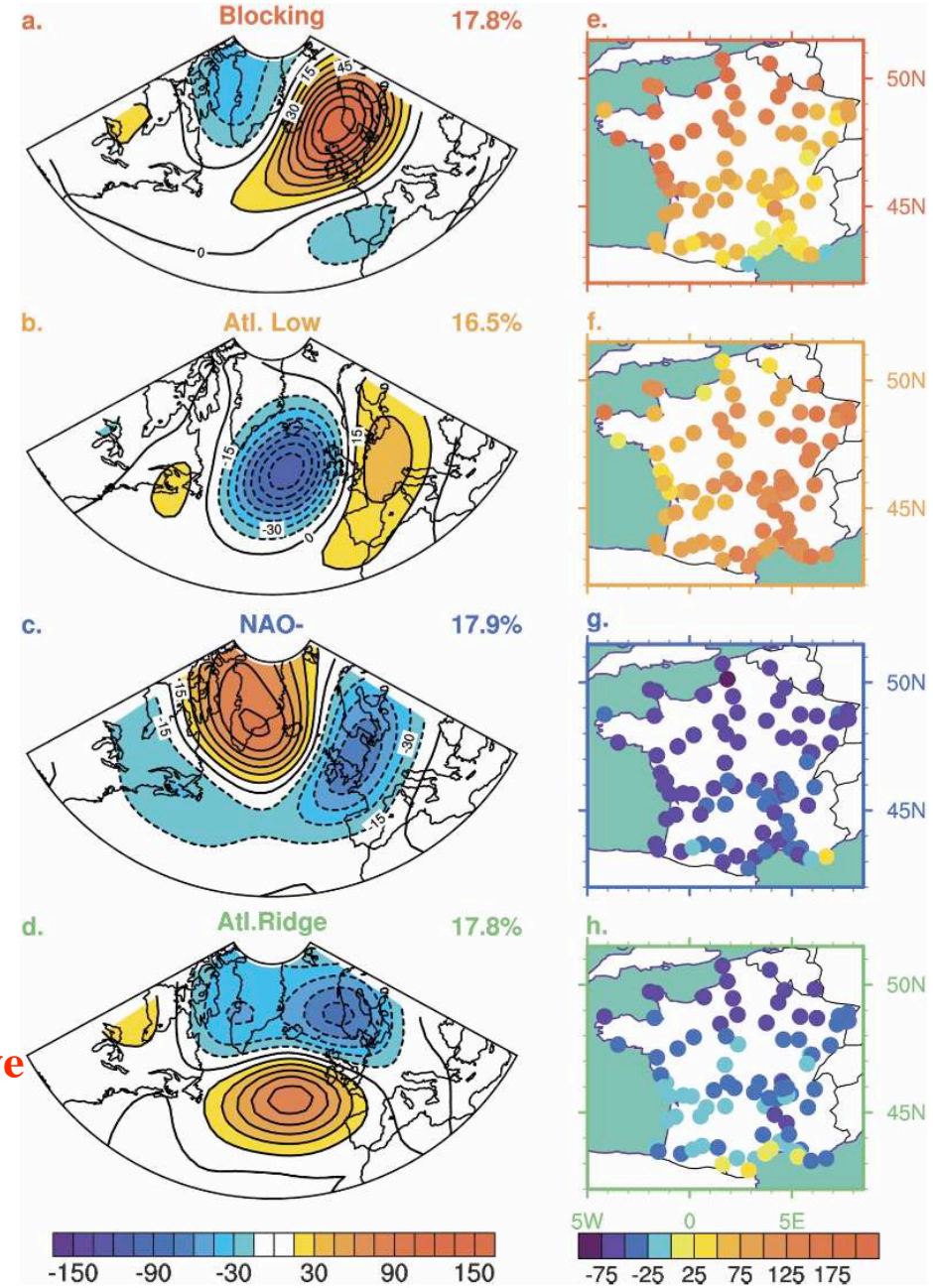


FIG. 1. (a)–(d) Summer Z500 weather regimes computed over the North Atlantic–European sector from 1950 to

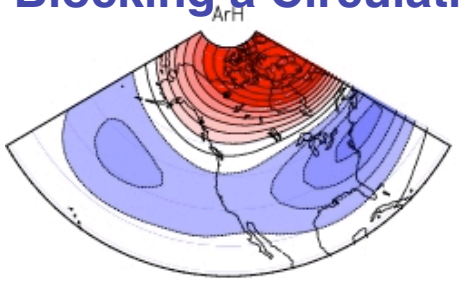
Relative changes (in percent) in the frequency of extreme warm days (95% percentile):

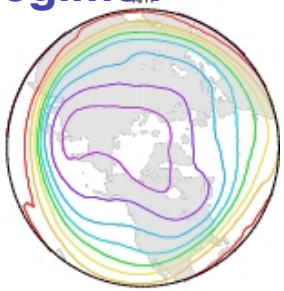
100% means twice as likely to have extreme warm day

Is Blocking a Circulation Regime?

Arctic High

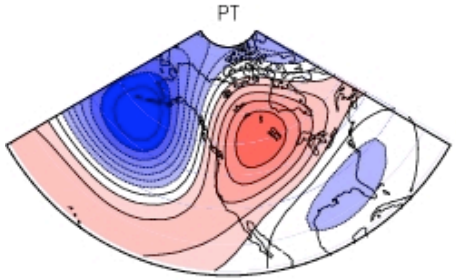
Stan, C. and D. M. Straus, *Monthly Weather Review* **135,** 2406–2413

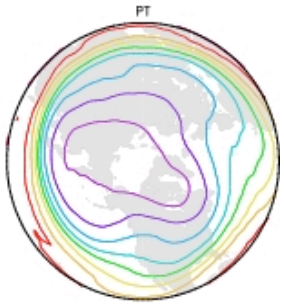


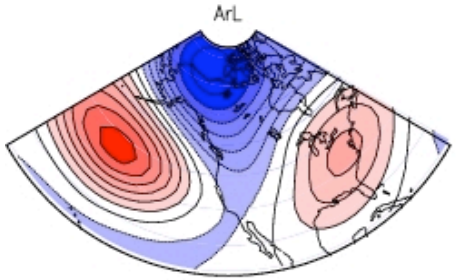


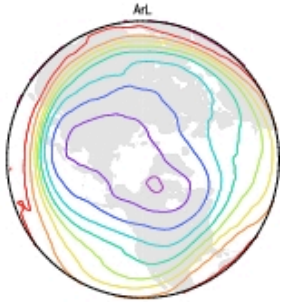
Corresponding potential temperature θ on PV = 2 surface (tropopause)

Pacific Trough

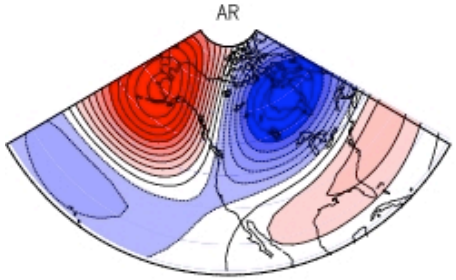


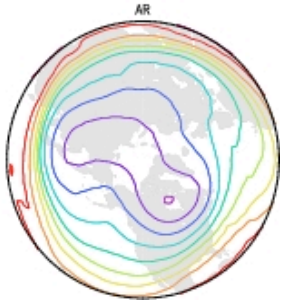




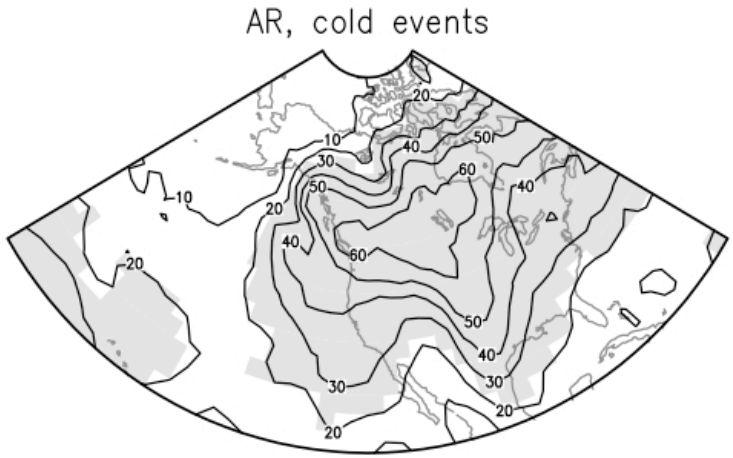


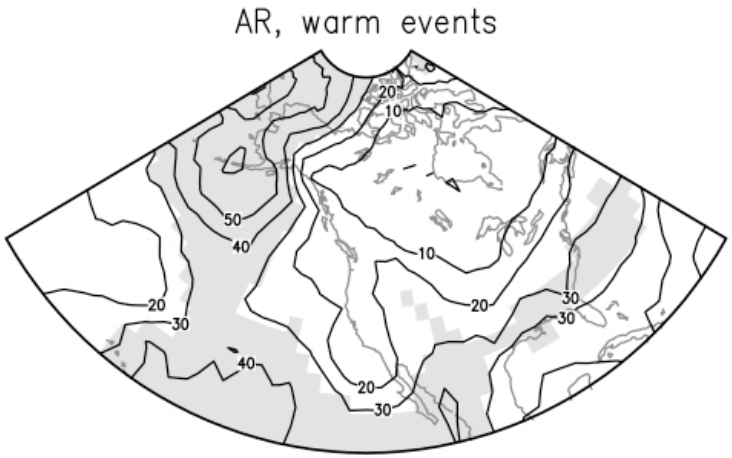
Alaskan Ridge





How often are extremely warm and cold days associated with the AR cluster?





Cold Events: Days for which

1000 hPa T is below 95% percentile

Warm Events: Days for which

1000 hPa T is above 95% percentile

Plots show percentage of extreme cold (warm) days for which the circulation is in the Alaskan Ridge regime

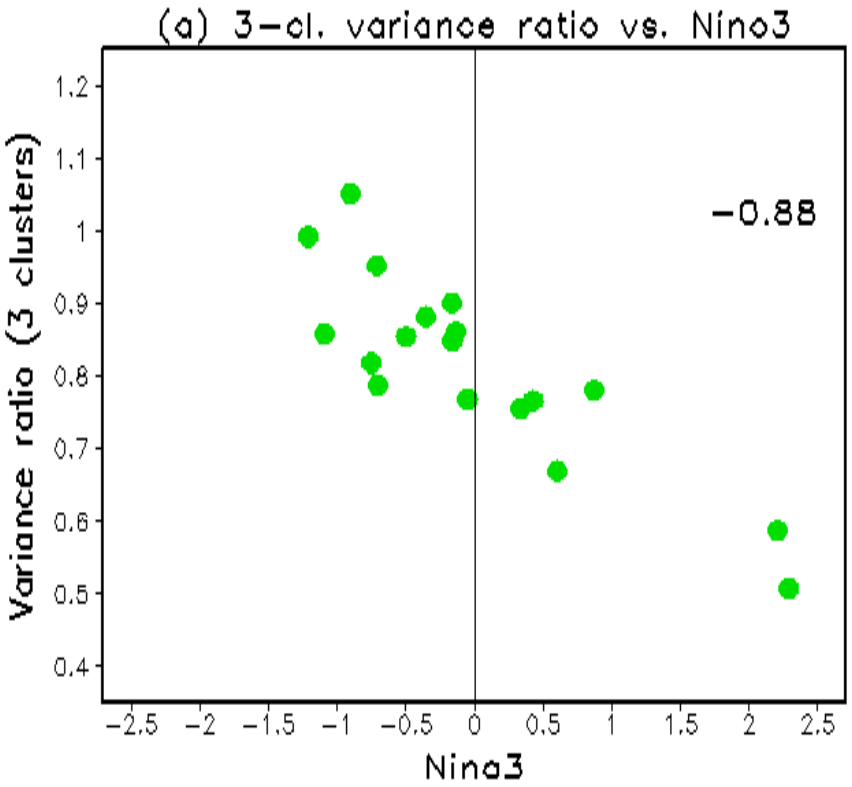
Palmer's hypothesis and inter-annual variability

Relationship to Boundary Forcing - Tropical SST

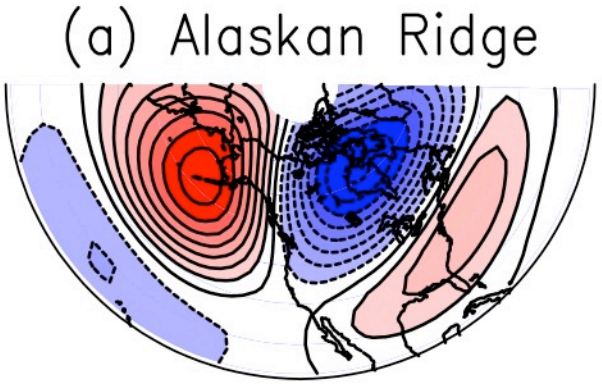
Examine "super-ensembles" of seasonal AGCM simulations made **with observed SST** for each of 18 recent winters. (Ensemble size = 55).

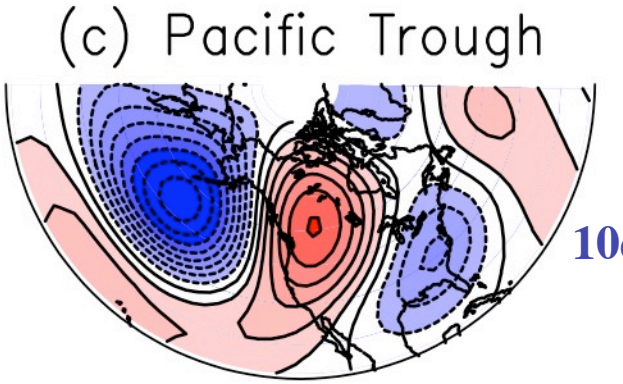
Cluster analysis on each winter (55 realizations) **separately** --> set of 18 independent analyses.

Results show significant clustering for each winter **except the warm ENSO winters** (El-Ninos): 1982/83, 1986/87 and 1997/98.



Straus and Molteni, 2004: Circulation Regimes and SST Forcing: Results from Large GCM Ensembles. *J. Climate*, **17,** 1641-1656.

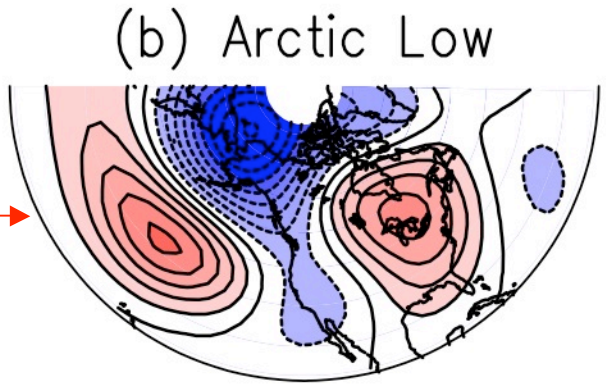




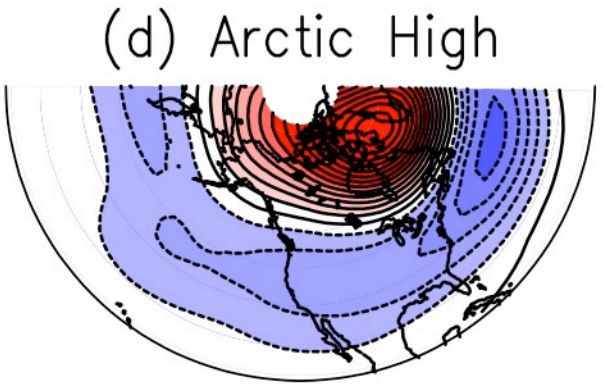
10d < τ < 90d

Relationship to Boundary Forcing in observations (NCEP54)

Straus, Corti and Molteni, 2007: Circulation Regimes: Chaotic Variability versus SST-Forced Predictability. *J. Climate*, vol. 20, pp. 2251–2272

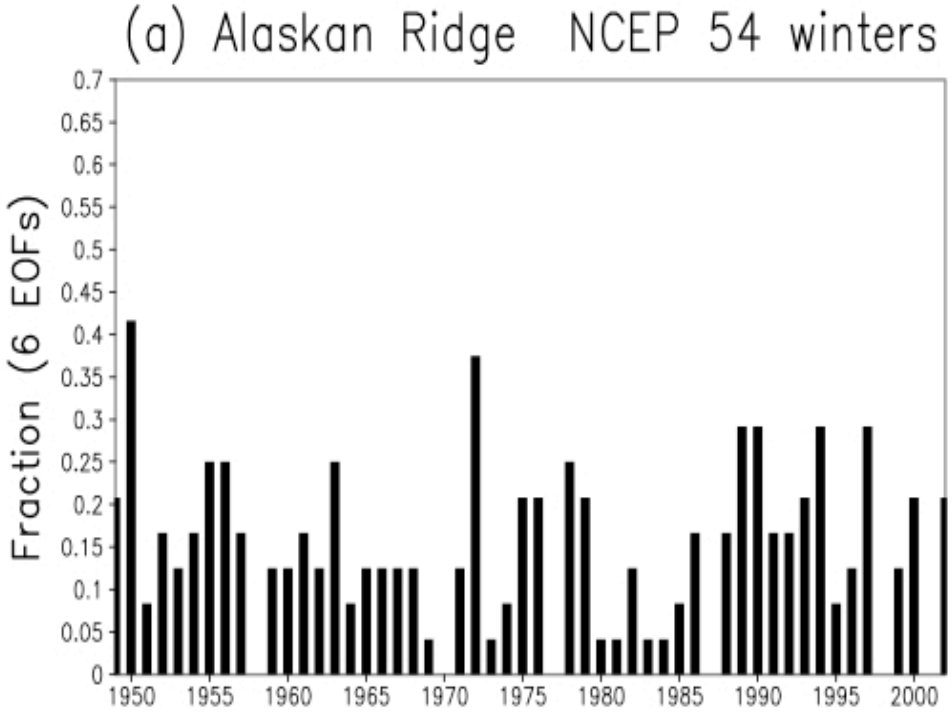


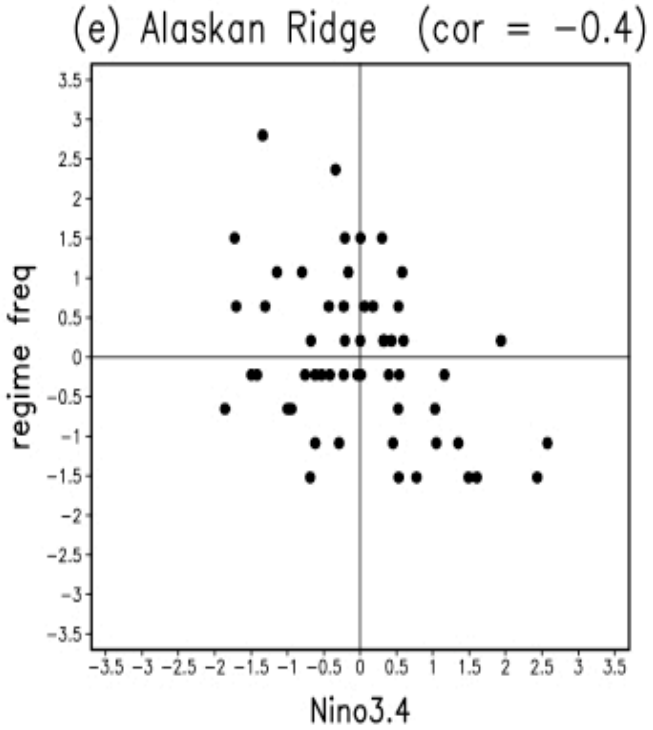
least well-defined →

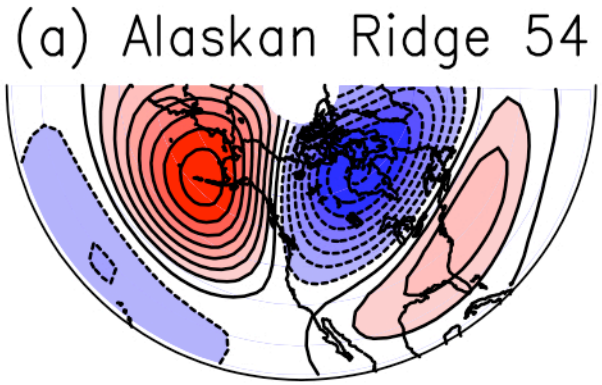


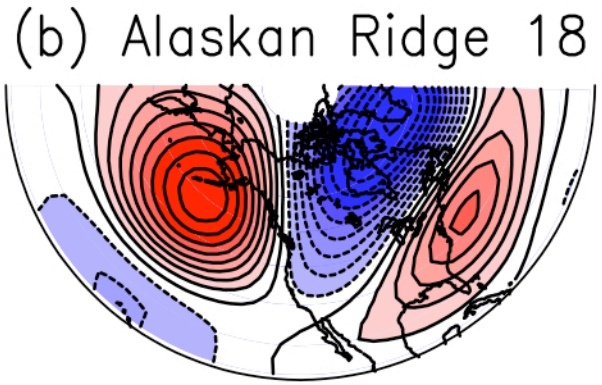
Relationship to Boundary Forcing - Tropical SST

Interannual Variation of Regime Population (Frequency of Occurrence







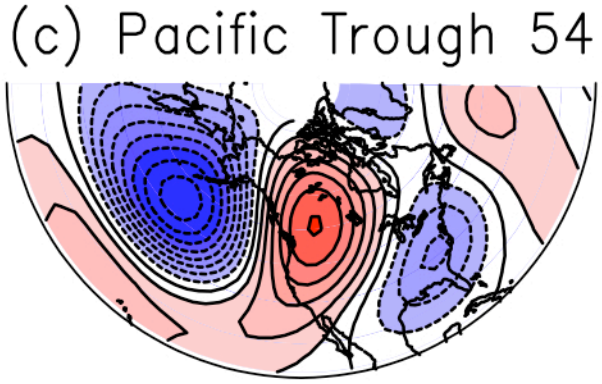


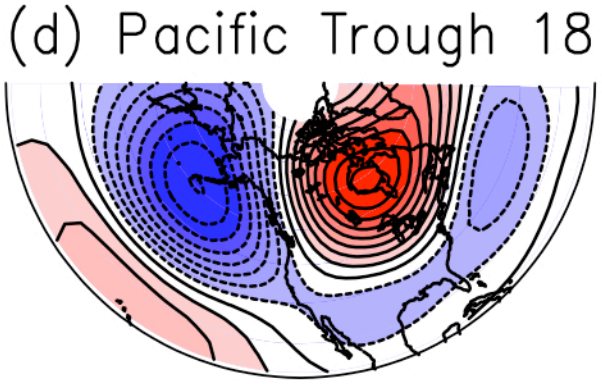
Lets compare these "NCEP54" preferred patterns "Alaskan Ridge" and "Pacific Trough" with analogous states obtained for a shorter, more recent 18 winter record (81/82-98/99)

Is the change from "PNA"-like to "ENSO"-like a real effect?

With only 18 winters there is no way that statistical significance can be established!

We use GCM "super-ensemble" simulations (55 members per winter for each of the same 18 winters with obs SST) to establish significance for the change in pattern!





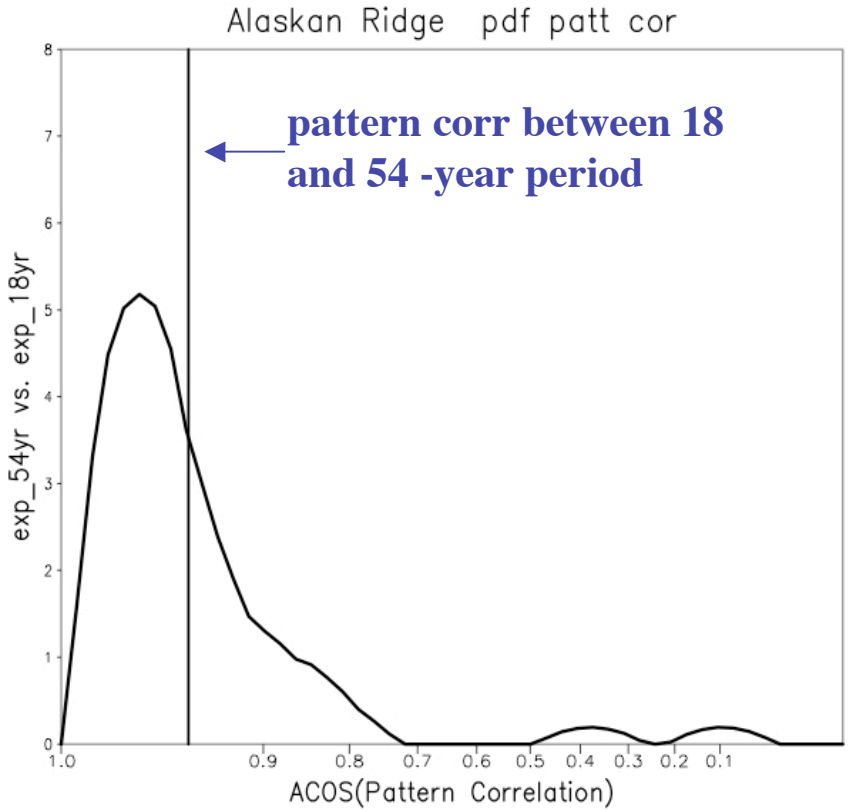
From 18 x 55 simulations, pick many "paired samples"

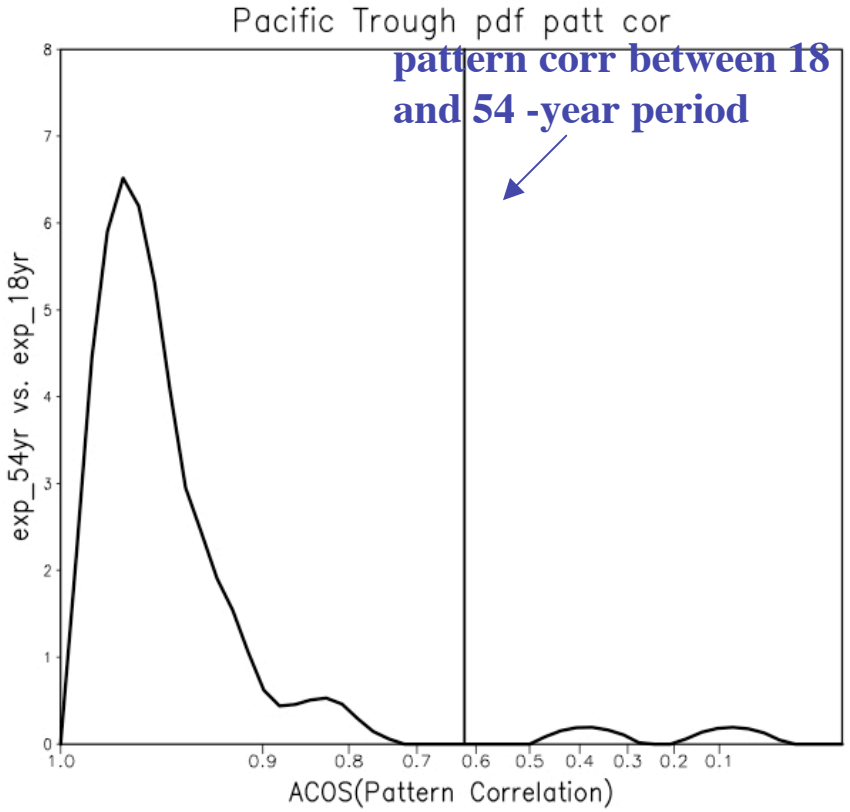
Sample A - 1 simulation (out of 55) per winter, for each of 18 winters - size 18

Sample B - 3 simulations (out of 55) per winter, for each of 18 winters - size 54

Each Sample A (B) equivalent to NCEP18 (NCEP54) record, ***but SSTs are the same!***

Difference between two sets of paired samples is due to ***internal variability*** *only!*

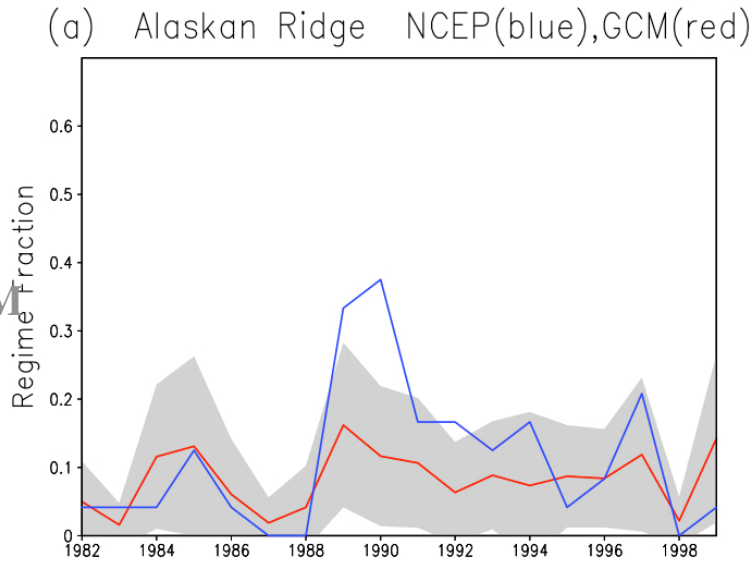




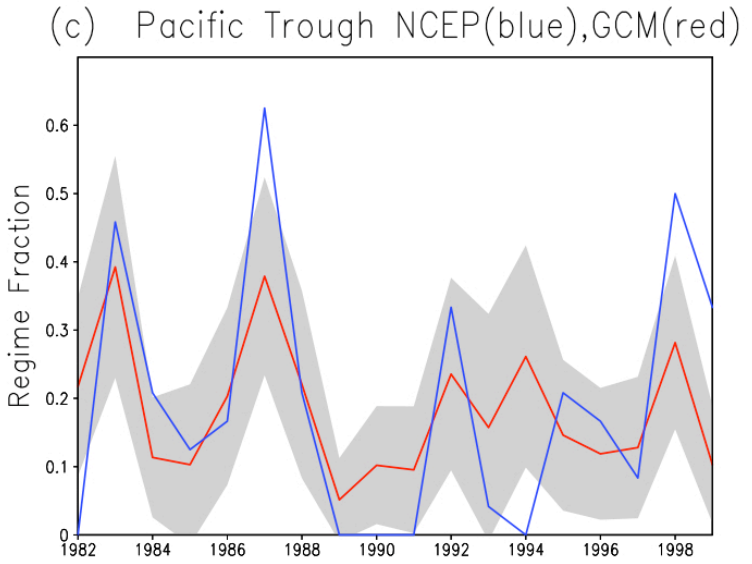
Red line: GCM

Blue line: NCEP

Gray: intra-ensemble σ in GCM



Is the frequency of occurrence of Alaskan Ridge and Pacific Trough even partly predictable on the basis of SST? - Look at frequency of occurrence year by year for the recent 18-winter period - *results are encouraging!*



Regimes and Error Growth in the CFS Interactive Ensemble

- **SST Forced AGCMs have important physical distortions (errors)**
  - **No energy balance at the atmosphere/ocean boundary**
  - **SST anomalies are forced by the atmosphere in many regions of the world.**

- **But ensemble forecasts using coupled atmosphere-ocean models have a disadvantage - since SST state will differ from member to member, the (useful) connection between regime occurrence and SST may get blurred.**

- **The Interactive Ensemble Retains the Best of Both Approaches!**

The Interactive Ensemble!

(Ben Kirtman)

- **The Ocean Model communicates to multiple (6) realizations of the Atmosphere Model, which run in parallel**
  - **The ensemble mean of the atmosphere-to-ocean fluxes of momentum, heat and moisture are used to force the ocean model**
  - **The SST of the ocean model is felt by each atmospheric realization**
  - **Atmosphere / Ocean Communication occurs once per day**

- **Surface energy balance at the atmosphere/ocean interface is satisfied, while at the same time we have access to an ensemble of atmospheres which feel the same SST !**

- **Use the Coupled Forecast System of NCEP (atmosphere has T62 horizontal resolution with 64 levels, coupled to MOM3)**

Interactive Ensemble (IE) Re-Forecasts

- Stan, C. and B. P. Kirtman, 2007: The influence of atmospheric noise and uncertainty in ocean initial conditions on the limit of predictability in a coupled GCM. (under revision for J. Climate)

- **Initialize the IE ocean January 1 of given year, and construct 4 small perturbations of the ocean initial state, leading to a "super-ensemble" of 5 IEs**

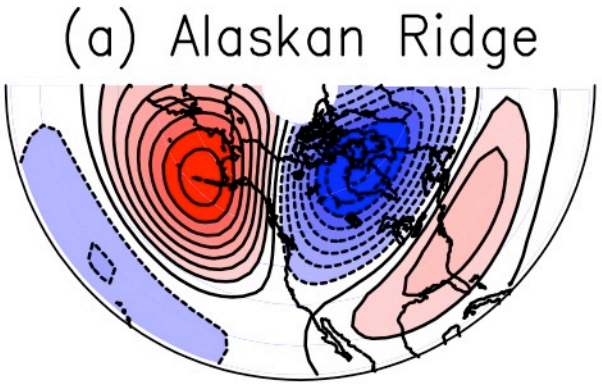
- **For each ocean state (IE) initialize each of the 6 atmospheres from the reanalysis for January 1 + a small perturbation**

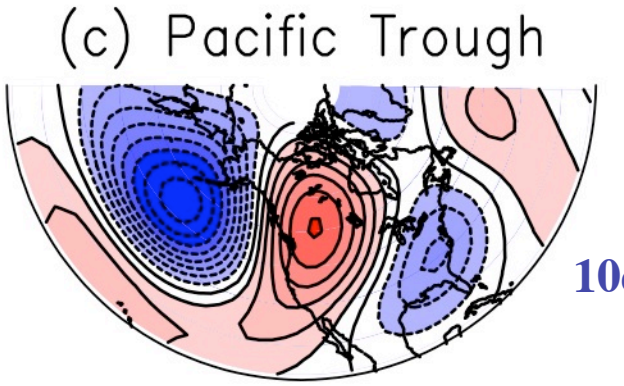
- **Each IE gives an ensemble of 6 atmospheric realizations close together initially, whose "errors" grow with time**

Circulation Regimes of the IE

- **The super-ensemble of IEs are run for one year, but we use only the first 90 days for the cluster analysis**
- **Repeat for 11 January initial dates taken in the period 1980-1998**
- **We have in total 11 x 5 = 55 IEs,**
- **Each IE gives an ensemble of 6 atmospheric realizations close together initially, whose "errors" grow with time**

Straus, Corti and Molteni, 2007





$10d < \tau < 90d$

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

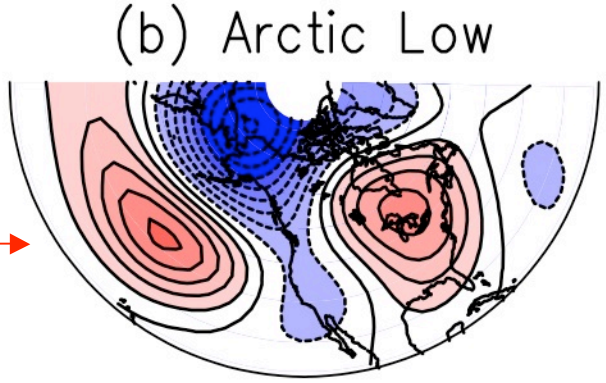
(a) Only quasi-stationary time periods used

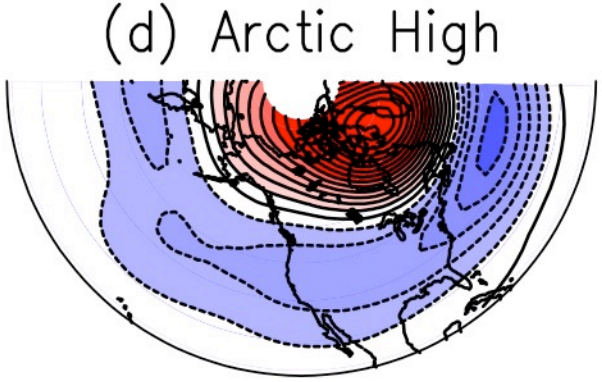
(b) H0 can be rejected at the 90% level using partitioning method

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

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

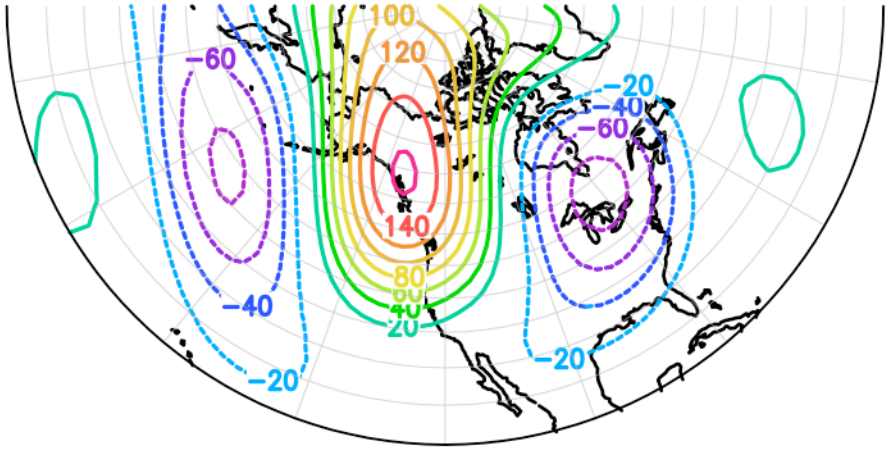
(e) Clusters are due to true "clumping" of states in PC-space, and not just skewness



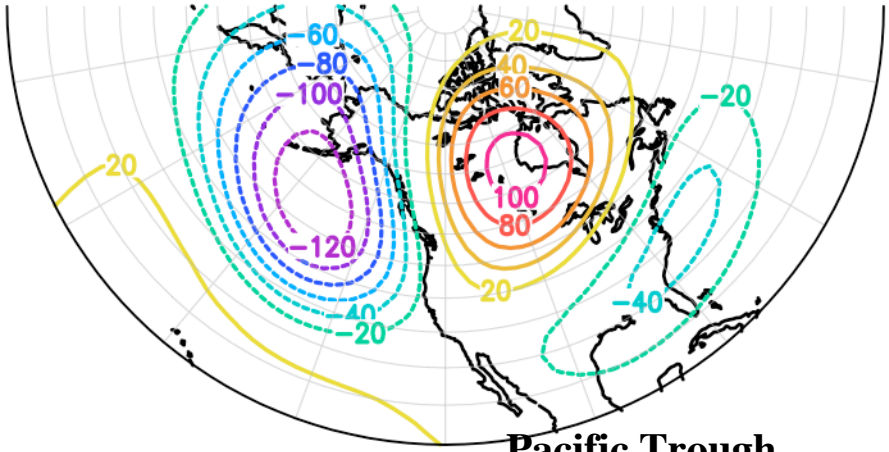


least well-defined →

(1|4) zav1_zav1 z200 6pcs



(2|4) zav1_zav1 z200 6pcs

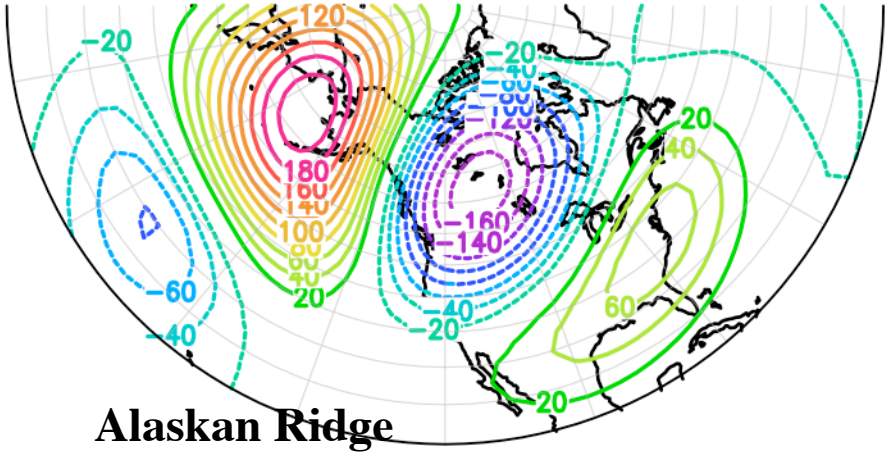


Pacific Trough

Regimes from Interactive Ensemble 10-day mean 200 hPa height field:

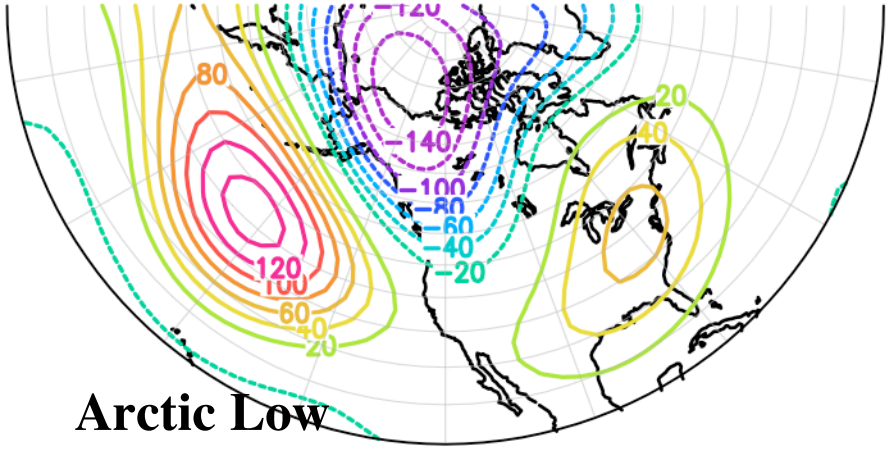
Composites of 200 hPa height

(3|4) zav1_zav1 z200 6pcs



Alaskan Ridge

(4|4) zav1_zav1 z200 6pcs



Arctic Low

Attempt to Show Existence of Preferred States using pdf of errors

(Anna Trevisan, 1993)

Systems with strong regimes (Lorenz's 3-component system) show strong bi-modality in pdfs of errors between large number of solutions starting from almost the same initial conditions.

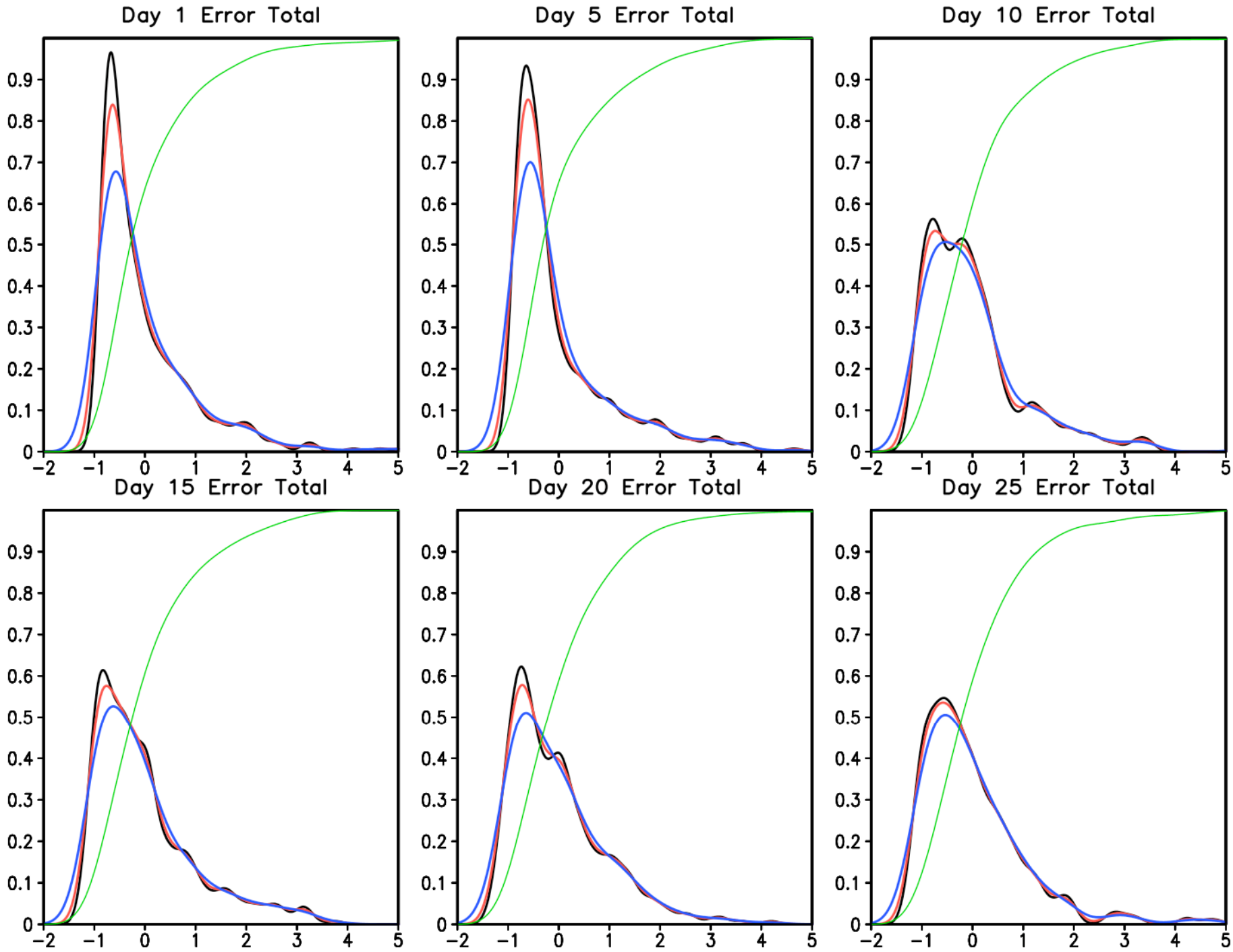
In simple systems this occurs when the trajectories begin to "split" into different regimes.

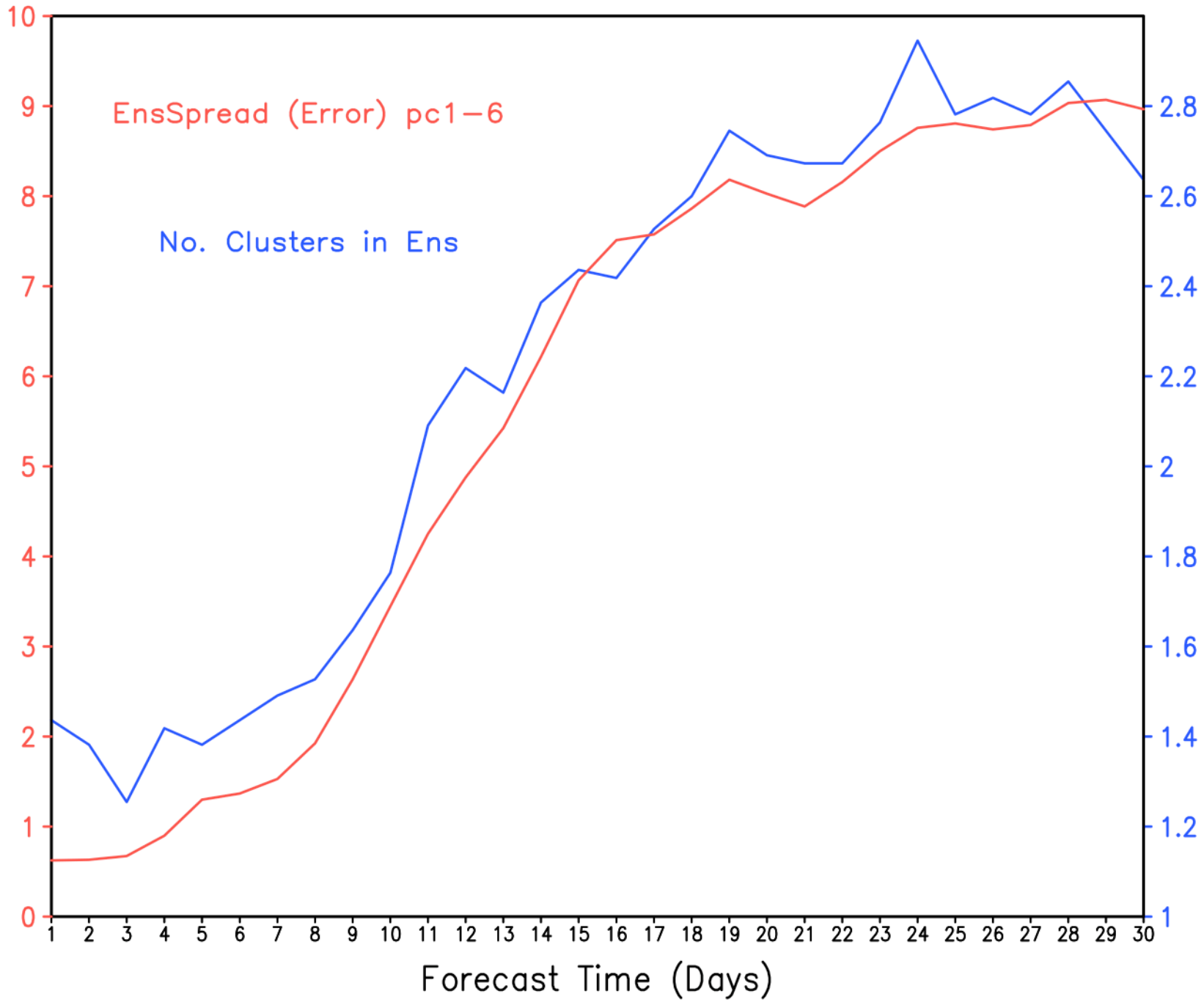
Is there any hint of this happening in the Interactive Ensemble?

Compute E = mean squared deviation of 200 Z for each atmosphere about the 6-atmosphere ensemble mean (using first 6 PCs) for each forecast day.

There are 11 x 5 = 55 realizations of E (for each forecast day)

==> Construct a pdf


Day 1 Error Total
Day 5 Error Total
Day 10 Error Total
Day 15 Error Total
Day 20 Error Total
Day 25 Error Total
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
−2
−1
0
1
2
3
4
5

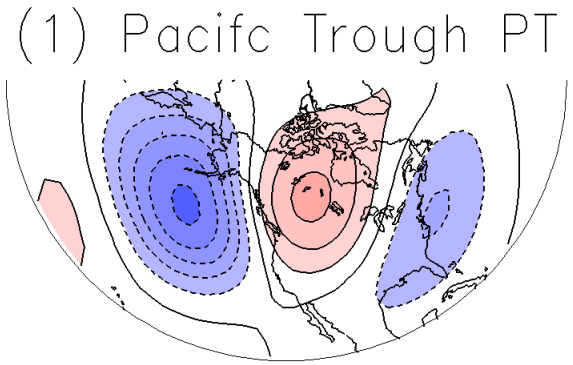

EnsSpread (Error) pc1–6
No. Clusters in Ens
10
9
8
7
6
5
4
3
2
1
0
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Forecast Time (Days)

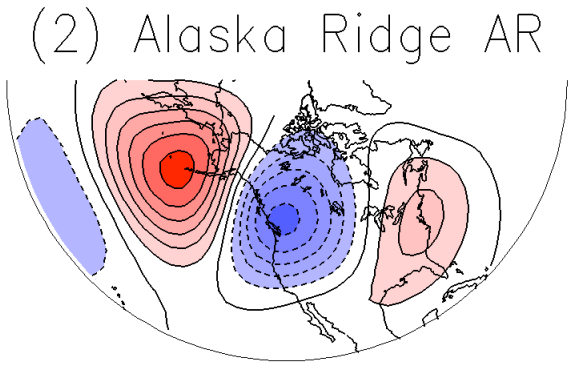
Conclusions

- There is enough evidence for significant circulation regimes in quasi-stationary, data records of sufficient length for the concept to be taken seriously.
- However, statistical significance, reproducibility, are still real issues to be dealt with for each region, variable, period.
- Large ensembles of model simulations can provide some estimates of significance, pdfs, when observed data record is too short
- Regimes respond to changes in SST forcing *both* by changes in the refimes and in their population of occurrence.
- Frequency of occurrence as a function of SST gives some hope of predictability
- Link to true weather regimes has proven to be useful

Current and Future Directions

- **More explicit connections between regional circulation regimes and weather regimes need to be made**
- Use CFS historical forecasts - daily values.
  - LP filtered Z200 - (LP = retain periods > 10 days)
  - **Storm Track "Envelope Function" = LP filtered {square of v200 and v850 high pass data = periods < 10 days} This gives a measure of the movement of storm tracks.**
- The transitions between circulation regimes within a season need to be more intensively studied - are they totally unpredictable?





Clusters of LP 200Z from NCEP historical forecasts:

All Dec start forecasts used- data from 12 Dec-31 March used