Circulation Regimes as a way of understanding tropical-extratropical interactions

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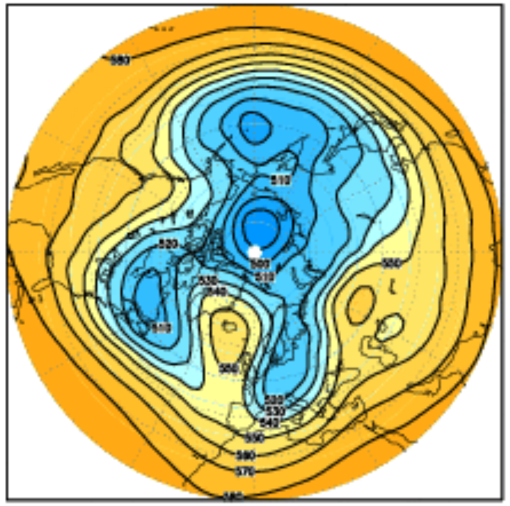
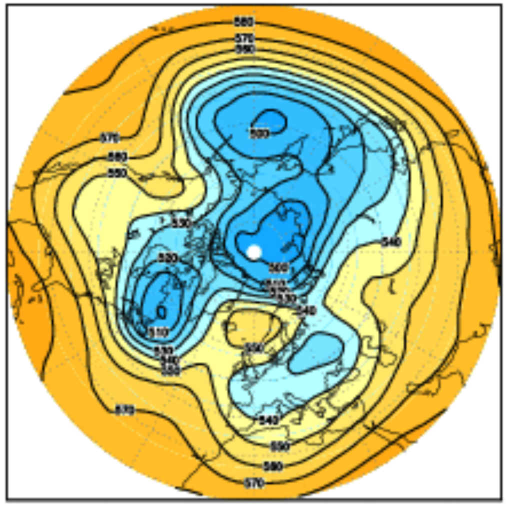
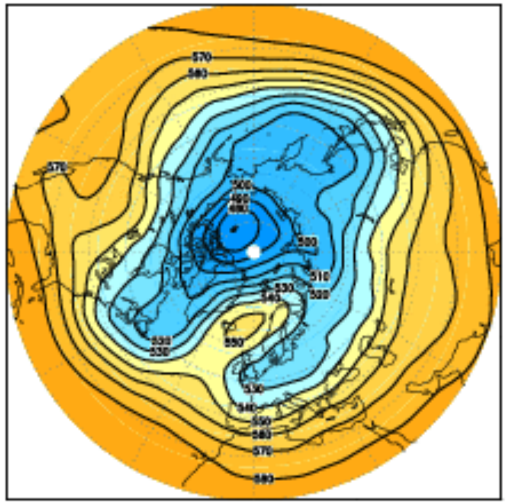
Recurrent flow patterns: examples



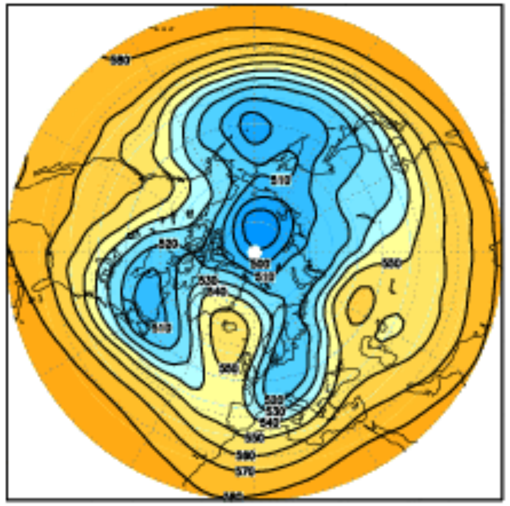


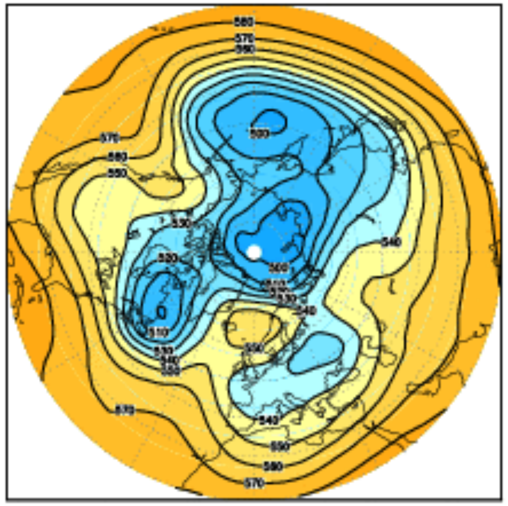


A sequence of 5-day mean fields of 500 hPa geopotential height during boreal winter …

Recurrent flow patterns: examples

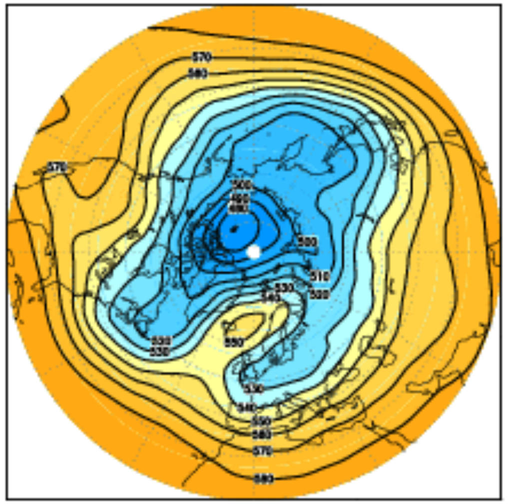
5-9 Jan 1985





4-8 Feb 1986

… but each one occurred in a different winter !



10-14 Jan 1987

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

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:

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

Papers on multiple equilibria and quasi-stationary states

Orographically forced models:

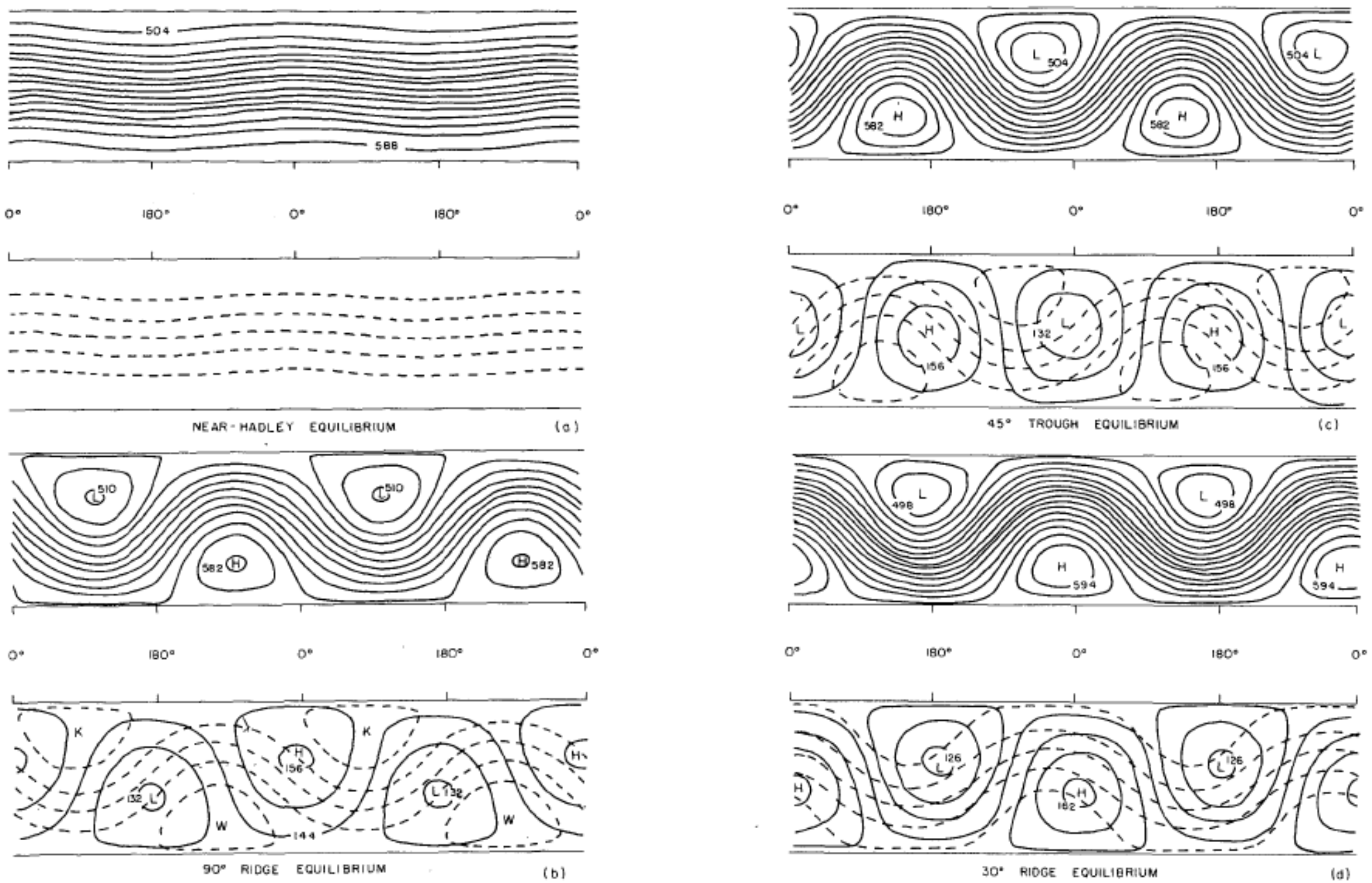
- **Charney and DeVore 1979:** *Multiple flow equilibria in the atmosphere and blocking*
- **Charney and Straus 1980:** *Form-grad instability, multiple equilibria and propagating planetary waves in baroclinic, orographically-forced planetary wave systems*
- **Charney, Shukla and Mo 1981:** *Comparison 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*

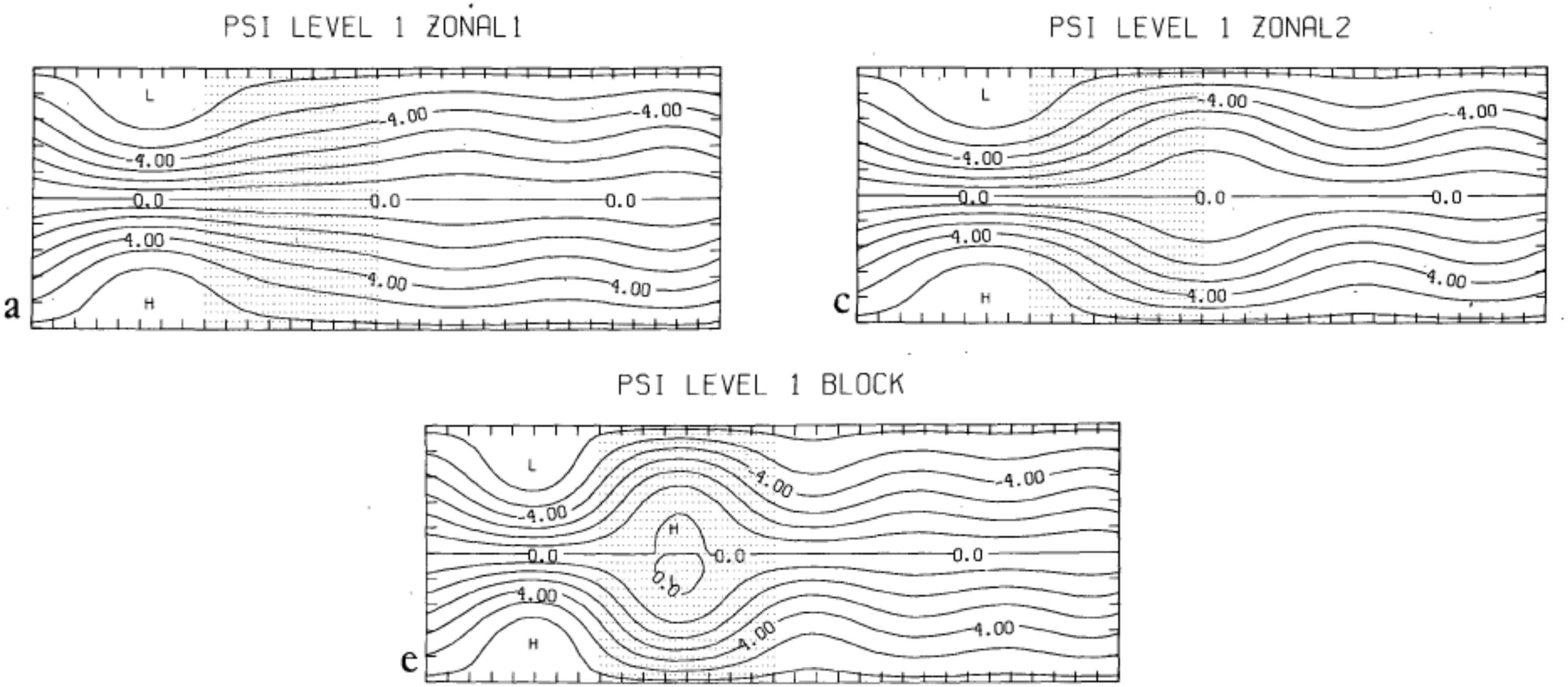
Papers on weather regimes: Reinhold and Pierrehumbert 1982

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



Papers on weather regimes: Vautard and Legras 1988

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



Looking for observational evidence: 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)

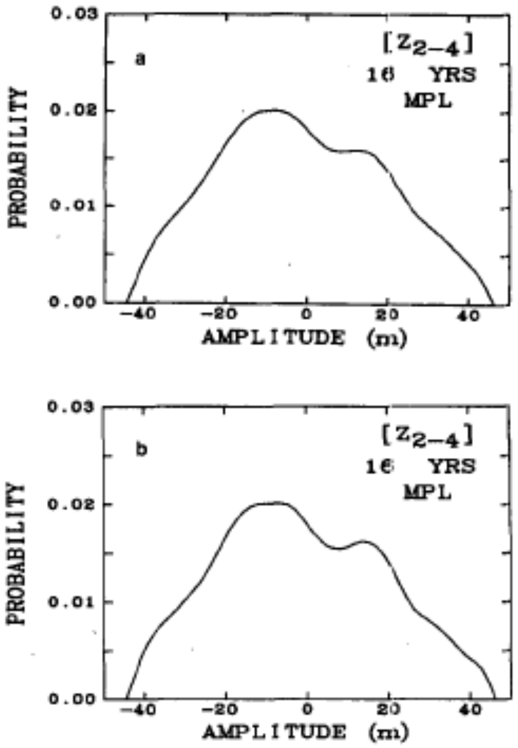
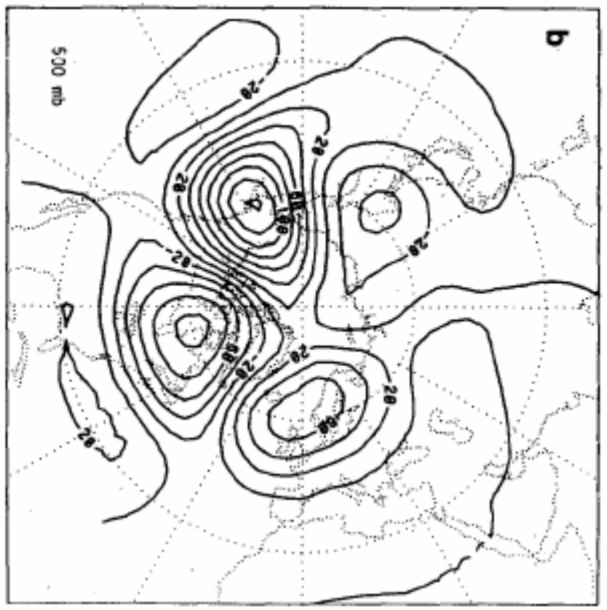


FIG. 4. MPL probability density estimates of [Z_{2-4}] formed from the 16 winter composite filtered data for (a) $\alpha = 10^7$ and (b) $\alpha = 5 \times 10^6$.

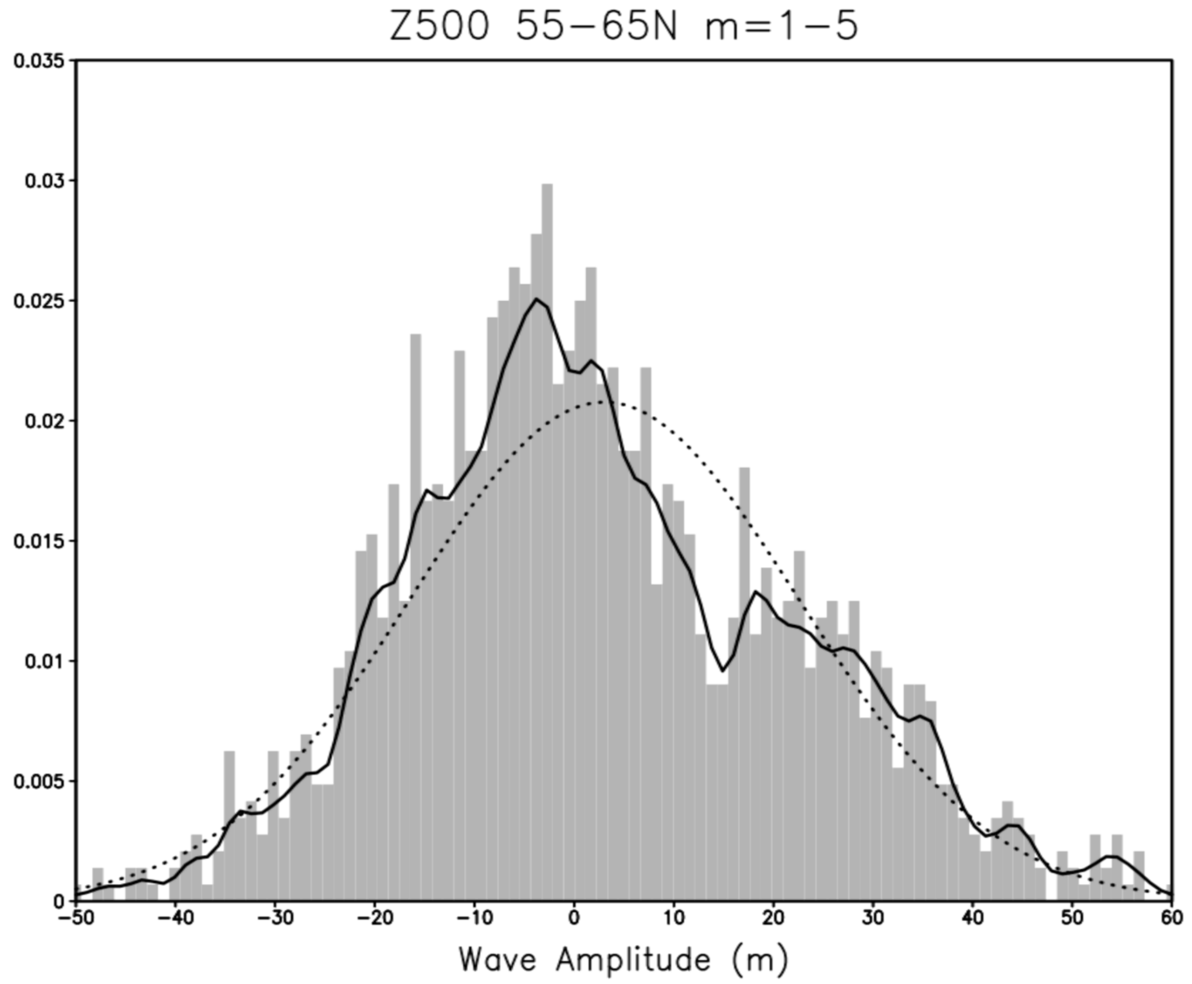


Computing a planetary wave index: Straus et al. 2017

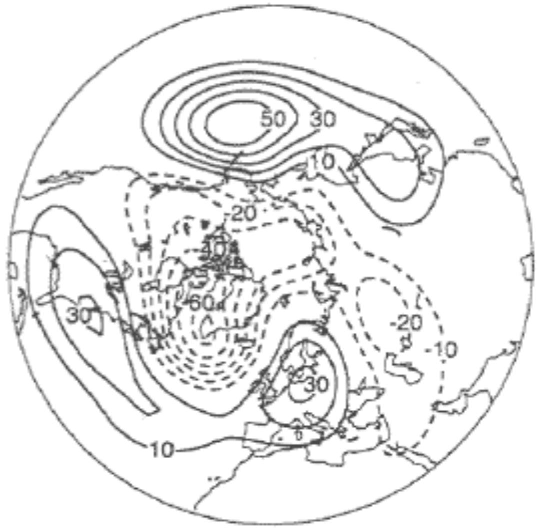
- **Take daily Z500 fields from 01 December through 28 February for each of the 33 winters 1980/81 - 2011/12**
- **Filter the daily fields in time to remove the rapidly propagating weather disturbances (periods less than 8 days)**
- **Further filter the fields in space to retain only the large-scale waves (zonal waves one through five)**
- **Average each 2-d filtered field over a latitude band (in this case 55-65N) to obtain 1-d fields**
- **Take the square root of the zonal mean of the squared amplitude of the 1-d fields to obtain a single number, the planetary wave index (PWI) for each day**
- **Compute and remove a smooth climatological seasonal cycle of the PWI**
- **Accumulate a histogram showing how many times the PWI lies within given ranges of values**
- **Estimate a smooth probability distribution function (pdf) based on this histogram**

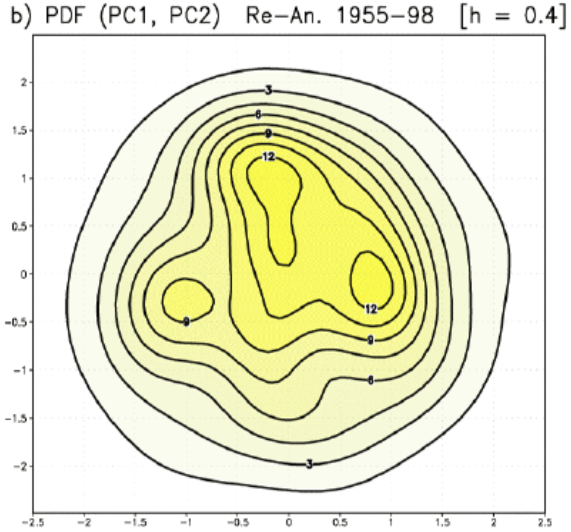
- *From Straus et al. 2017, in: Nonlinear and Stochastic Climate Dynamics, editors: C.L.E. Franzke & T. J. O'Kane, Cambridge University Press*

Computing a planetary wave index: Straus et al. 2017

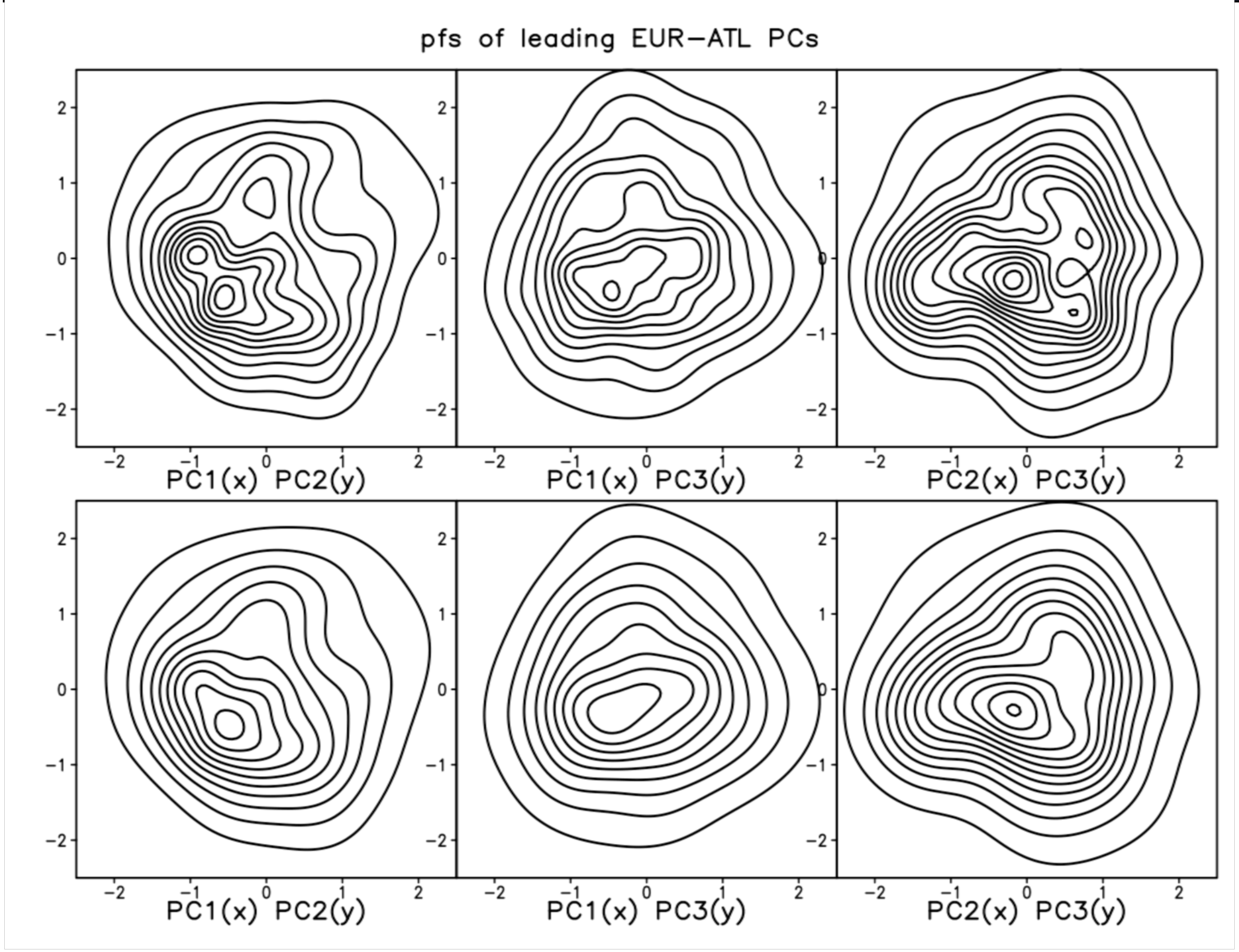


Regimes from 2-dim. PDF estimation (Corti et al. 1999)





2-dim PDFs for Euro-Atlantic princ. components: Straus et al. 2017



Probability functions in the planes of the three leading PCs of low-frequency 500 hPa height anomalies in the North Atlantic region.

Abscissas and ordinates are labeled as (x) and (y), respectively.

Units along the axes are given in units of standard deviation: 1054 m, 790 m and 760 m for PC-1, PC-2, and PC-3 respectively.

N. Hemisphere and Euro-Atlantic regimes from cluster analysis

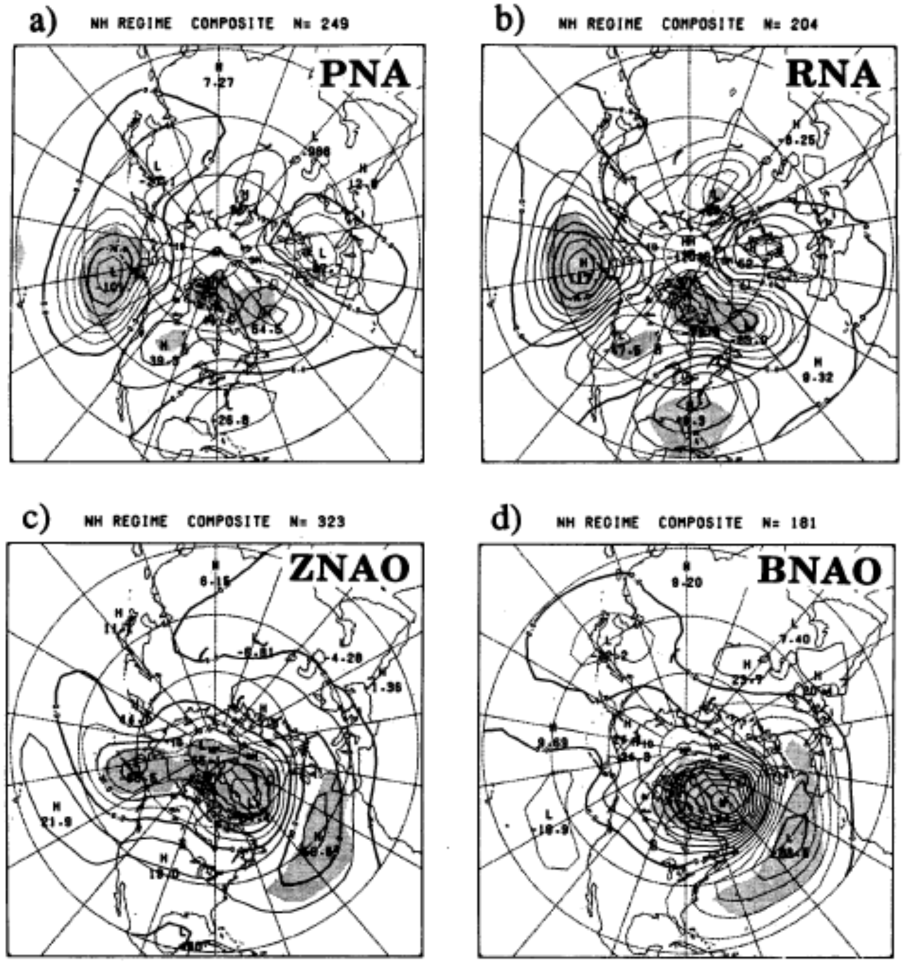
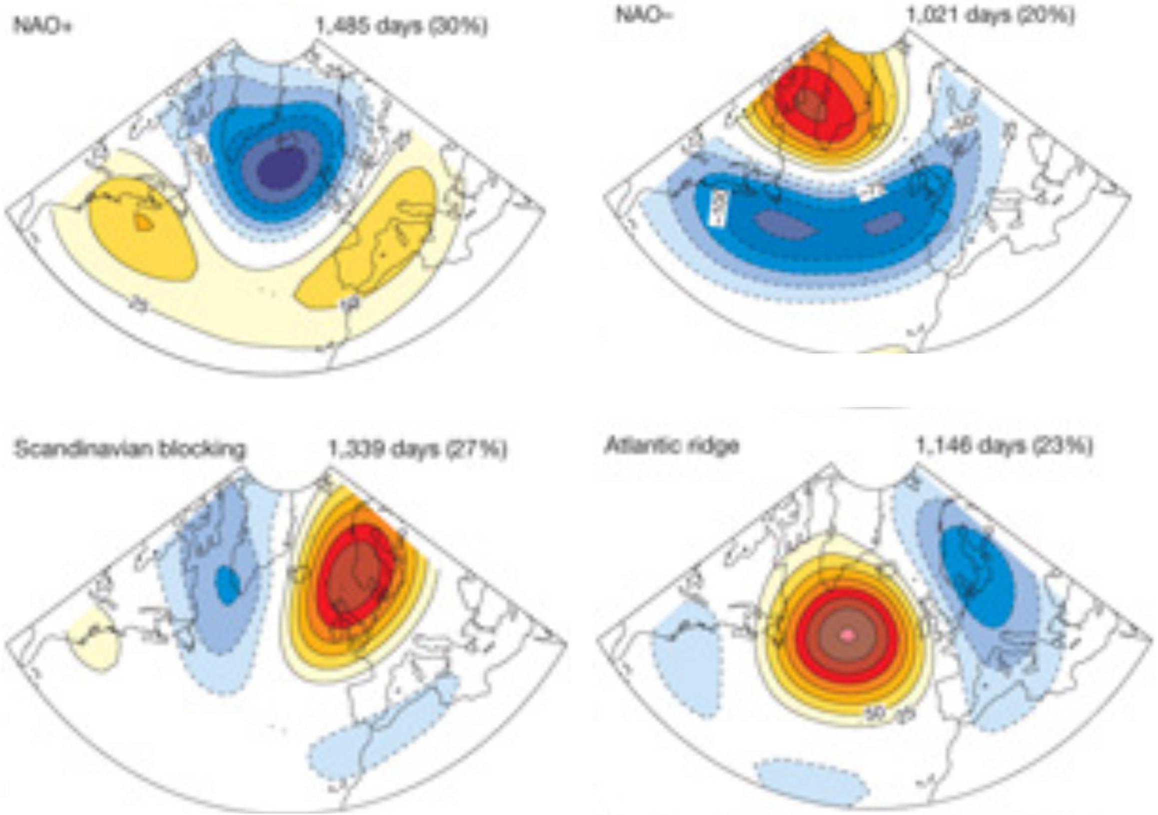


FIG. 14. Composite maps of unfiltered anomalies for the four NH regimes. Those samples falling in either of the four rectangles in Fig. 11a are collected for (a) PNA, (b) RNA, (c) ZNAO, and (d) BNAO. Numbers of collected daily maps are (a) 249, (b) 204, (c) 323, and (d) 181, respectively. Contour interval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

Kimoto and Ghil 1993

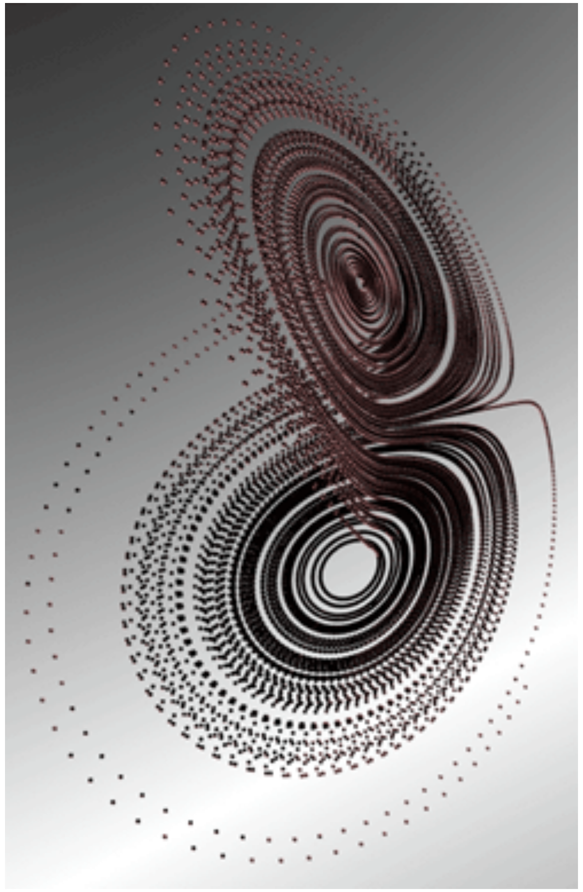


Michelangeli et al. 1995
Cassou 2008

Impact of "external" forcing in non-linear systems

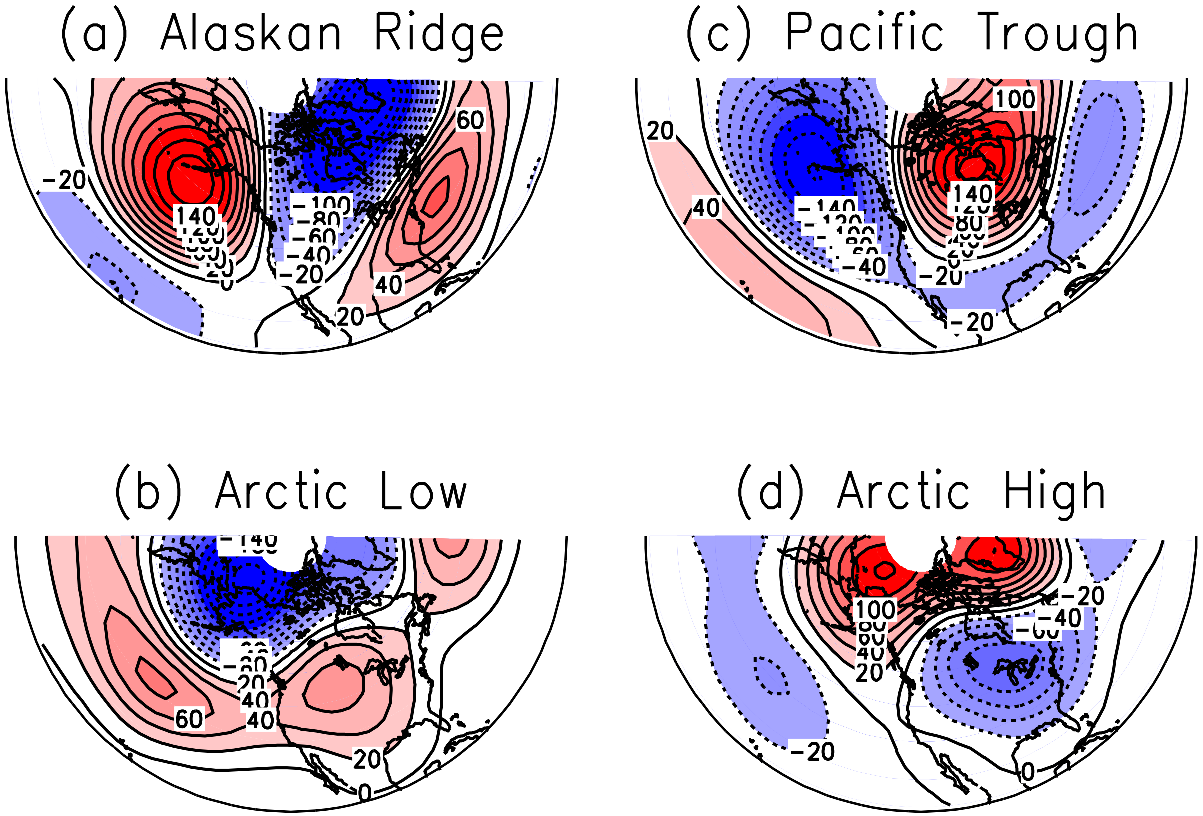
The properties of flow regimes may be affected by anomalous forcing in two different ways:

- **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



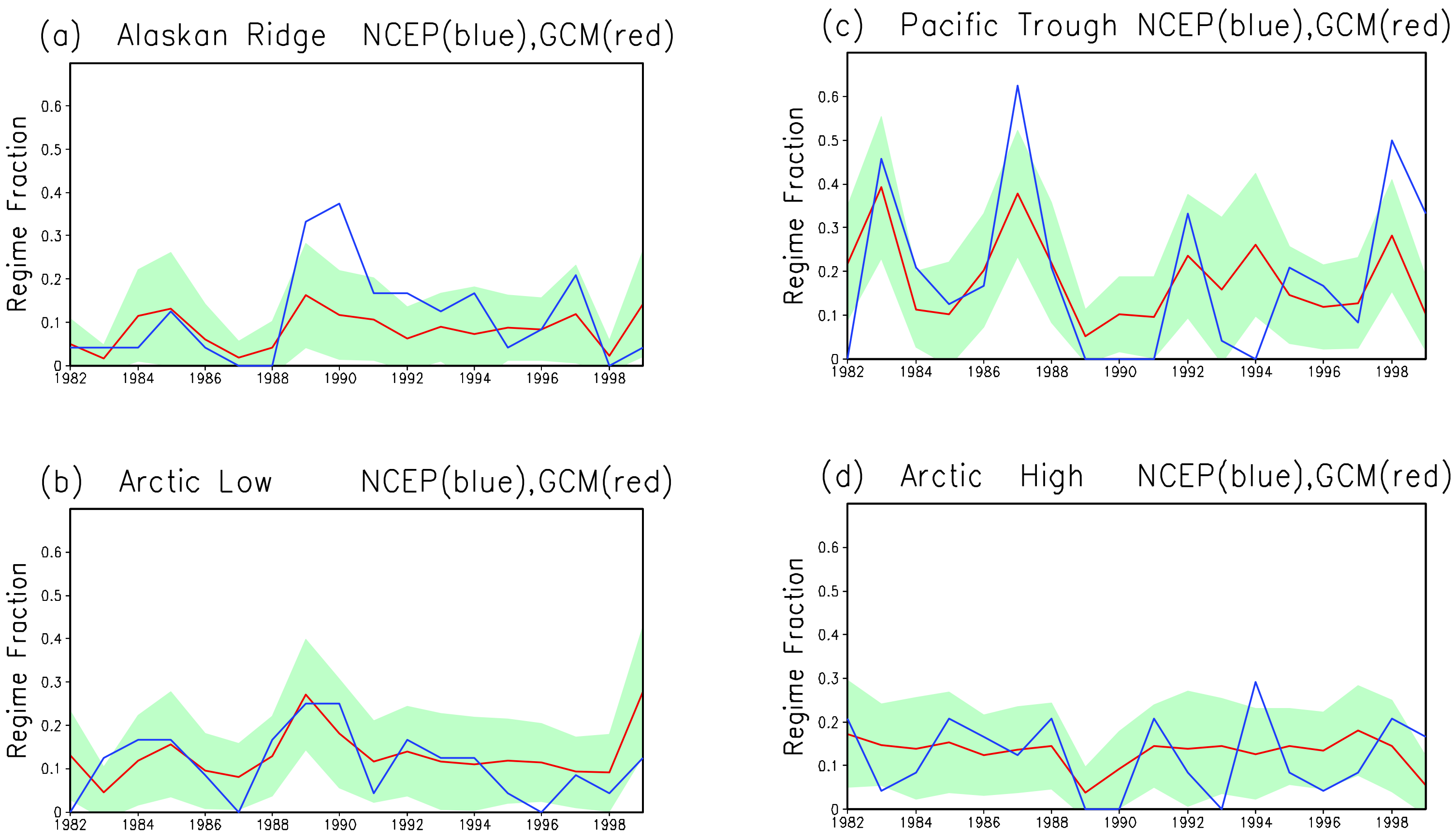
A regime approach to seasonal predictions

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)

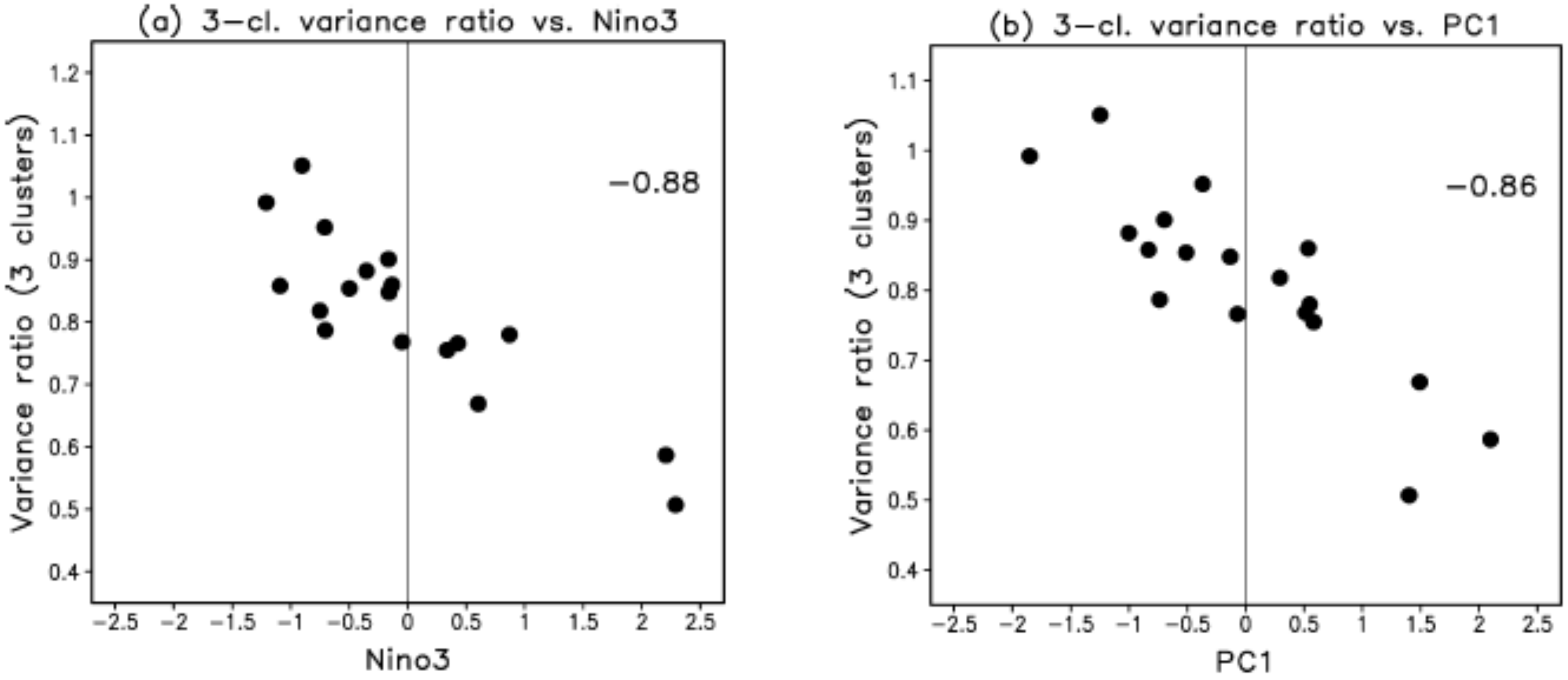
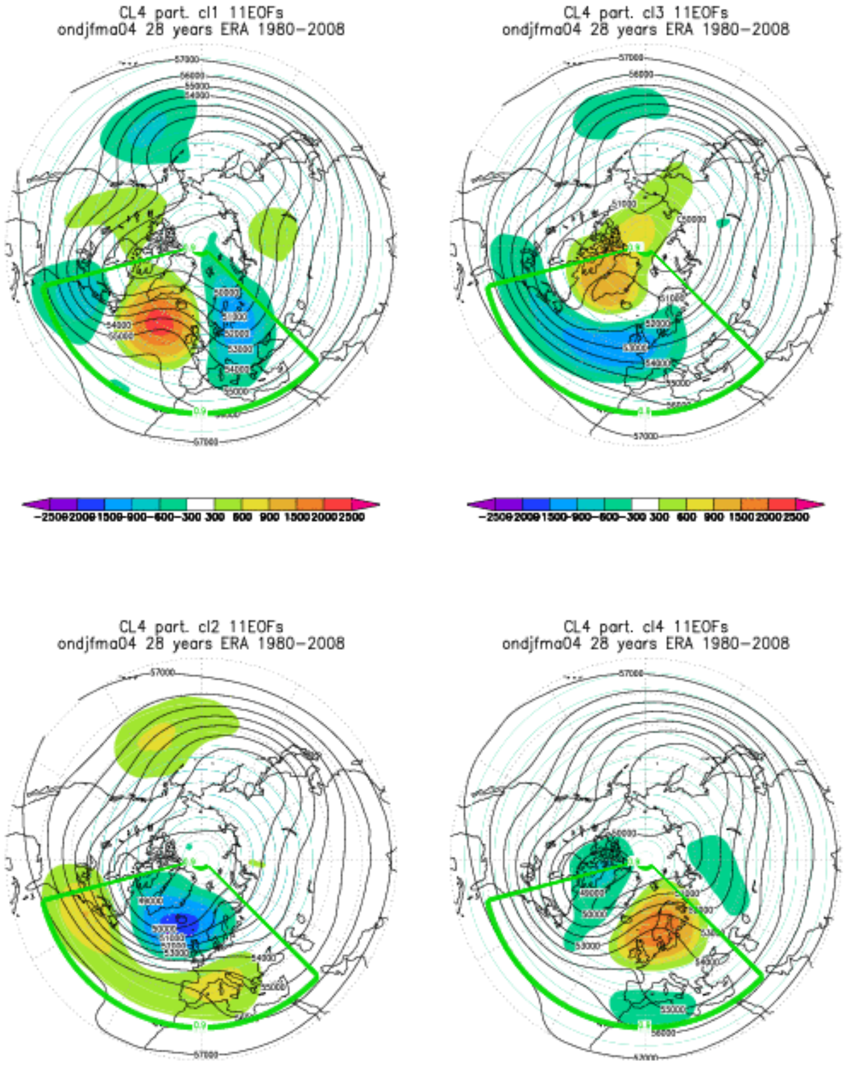
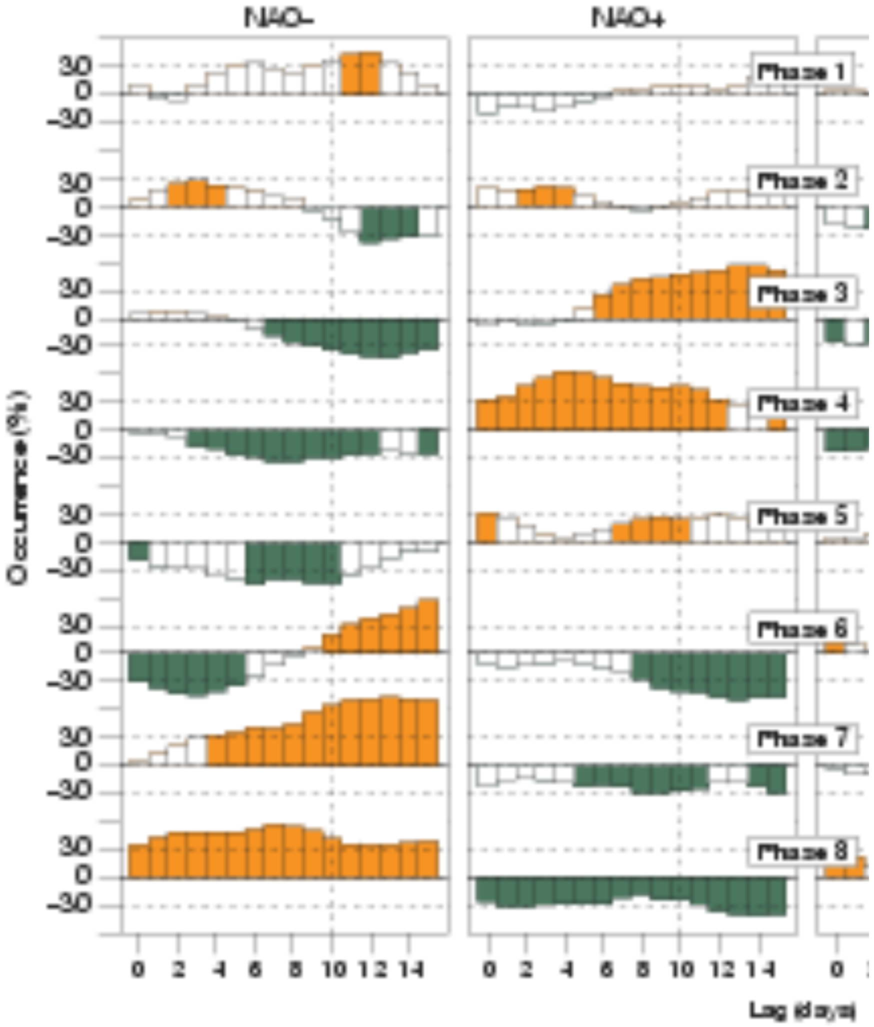


FIG. 4. Scatterplots of (a) the 3-cluster ($k = 3$) variance ratio vs Niño-3, and (b) the 3-cluster variance ratio vs the leading PC of ensemble/seasonal means. The leading PC and SST index time series are standardized.

Impact of MJO on Euro-Atlantic regimes





Cassou 2008

Influence of land-sea contrast on planetary wave variability

- **Thermal equilibration of planetary waves**: Variability in the phase of planetary waves with respect to the surface temperature distribution
  - Mitchell and Derome (1983)
  - Shutts (1987)
  - Marshall and So (1990)

- **The Cold Ocean Warm Land pattern**: observations and dynamics
  - Wallace, Zhang and Bajuk (1996)
  - Molteni, King, Kucharski and Straus (2011)

A simple diagnostic for thermal equilibration

- **An index of the Thermal balance of planetary Waves (TW) :**

  Zonal wavenumber-2 component of net surface heat flux (NSHF, positive downward) in the 40-70 ^{o}N latitudinal band:

  (Molteni, King, Kucharski and Straus, Clim. Dyn. 2011)

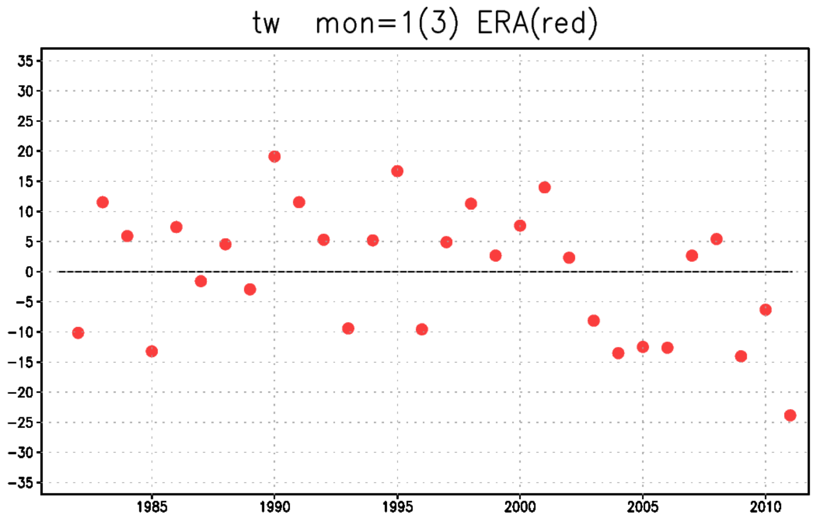
  TW = 0.5 * (NSHF [30E-120E] + NSHF [150W-60W]
  - NSHF [120E-150W] - NSHF [60W-30E])

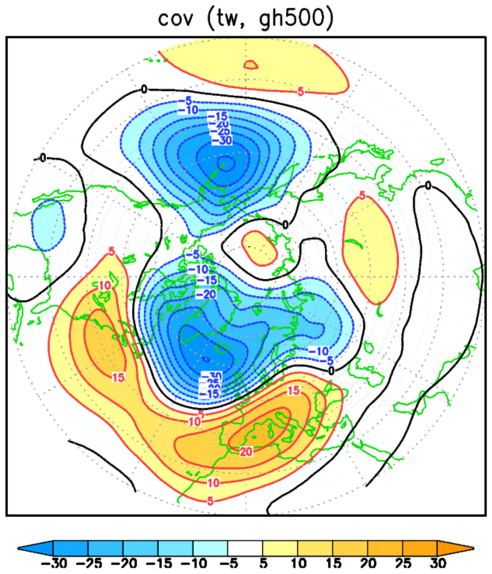
TW anomalies are:

- positive when heat flux from the northern oceans to the atmosphere is increased (COWL pattern)
- negative when warm atm. anomalies are located over the ocean (equilibrated phase)

The TW index and co-varying patterns in ERA-Interim

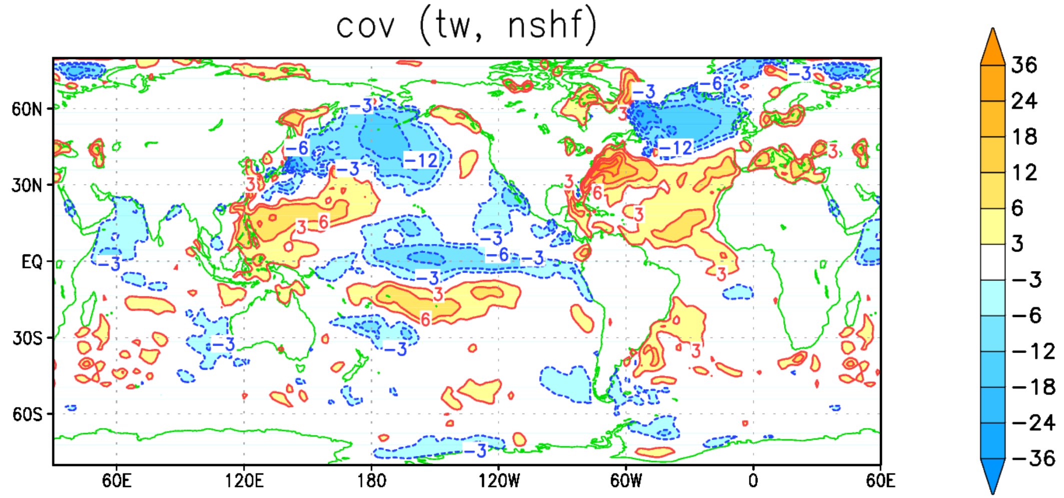
TW index (positive in COWL phase) in DJF 1982 - 2011





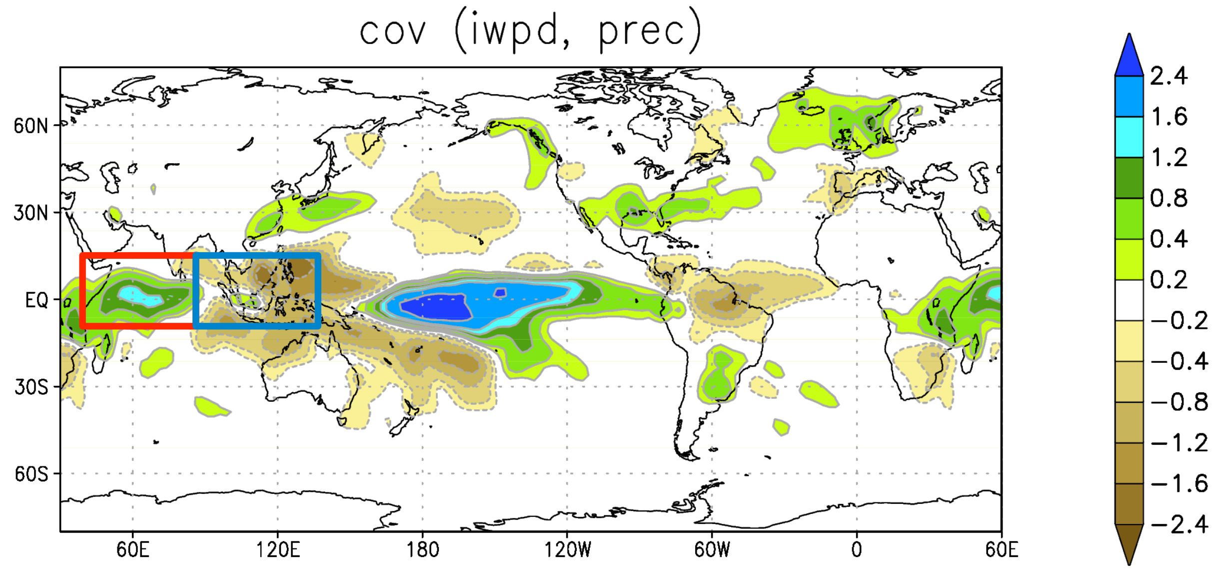
Covariance with TW index in DJF:

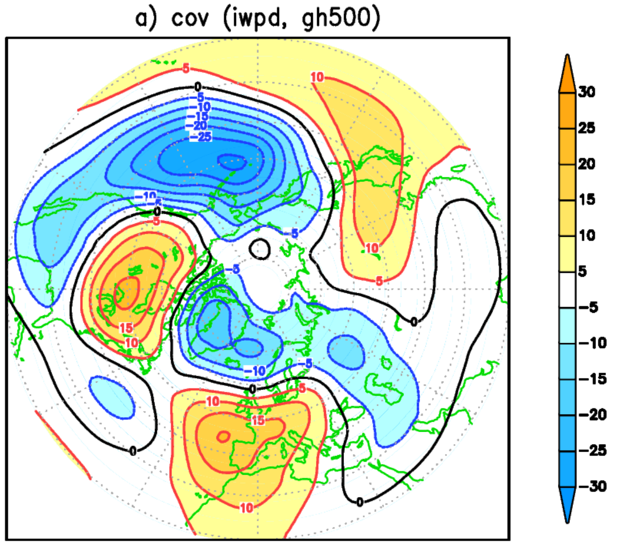
Z 500 hPa

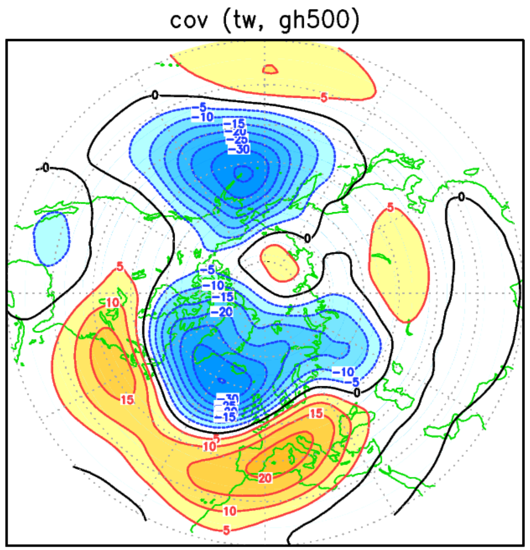


Net surface Heat flux

TW pattern and the teleconnection from Ind.Oc. – W.Pac. in DJF







Conclusions

- Circulation regimes represent an important dynamical feature of many non-linear models of the atmospheric circulation.
- In regimes of the extratropical circulation, a balance occurs between the dynamical tendencies of the large-scale flow and the non-linear feedback of synoptic-scale, high-frequency transients, on a time scale longer than ~ 10 days.
- Regimes have been detected in long records of analyses and/or GCM data using one- or two-dimensional PDFs and cluster analysis, applied on either a hemispheric or a sectorial domain.
- Anomalous forcing (eg from ENSO or MJO) can affect the properties of regimes by modifying their frequency of occurrence (weak forcing anomaly) or changing the number of regimes (if the anomalous forcing is strong enough to move the system across a bifurcation point). Both cases have been detected in data from large GCM ensembles.
- The teleconnection pattern associated with rainfall variability in the tropical Indian Ocean and the Maritime Continent shows a close similarity to a planetary wave pattern that modulates air-sea fluxes over the norther oceans. This suggests that the Indian Ocean teleconnection to the North Pacific & Atlantic may lead to the stabilization of one specific equilibrium for the thermal balance of planetary waves.