Mid-Latitude Atmospheric Regimes, Subtropical Jet, and ENSO

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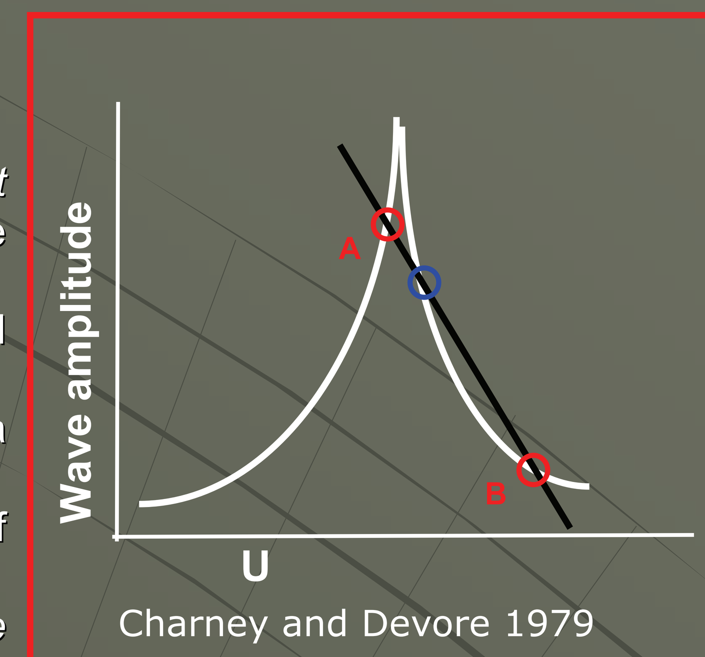
Some issues regarding the theory of the General Atmospheric Circulation

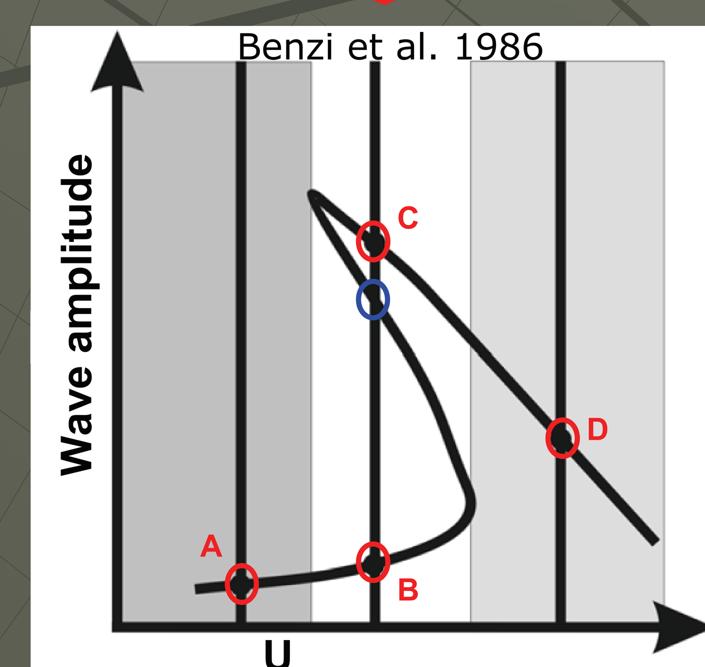
- The stability properties of the *time mean state* do not approximate the dynamical properties of the full nonlinear system
  - Impossibility of creating a self-consistent theory of the time-mean circulation relying only on the time-mean fields.
- Impossibility of using straightforwardly the fluctuation-dissipation theorem, since ergodicity is only restricted to the attractor, and the externally induced fluctuations move the system out of the attractor with probability 1 (Gallavotti/Cohen)
  - Impossibility of parameterizing exactly a Climate Change theory: external and internal fluctuations are not equivalent.
- In the limit of infinite resolution for any numerical model of fluid flow, the numerical convergence to the statistical properties of the continuum real fluid flow dynamics is not guaranteed
  - Models of ever-increasing resolution may not give the ultimate answer.

Goals of this Work

- The notion that well-defined winter mid-latitude atmospheric *patterns of flow* are *recurrent* during the NH winters has been debated since the definition of Grosswetterlage, to the identification of Atlantic blocking, to recent work on regimes detection and identification.
- Planetary waves contribute to a large portion of the eddy meridional heat transport $\Longrightarrow$ good representation by GCMs is needed.
- A widely accepted theory for planetary waves is not available (bimodality?) and reliable data are needed to test new theories.
- Understanding the properties of planetary waves may help in addressing the feasibility of extended range forecasts or the robust detection of climate changes.
- This work is part of the IPCC sub-diagnostics project *Regimes of the Mid-latitude Atmosphere* by Speranza and Lucarini.



Charney and Devore 1979



Theoretical Background

- At first, the zonal flow – wave field interaction (via form-drag) was proposed as driving mechanisms allowing for the establishment of multiple equilibria of the planetary waves amplitude (Charney and DeVore, 1979)
- However, the transitions between the quasi-stable equilibria require for energetic reasons large variations (Δ u ≈ 40 *m/s*) of the mean westerlies, at odds with the "normality" of the distribution of the observed westerlies strength
- The bent resonance curve obtained in non-linear wave self interaction theories by Benzi et al. [*1986*], not only explains the existence of the multiple equilibria of the planetary wave amplitude, but allows that relatively small changes of the jet strength may imply a switch from unimodal to multimodal regimes of the atmospheric circulation $\Longrightarrow$ Baroclinic processes are relevant for the onset and maintenance of planetary waves, and that topography might be crucial.

Data and Methods

Two proper counterparts to the dynamical parameter employed in the theories are extracted from such data sets by computing two robust indicators of relevant large scale features of the midlatitude troposphere. The Wave Activity Index (WAI), introduced by Hansen and Sutera [1986], is computed as the root mean square of the zonal wavenumbers 2 to 4 variance of the winter 500 hPa geopotential height averaged over the channel 32°N–72°N. The WAI provides a synthetic picture of the ultra long planetary waves and captures the orographic resonance, since an approximate mode of zero phase velocity (resonance) is 3. The Jet Strength Index (JSI) is computed daily as the maximum of the zonal mean of the zonal wind at 200 hPa, where the sub-tropical jet peaks.

$$WAI = \left(\sum_{k=2}^{4} 2|Z_k|^2 \right)^{\frac{1}{2}} \qquad JSI = \max \langle U \rangle \Big|_{200hPa}^{32^\circ N - 72^\circ N}$$

For filtering out the synoptic atmospheric variability, we apply a low-pass filter to both WAI and JSI indexes, whereas, for capturing the anomalies with respect to the seasonal cycle we filter out from the WAI signal the spectral peaks occurring at 12, 6 and 4 months, directly directly related to influence of the external solar forcing. Since in the context of the bent resonance theory the jet strength is considered as an autonomous forcing parameter of the system, controlling and catalysing its internal variability, we do not filter out from the JSI the seasonal cycle and its harmonics as done for the WAI. Furthermore, the results are robust with respect to the different filtering techniques.

Reanalyses:

- We consider the 1958-2002 DJF [JSI,WAI] time series derived from the NCEP/NCAR and ERA40 reanalysis daily data. Both the 2D [WAI,JSI] and the 1D WAI and JSI time series of the two datasets are determined as equivalent by the 2D and 1D Kolmogorov-Smirnov tests, respectively.

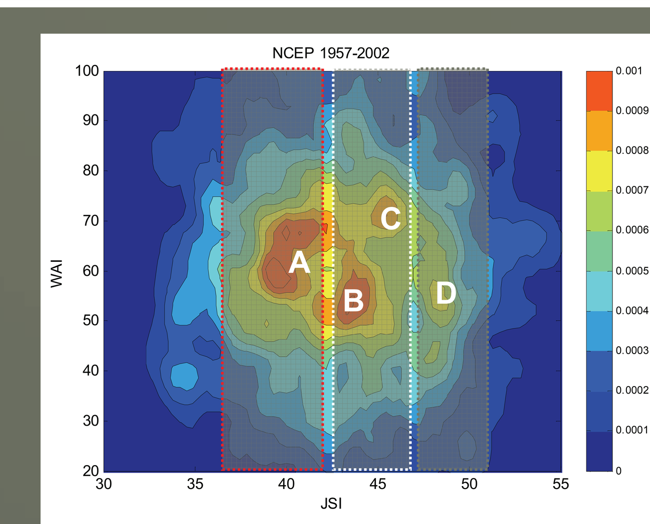
IPCC 4AR GCMs:

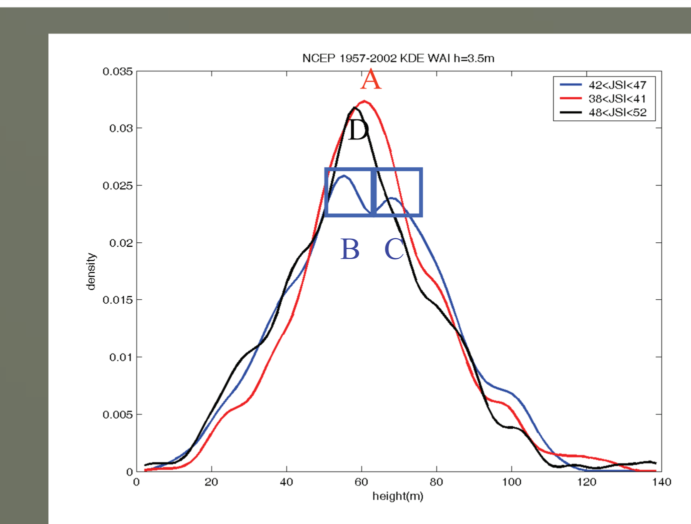
- We also consider the 1961-2000 simulations of the MIROC(hires) and GFDL2.1 models, which have been shown to provide the best representation of NH mid-latitude winter atmospheric variability. When considering GCMs data, we face the difficulty that Z levels are not included in the PCMDI dataset!
  - •Option 1: Z500 reconstruction via hydrostatic relations – almost exact but computationally expensive, boundary conditions, etc
  - •Option 2: Geostrophic relation at 500hPa + Latitudinal averaging (we need only the anomalies!), using the geostrophic relationship.
- We choose Option 2 and obtain the 1961-2000 DJF [JSI,WAI] time series from the two GCMs. The time-series generated by the two models are not equivalent between themselves and are not equivalent to those of the reanalyses.

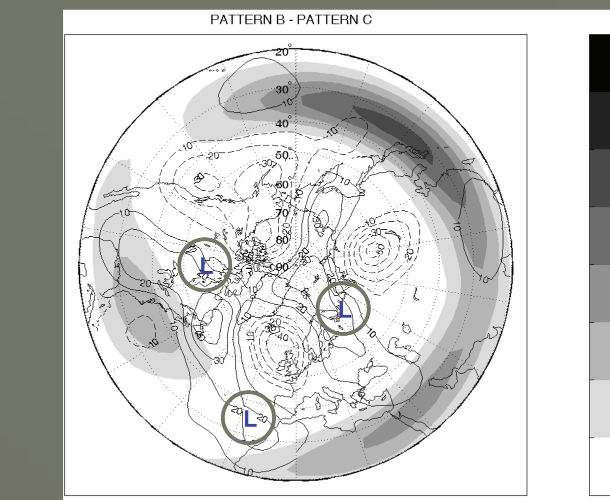
Results

Reanalyses

The empirical 2D joint pdfs, constructed by means of 2D Gaussian estimators, present multiple, well defined, peaks. NCEP results are shown. A major peak (A) corresponds to weak upper tropospheric jet (JSI = 40 ms^{-1}) and low-to-intermediate activity of the planetary waves (WAI = 60 m). A second peak (B) corresponds to intermediate values of JSI and low values of WAI (JSI = 43 ms^{-1}; WAI = 55 m). The third peak (C) corresponds to similar intensities of the jet (JSI = 45 ms^{-1}) and very high values of (WAI = 70 m). The fourth peak (D), corresponding to intense jet (JSI = 50ms^{-1}), features relatively weak planetary waves (WAI = 55 m).





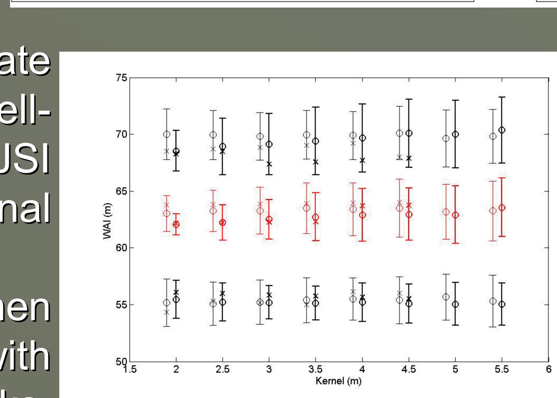


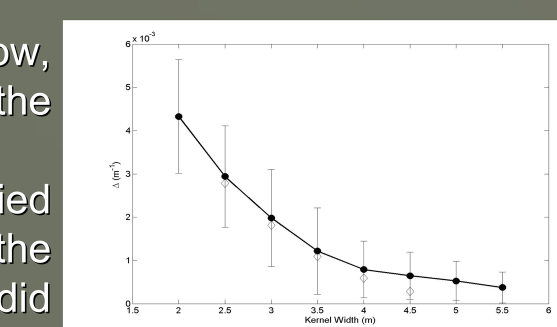
We stratify the data according to the value of JSI: we select low (38 ms^{-1}<JSI<41ms^{-1}), intermediate (42 ms^{-1}<JSI<47 ms^{-1}) and high (48 ms^{-1}<JSI<52 ms^{-1}) ranges for the intensities of the jet. Well-distinct peaks are observed in the 1D pdf in the intermediate range, while for weak or strong JSI unimodal distributions appear. Notice that strong oceanic tropical forcing (El Nino) implies zonal elongation and strengthening of the sub-tropical jet, resulting in strong JSI.

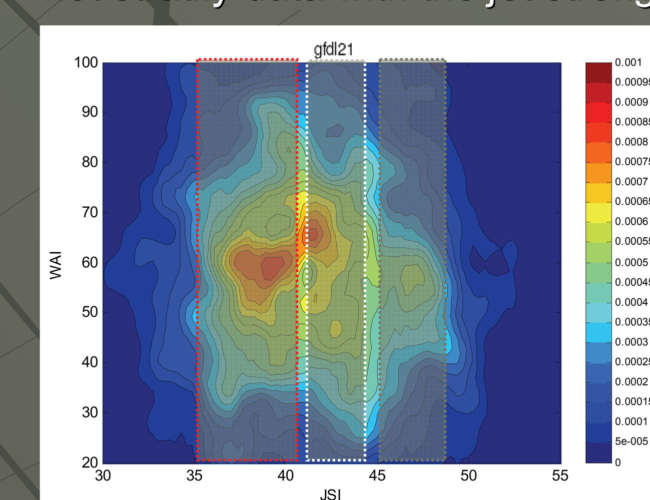
We estimate the optimal kernel width *h* by generating an ensemble of surrogate data sets and then choosing the value of *h* maximizing the trade-off between having as many surrogate distributions with the correct number of peaks and as few surrogate distributions with the wrong number of peaks. obtain that the best trade-off is realized for *h* = 3.5 m.

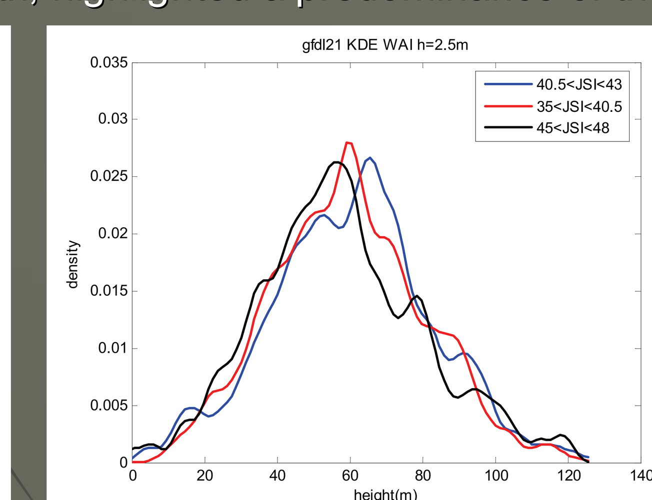
These results are consistent with the theory defining 3 different regions, characterized by low, intermediate and high intensities of the jet and by a different number of equilibrium amplitudes of the planetary waves.

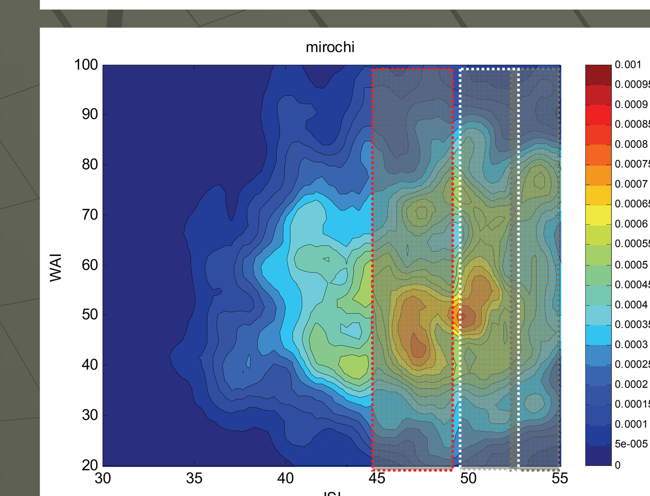
The difference map between the two intermediate JSI patterns B and C indicates a more amplified wave number three component for the pattern C, with higher geopotential height centers over the northern Pacific and Alaska, the Northern Sea, and the Siberian land. Previous analyses, which did not stratify data with the jet strength, highlighted a predominance of the wave 2 in the difference map.

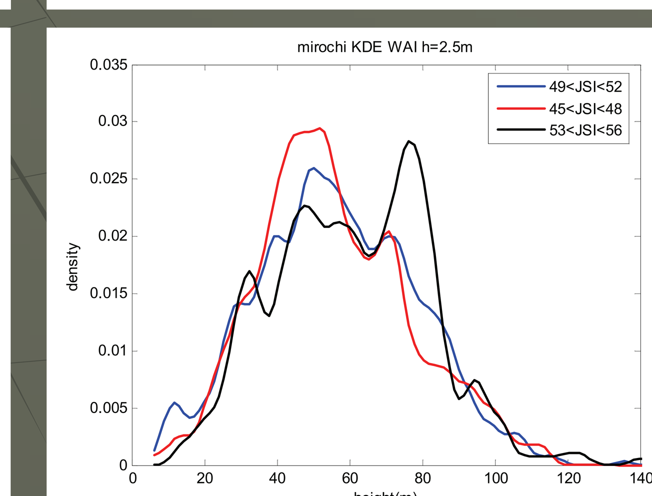

Position of the extrema of the 1D pdf


Depth of the local minimum









Models

The [JSI,WAI] time series of the two considered GCMs are not in statistical agreement. In particular we observe a large bias in the mean value of JSI, which is around 40 ms^{-1} for the GFDL2.1 model and around 48 ms^{-1} for the MIROC(hires) model. Similarly, a bias exists for the statistics of WAI. The mean value of WAI si around 60 m for the GFDL2.1 model and around 55 m for the MIROC(hires) model. This causes the bulk of the two 2D joint PDFs to have almost no overlap.

Apart from the JSI and WAI biases, the features of the 2D pdfs are also rather different, so that the 2D Kolmogorov-Smirnov test shows that they are not compatible also when the biases are removed.

When observing the resulting 1D pdfs, where the stratification of the data occurs in different JSI ranges in the two models, the signature of a JSI-dependent transition from unimodal to bimodal to unimodal distributions, as observed in the reanalyses data, is rather weak and anyway not statisticaly significant. This implies that these GCMs cannot describe properly the close connection between the statistics of planetary waves and that of the tropospheric jet, so that they ability to capture properly the topographic baroclinic instability is dubious. Nevertheless, there is a clear signature of a non-normal bigaussian statistics.

Summary & Conclusions

Understanding the atmospheric low-frequency variability is of crucial importance in fields such as climate studies, climate change detection, and extended range weather forecast. The Northern Hemisphere climate features the planetary waves as a relevant ingredient of the atmospheric variability. Several observations and theoretical arguments seem to support the idea that winter planetary waves indicator obey a non-Gaussian statistics and may present a multimodal probability density function, thus characterizing the low-frequency portion of the climate system.

Using data derived from the 1957-2002 NCEP/NCAR and ECMWF reanalyses datasets, we show that the upper tropospheric jet strength is a critical parameter in determining whether the planetary waves indicator exhibits a uni- or bimodal behavior, and we determine the relevant threshold value of the jet. These results are obtained by considering the data of the for the overlapping period.

Our results agree with the non-linear orographic theory, which explains the statistical non-normality of the low-frequency variability of the atmosphere and its possible bimodality.

Our results conjecture the existence of an additional tropical-extratropical dynamical link: during El Nino years the JSI is rather high, whereas during La Nina years the JSI is rather low. In both cases the pdf of WAI is unimodal. In the intermediate years, the JSI has intermediate values and the pdf of the WAI is bimodal. This may have consequences also in terms of extended range forecast.

The GFDL2.1 and MIROC(hires) GCMs do not reproduce accurately the above-mentioned properties, thus suggesting that GCMs are still deficient in representing topographic-baroclinic processes. Nevertheless, their 2D [JSI,WAI] pdfs are definitely non-normal.

Concluding, we point out some caveats:

- •Peaks in the PDF ≠ Fixed points + noise! This is a fully nonlinear system.
- •Let's not be too fond of the simple interpretation schemes we are using: nevertheles, they may point at right basic mechanism
- •We are not sure whether more complex interpretations based on low-dimensional dynamical system concepts are useful
- •We should investigate the geometrical properties of the attractor