Intercomparison of the N.H. winter mid-latitude atmospheric variability of the IPCC GCMs

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Some issues regarding the theory of the General Atmospheric Circulation

- The stability properties of the *time mean state* do not provide any approximation of 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, since the parameterized eddy fluxes cannot provide a closure to the equations.
- 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, due to the non-equivalence between the external and internal fluctuations.
- 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
  - [illegible]r-increasing resolution may not give the ultimate answer.

Goals of this Work

- The mid-latitude winter atmosphere is a key ingredient of the climate dynamics: it vehiculates the northward transport of heat via baroclinic disturbances.
- GCMs able to simulate correctly the mid-latitude atmosphere are needed both for paleoclimatic simulations and climate projections.
- Diagnostic studies performed on NWP models showed overestimation of baroclinic short waves and underestimation of planetary waves (Tibaldi, 1986).
- What happens under Global Warming Scenarios?

Climate Models Auditing

- Auditing = Intercomparison + Verification = Assessment of Self-Consistency + of Realism
- How to compare climate models? It may be like comparing a Ferrari to a Fiat 500! How to assess a model performance? Which model is the best one? Does "the best one" exist?
  - We do not know the truth … and we have only imperfect models!
- We want to define simple metrics for models intercomparison:
  - The total wave variability is taken as a **global scalar metrics** describing the overall performance of model
  - The total variability pertaining to the eastward propagating baroclinic waves and to the stationary planetary waves are taken as a **process-oriented scalar metrics**
- Does it make sense to make model ensembles?

Model	H. Res.	Z
BCCR-BCM2.0	T63	h31
CNRM-CM3	T63	h45
CGCM3-1(T47) CGCM3.1(T63)	T47(T63)	z31
CSIRO-Mk3.0	T63	h18
ECHAM5/ MPI-OM	T63	h31
ECHO-G	T30	h19
FGOALS-g1.0	2.8° x 2.8°	σ26
GFDL-CM2.0 GFDL-CM2.1	2.5° x 2.0°	h24
GISS-AOM	4° x 3°	h12
GISS-EH, GISS-ER	4° x 5°	σ20
INGV-SXG	T106	h19
INM-CM3.0	5° x 4°	σ21
IPSL-CM4	2.4° x 3.75°	h19
MIROC3.2(*hires*) MIROC3.2(*medres*)	T106(*hires*) T42(*medres*)	σ56(*hires*) σ20(*medres*)
MRI-CGCM2	T42	h30

Data and Methods

Daily data range from 1/1/1961 to 31/12/2000 (1/1/2181 to 31/12/2200 for SRESA1B scenario). We select the Z500hPa DJF (NH) data relative to the latitudinal belt 30°N-75°N, where the bulk of the baroclinic and of the low frequency waves activity is observed.

Space-time decomposition will not distinguish between standing and travelling waves: a standing wave will give two spectral peaks corresponding to travelling waves moving eastward and westward. The problem can only be circumvented by making assumptions regarding the nature of the wave. We may assume complete coherence between the eastward and westward components of standing waves and attribute the incoherent part of the spectrum to real travelling waves, following the Fourier space-time decomposition introduced by Hayashi (1971,1979). Hayashi Spectra allow separation between travelling vs. standing waves of the 1D+1D field $Z(\lambda,t)$:

$$Z(\lambda,t)=Z_0(t)+\sum_{j=1}\left\{C_{k_j}(t)\cos(k_j\lambda)+S_{k_j}(t)\sin(k_j\lambda)\right\}$$

Fourier Space-Time analysis

Z levels are not included in the PCMDI dataset $\Longrightarrow$ Geostrophic relation at 500hPa + Latitudinal averaging (10% of the signal is lost)

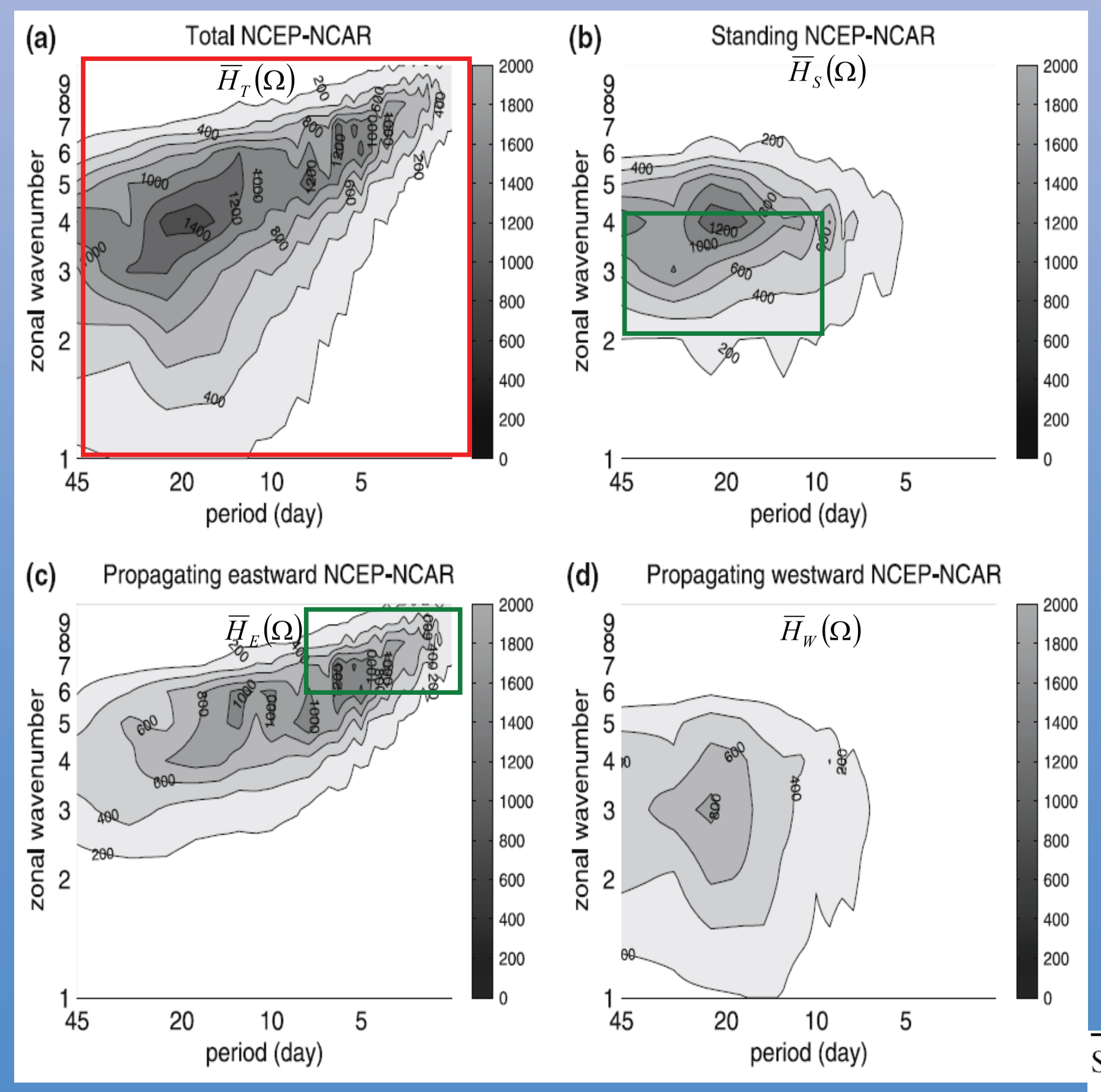
Components of the Hayashi spectra

$$H_T(k_j,\omega_m)=\tfrac{1}{2}\left(P_{\omega_m}(C_{k_j})+P_{\omega_m}(S_{k_j})\right)$$ Total variance

$$H_P(k_j,\omega_m)=\left|Q(k_j,\omega_m)\right|\Rightarrow H_S(k_j,\omega_m)=H_T(k_j,\omega_m)-H_P(k_j,\omega_m)$$ Standing waves

$$H_E(k_j,\omega_m)=\tfrac{1}{4}\left(P_{\omega_m}(C_{k_j})+P_{\omega_m}(S_{k_j})\right)+\tfrac{1}{2}Q_{\omega_m}(C_{k_j},S_{k_j})$$ Eastward waves

$$H_W(k_j,\omega_m)=\tfrac{1}{4}\left(P_{\omega_m}(C_{k_j})+P_{\omega_m}(S_{k_j})\right)-\tfrac{1}{2}Q_{\omega_m}(C_{k_j},S_{k_j})$$ Westward waves



Mean Hayashi spectra for NCEP/NCAR

Model Metrics

$$\overline{E}_a(\Omega)=\sum_{n=1}^{N}E_a^n(\Omega)=\frac{1}{N}\sum_{n=1}^{N}\sum_{k,m\in\Omega}H_a^n(\Omega)$$

$$\sigma_{E_a(\Omega)}=\sqrt{\frac{1}{N-1}\sum_{n=1}^{N}\left(E_a^n(\Omega)-\overline{E}_a(\Omega)\right)^2}$$

Global metrics

$$\overline{E}_T(\Omega)\qquad\sigma_{E_T(\Omega)}$$

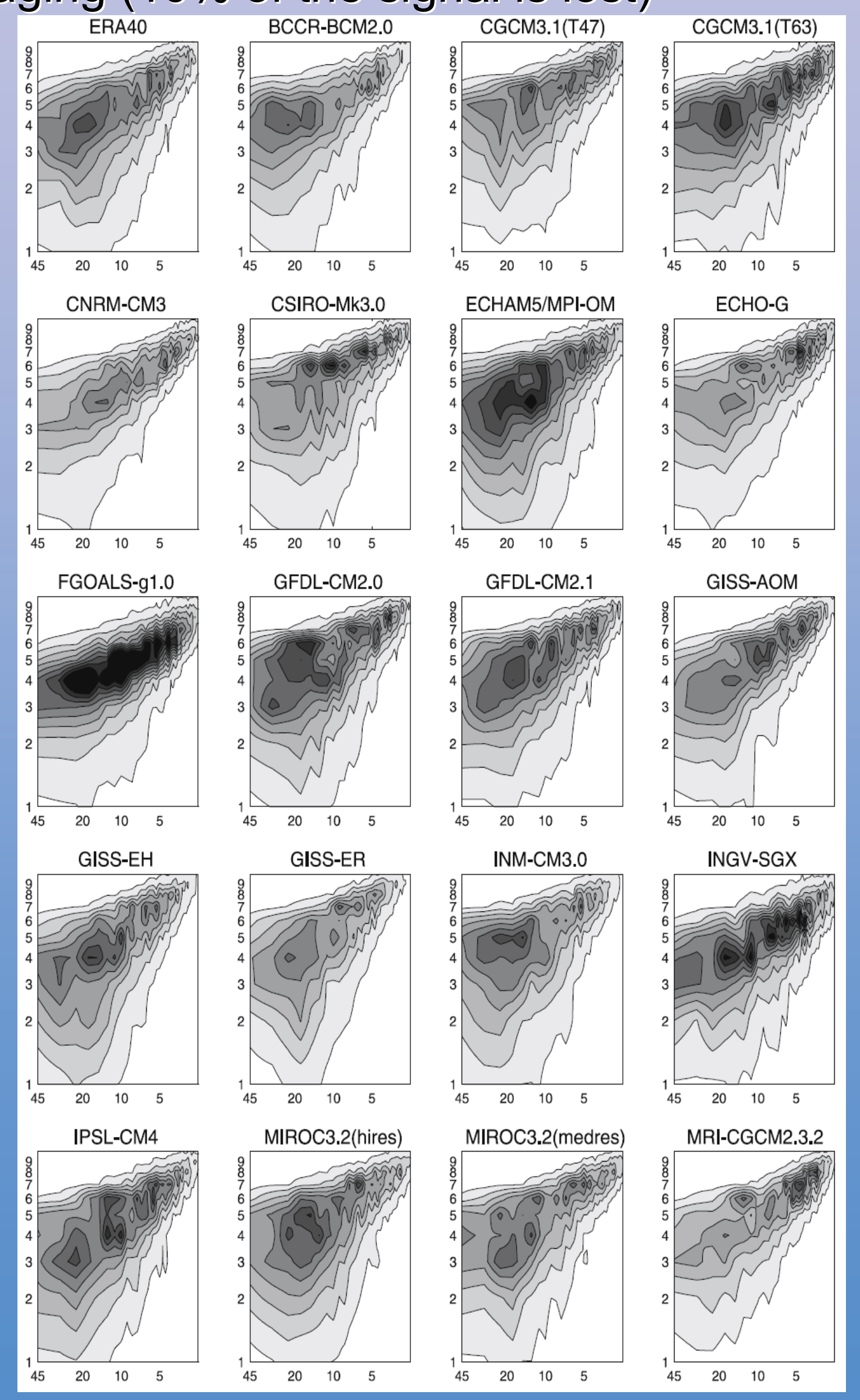
What is the total atmospheric wave activity and its variability?

Process metrics

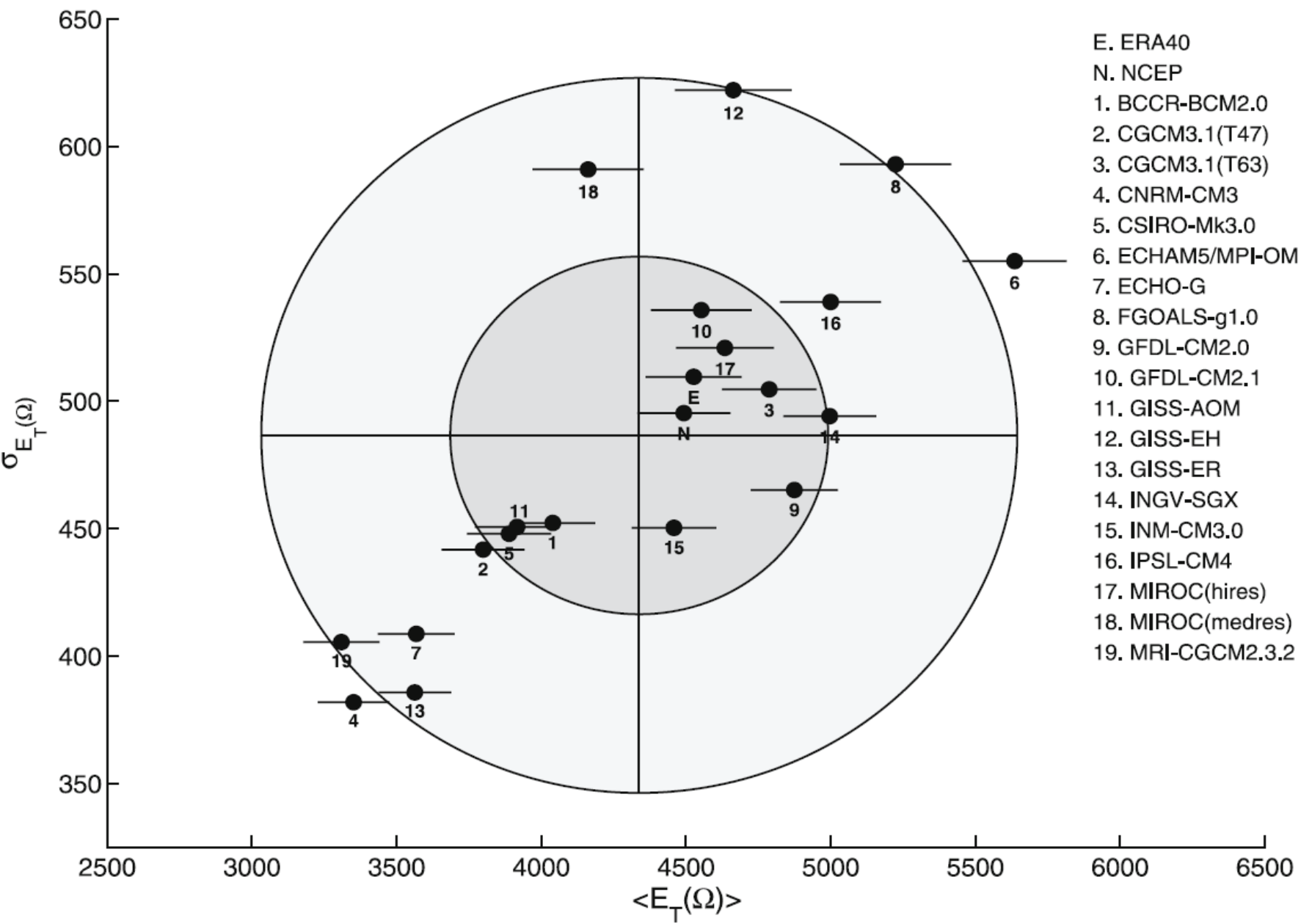
$$\overline{E}_S(\Omega_{LFLW})\quad\sigma_{E_S(\Omega_{LFLW})}\Big/\sqrt{N}$$
$$\overline{E}_E(\Omega_{HFHW})\quad\sigma_{E_E(\Omega_{HFHW})}\Big/\sqrt{N}$$

How well do the models simulate specific processes?

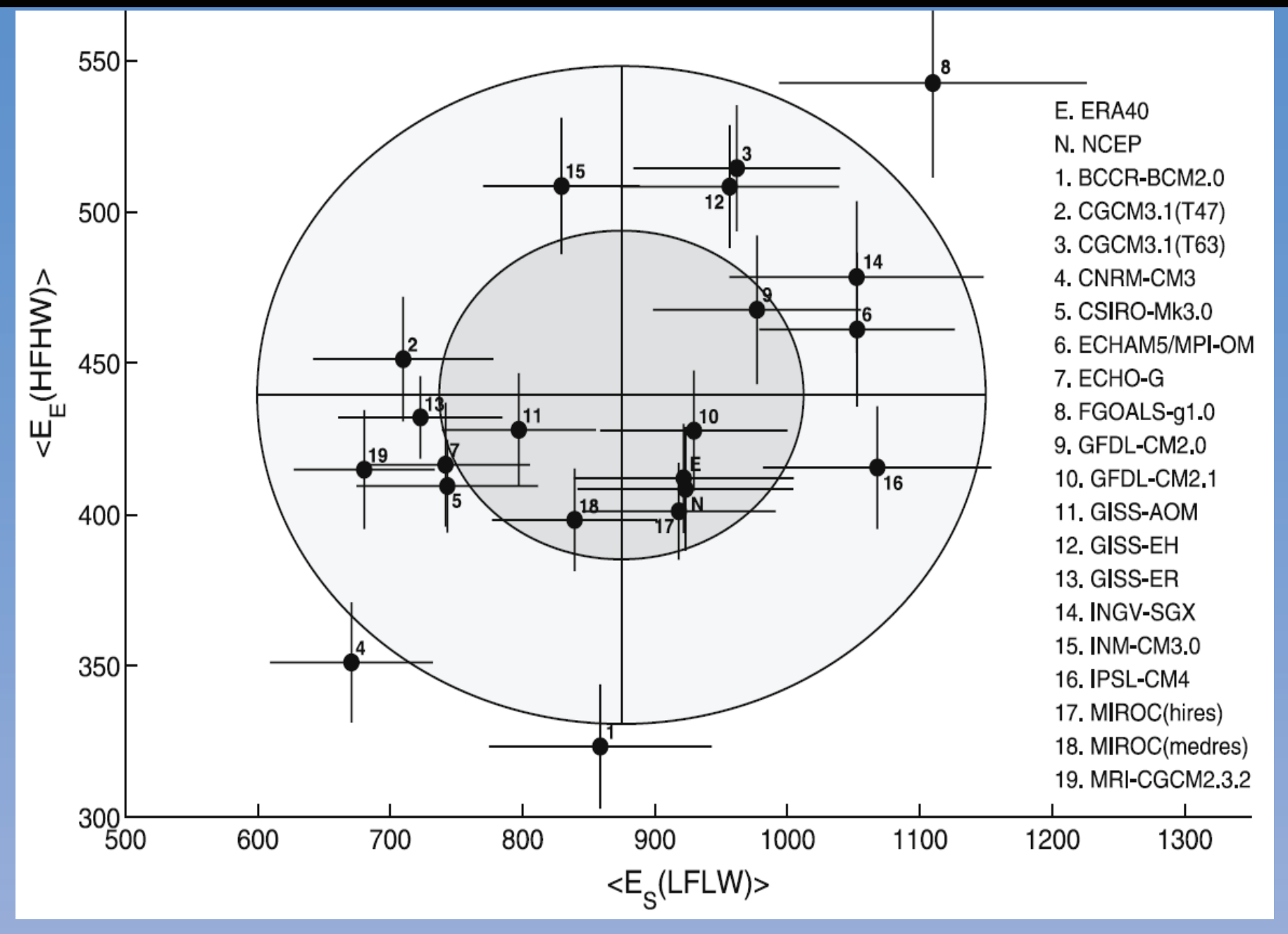
Spectral properties	$j_1 = 2, j_2 = 4$	$j_1 = 6, j_2 = j_{\max}$
$m_1 = 2, m_2 = 9$	Ω = LFLW	Ω = LFHW
$m_1 = 13, m_2 = 45$	Ω = HFLW	Ω = HFHW



Mean 1961-2000 Hayashi spectra for ERA40 and IPCC GCMS Total Signal

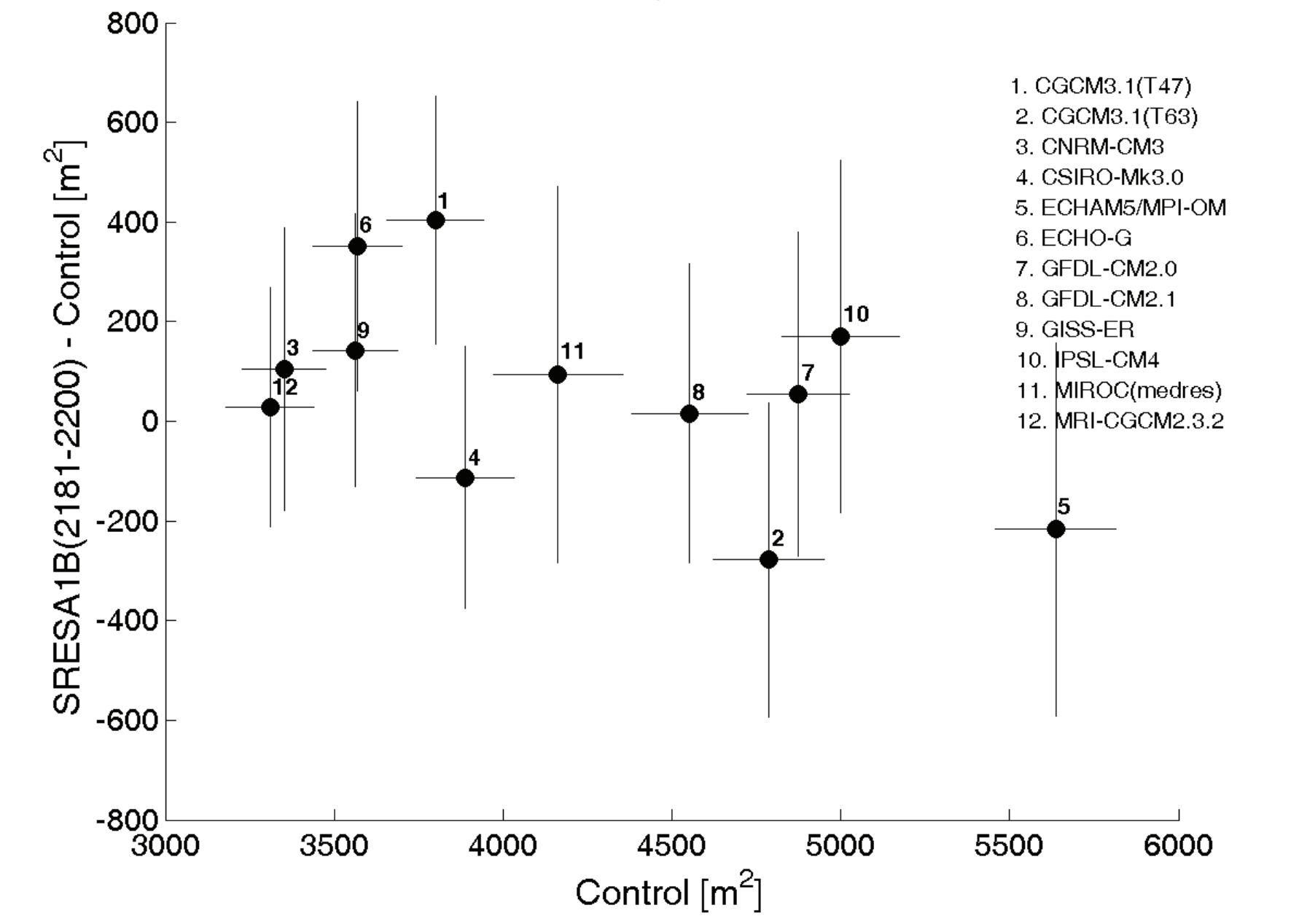


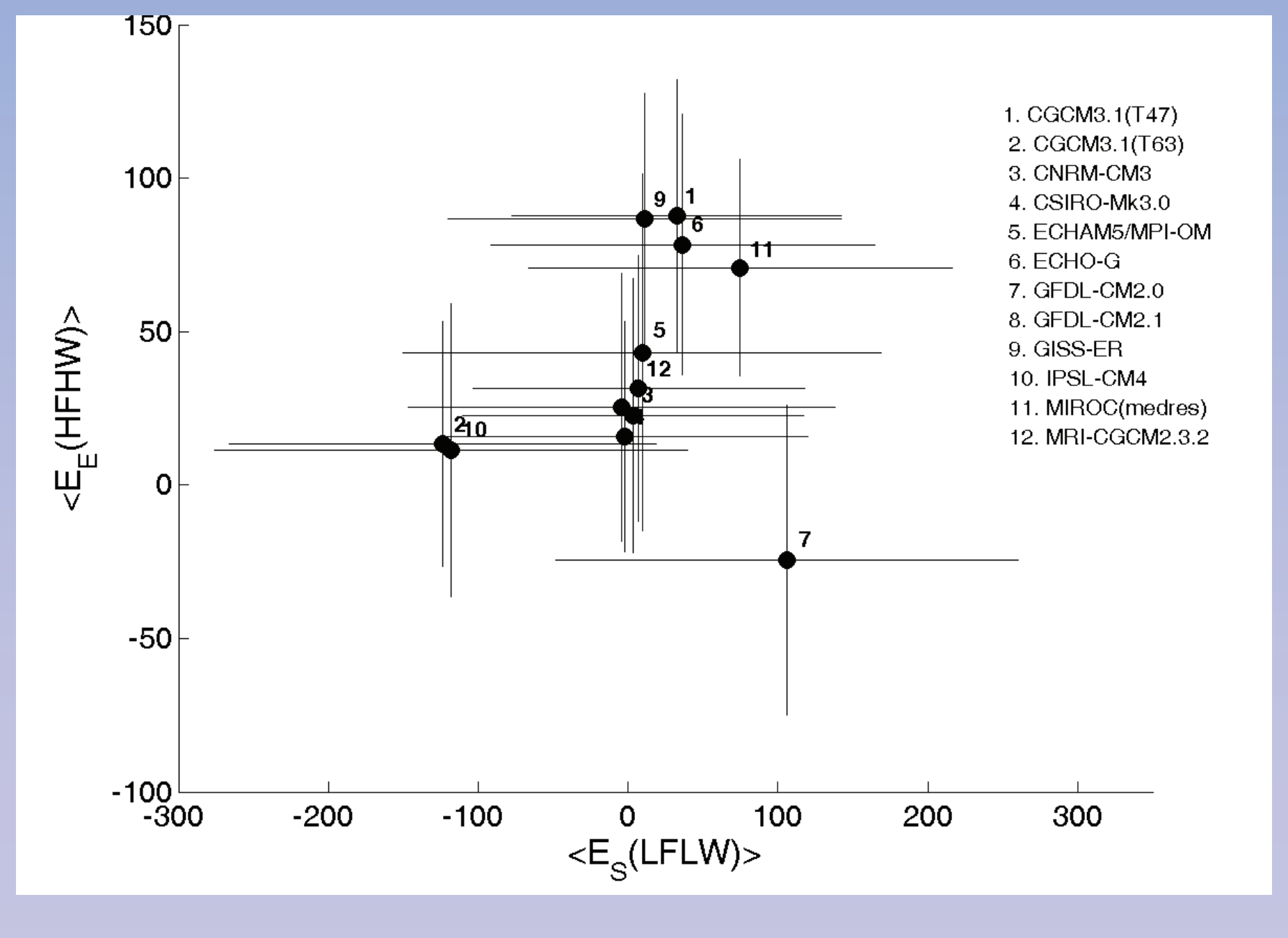
Global Metric



Process-Oriented Metric

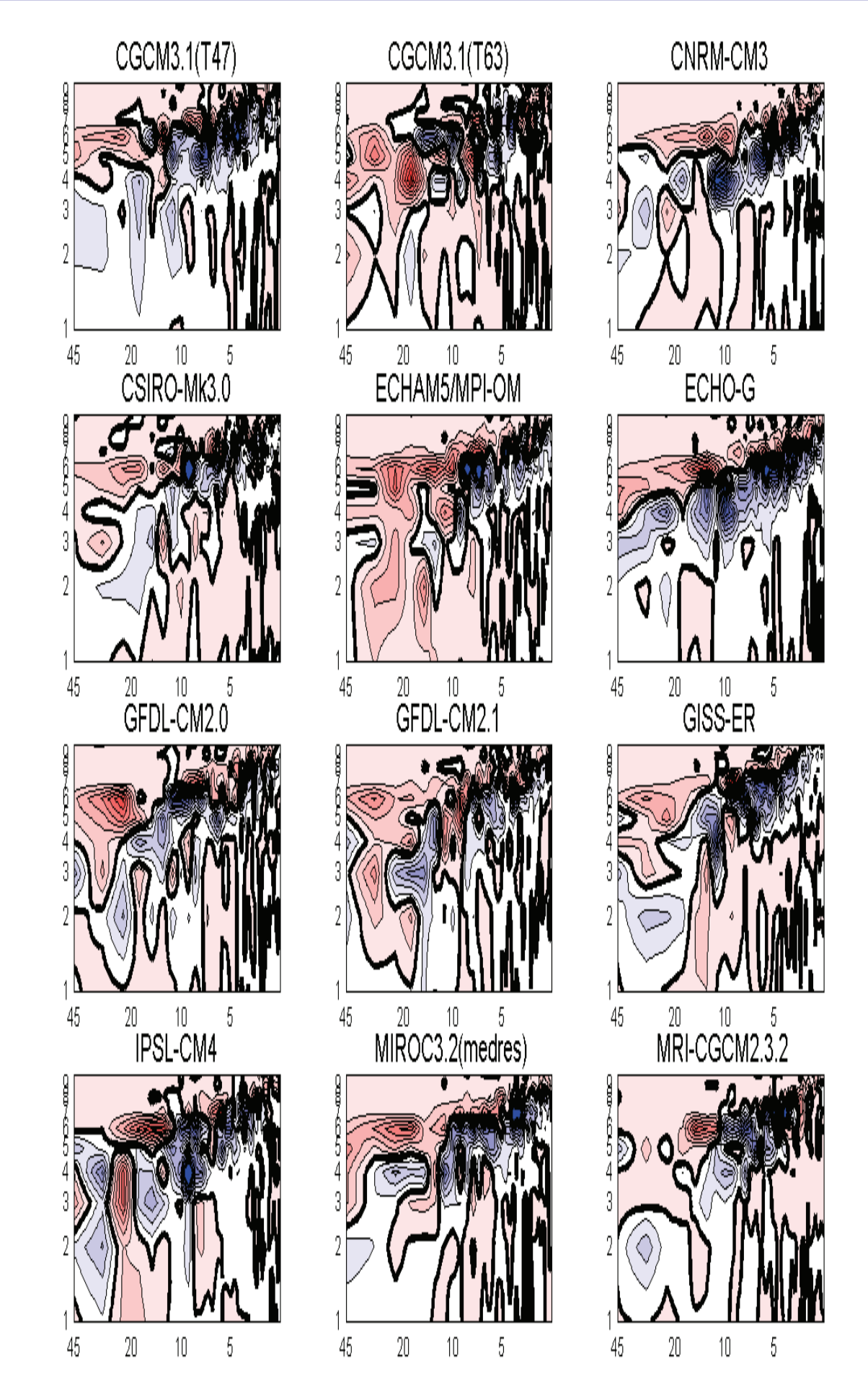
1961-2000 Mean





2180-2200 Mean Minus 1961-2000 Mean

Evaluation of the Performance of the IPCC GCM –runs



Mean 2180-2200 Minus Mean 1961-2000 Hayashi spectra - Total Signal

Summary & Conclusions

We have compared for 1962-2000, the estimate of the NH mid-latitude winter atmospheric variability within the XX century simulations of 19 GCMs included in the IPCC4ARt with the NCEP-NCAR and ECMWF reanalyses. We compute the Hayashi spectra of the 500hPa geopotential height fields and introduce an *ad hoc* integral measure of the variability observed in the NH on different spectral sub-domains. The total wave variability is taken as a global scalar metric describing the overall performance of each model, while the total variability pertaining to the eastward propagating baroclinic waves and to the planetary waves are taken as scalar metrics describing the performance of each model phenomenologically in connection with the corresponding specific physical process.

Only two very high-resolution global climate models have a good agreement with reanalyses for both the global and the process-oriented metrics. Large biases, in several cases larger than 20%, are found in all the considered metrics between the wave climatologies of most IPCC models and the reanalyses, while the span of the climatologies of the various models is, in all cases, around 50%. In particular, the travelling baroclinic waves are typically overestimated by the climate models, while the planetary waves are usually underestimated, in agreement with what found is past analyses performed on NWF models.

When comparing the results of similar models, we note that in some cases the vertical resolution of the atmosphere, the adopted ocean model, and the advection schemes seem to be critical in the bulk of the atmospheric variability. In particular, the vertical resolution should impact the meridional and vertical heat fluxes associated with baroclinic perturbations, whereas differences in the subgrid-scale orography parameterization may be a critical element for the planetary waves.

The models ensemble obtained by arithmetic averaging of the results of all models is biased with respect to the reanalyses but is comparable to the best 5 models. Nevertheless, the models results do not cluster around their ensemble mean.

A relevant questions is whether and, if yes, how much the statistical properties of the atmospheric waves change when global warming conditions are considered. We have then evaluated the differences between the climatological properties of the 2181-2200 period (SRESA1B scenario, stabilized 720 ppm CO_2 concentration after 2100) and the 1961-2000 period.

The difference between the mean spectra reveal that shift in the relative weight of the spectral components are apparent: for a given period the waves tend to become longer in wavelength, and for a given wavelength periods tend to become shorter. Using the linear Eady wave theory as heuristical paradigm, we might guess that the product of the height of the tropopause and or the Brunt-Vaisala frequency may be increasing as result of Global Warming. When going to the quantitative estimators provided by the metrics we have introduced in this work, we have that for most GCMs the total wave activity seems to increase as a result of Global warming. A notable exception, with respect to the very high resolution GCMs, is given the ECHAM5 model, which had the strongest positive bias in the control run. Note also that the two versions of the CGCM3.1 model give opposite and incompatible results. When looking at the process-oriented metrics, we have that almost all models foresee an increase in the short eastward propagating waves, whereas the change in the standing long waves seems less relevant. Note that these resulst are in apparent contradiction with what could be guessed by baroclinic adjustment theory with decreasing meridional temperature gradient, due to the polar amplification of the warming: water vapour enrighment-driven enhancement of the perturbations might be at work.