

## CHAPTER 1

### GLOBAL-SCALE DECADAL HYPER MODES

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The article discusses the idea of global-scale multi-decadal hyper modes. In this simple stochastic model it is illustrated that multi-decadal climate variability is globally linked via the tropical regions by atmospheric teleconnections. The persistence of higher latitudes SST variability with an exponentially decreasing mixing into the deeper oceans leads to a power spectrum with a low-frequency tail and different slope compared to a red noise power spectrum. The main elements of this stochastic model do not involve any ocean dynamics beyond local vertical mixing.

#### Introduction

The climate varies on all time and spatial scales. The processes that cause the variability on different time and spatial scales can be quite different. They may be caused by external forcings (either natural such as volcano or variations in the solar radiation, or anthropogenic) or by chaotic process internal to the climate system. The aim of this study is to explore some simple mechanisms that lead to internal climate variability on multi-decadal time scales and on global spatial scales.

The study is based on Dommengeset and Latif <sup>1</sup> in which a simple mechanism for global-scale hyper modes was presented. The starting point for the analysis is the assumption that internal climate variability follows from the simple stochastic climate model after Hasselmann <sup>2</sup>. Dommengeset and Latif <sup>1</sup> extended Hasselmann's red-noise hypothesis by two aspects: First atmospheric teleconnections will

link remote regions on longer time-scales to synchronize the variability globally. Second the stratification of the ocean leads to an effective heat capacity of the ocean that is different on different time-scales. This alters the power spectrum to be slightly different from the red noise power spectrum by adding a low-frequency tail to the total variance.

In the study presented here we will further explore the hyper mode idea and discuss some of its aspects in more detail. The analysis starts with exploring the characteristics of the global teleconnections on longer time-scales. We will in particular focus on the tropical link in the teleconnections. In section 4 we will explore the characteristics of the power spectrum and discuss how different aspects of the climate dynamics alter the power spectrum. Finally, we will summarize the hyper modes idea with a simplified sketch and discuss current limitations in the understanding.

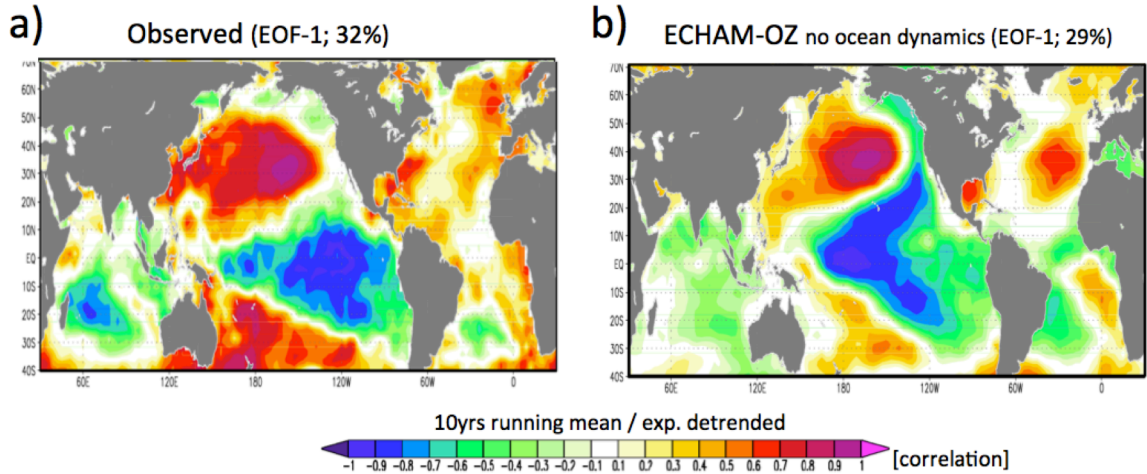


Fig. 1: (a) the leading EOF-mode of observed 10yrs running mean exponentially detrended SST. (b) the leading EOF-mode in the ECHAM-OZ simulation of 40yrs running mean SST. The percentage values in the headings are the explained variance for each mode.

### The spatial pattern of the leading Hyper Mode

An objective way to determine the spatial structure or teleconnections of global-scale multi-decadal climate variability is by means of principal component analysis (PCA). The leading empirical orthogonal functions (EOFs) are a very efficient way of presenting the most dominant spatial patterns or teleconnections. In Fig. 1a the EOF-1 mode is shown in terms of the correlation of the PC-1 with global SST based on the HADISST data set<sup>3</sup> from 1870-2004. The SST for this analysis has been filtered by a 10yrs running mean and by an exponential detrending to focus on internal natural variability on multi-decadal time-scales. A few aspects are remarkable about this pattern:

- The pattern is a near global multi-pole structure with large correlation values on both hemispheres and in all three oceans basins. Here it needs to be noted that PCA does have some constraints that do enforce global patterns<sup>4,5</sup>. However, from simple red noise processes, such as isotropic diffusion, we would expect a monopole as the leading EOF-mode. The fact that we have a quite significant multi-pole structure is a strong support for a global-scale teleconnections on the multi-decadal time-scale.
- It resembles the El Nino pattern in many aspects. The pattern in the whole of the Pacific and in the Indian Ocean is quite similar to the El Nino pattern. However, the equatorial Pacific node is wider in its lateral extend and the structures in the Atlantic do not fit to the typical El Nino teleconnections.

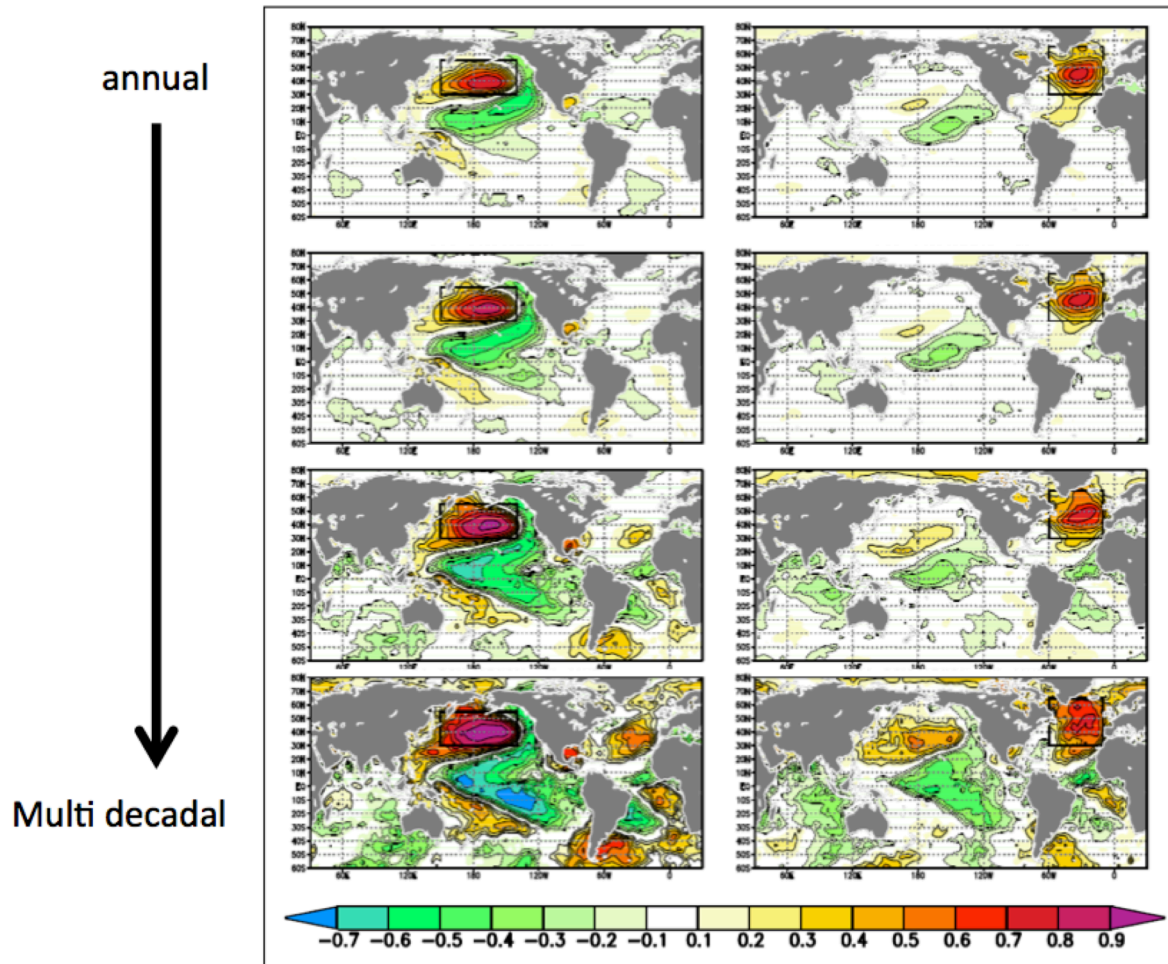


Fig. 2: left column: The correlation of the SST in the 2000yrs ECHAM-OZ simulation averaged over the North Pacific box with the SST in all regions of the world. Upper panel for high-pass 5yrs filter annual mean SST, second from the top for 5yrs to 10yrs filtered SST, third from the top for 10yrs to 40yrs filtered SST and lower panel for low-pass 40yrs SST. Right column the same as left, but for the SST-box in the North Atlantic.

- The EOF-1 mode does explain about 1/3 of the total variance on the multi-decadal time-scales suggesting a single mode does explain a large fraction of the variability. The effective number of spatial degrees of freedom (after Bretherton et al. [1998]),  $N_{spatial}$ , is about 6, again supporting the idea that the global-scale multi-decadal climate variability has very few degrees of

freedom.

Again, a note of caution has to be given here. The relative short time period of the observations can artificially force low  $N_{spatial}$ . Further, the limited number of observations in the earlier periods of the data set lead to large gaps in the data, which can also artificially force low  $N_{spatial}$ .

Given the interesting observational findings and knowing about the limitations of these observations we would like to find further support for these global-scale modes from model simulations to back-up the observational findings and to explore the physical mechanism causing these structures.

We therefore repeat the analysis for a coupled general circulation model (CGCM) simulation with fixed external boundary conditions (e.g. no greenhouse gas forcings and no change in the incoming solar radiation). The simulation we use is based on the ECHAM5 atmospheric general circulation model in low (T31;  $3.75^\circ \times 3.75^\circ$ ) resolution coupled to the simple single column ocean mixed layer model OZ. The model is integrated over 2000yrs and we refer to this model simulation as ECHAM-OZ.

The ECHAM-OZ simulation has some important characteristics in comparison to the observations: First, in the model world we do not have any data sampling problems. Second, the model has 2000yrs of data, which is 20-times more than we have from observations, which allows us to make stronger statements about the variability in this data set. Third and most importantly for the following discussion, the model makes an important simplification: ocean points do not interact laterally and subsequently all spatial coherence or teleconnections are entirely a result of the atmospheric dynamics. Thus ocean dynamics are essentially neglected.

If we compare the leading mode in the ECHAM-OZ simulation with the observations, we can find several important results:

- The two patterns of the leading EOF-modes match very well (pattern

correlation of 0.9). This holds for the structure within the whole of the Pacific, but also holds for the teleconnections to the Indian and Atlantic Oceans.

- The explained variance of the EOF-1 in the ECHAM-OZ simulation is roughly the same as in the observations. The ECHAM-OZ simulation has also a relatively low  $N_{spatial}=9$ , but still larger than the observations, which could suggest that the much shorter observations period does have some sampling problems. Note that  $N_{spatial}=20$  in the ECHAM-OZ simulation for annual mean SST without any low-pass filtering.
- Most remarkable is that the ECHAM-OZ simulation has the same El Nino-like pattern in the tropical Pacific, despite the fact that the ocean has no lateral dynamics and all spatial structure is entirely forced by the atmospheric teleconnections. It illustrates that El Nino like SST patterns can exist without any ocean dynamics, but forced by atmospheric feedbacks. This is supported by other studies as well <sup>6,7</sup>.

In summary, we find that the ECHAM-OZ simulation gives a good first order representation of the leading mode of observed multi-decadal global-scale climate variability. Therefore, it appears to be a good tool to study the physical mechanism of this type of climate variability.

### **The tropical link of the inter-hemispheric teleconnections**

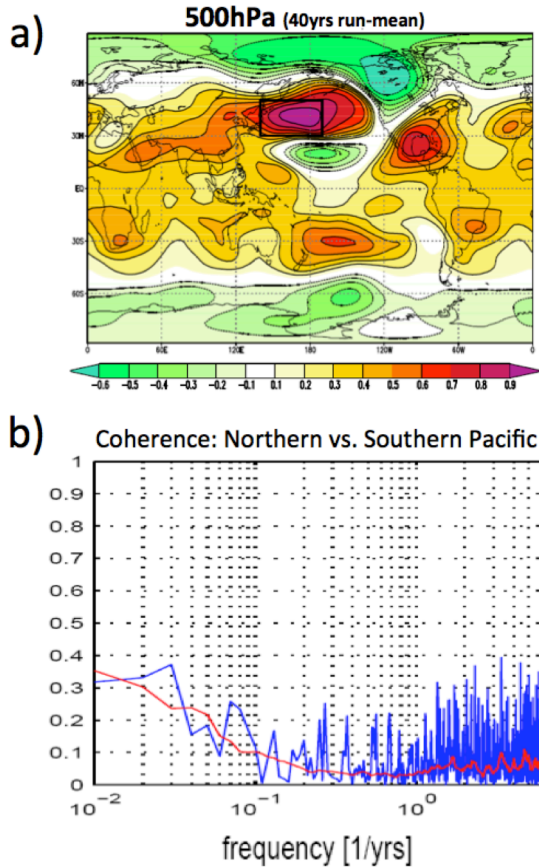


Fig. 3: (a) Correlation of the 500hPa geopotential height in the ECHAM-OZ simulation in the box over the western North Pacific with the geopotential height globally for 40yrs low-pass filter data. (b) cross-spectral coherence between the 500hPa geopotential height in the North Pacific box with the mid-latitudes South Pacific (20°S-40 °S; 170°E-230 °E). The red line is a smoothed version of the blue line to reduce the noise.

In the previous section we already indicated that the global modes of variability on the shorter, inter-annual, time-scales are much more complex ( $N_{spatial}=20$ ). It suggests that on the longer-times scales the more localized smaller scale modes of variability are somehow unified or linked by some teleconnections. To illustrate how this link may operate, we analyze how the global

correlation patterns change with time-scales. We therefore defined two reference regions in the North Pacific and North Atlantic (see boxes in Fig. 2) and correlate the mean SST in these boxes with the SST in all parts of the oceans. Fig. 2 illustrates how the teleconnections of these boxes changes with time-scales: On the shorter time-scales (annual) both SST-boxes correlate mostly to nearby regions. As the time scales increase to longer periods, the correlation of the SST-boxes spread out to near global teleconnections. Most interestingly, the teleconnections of the SST-box in the North Pacific and North Atlantic become more similar. It is also important to note, that even at the shortest time scales both SST-boxes have a similar link to the subtropical to equatorial north Pacific, suggesting that this region may be a central element to create the global link to remote regions.

To illustrate, that multi-decadal atmospheric variability in the northern and southern hemisphere are indeed linked we can analysis the global correlations of the 500hPa geopotential heights in the north Pacific with the rest of the world, see Fig. 3a. We find remarkable high correlations all over the world and in particular in the southern extra-tropical Pacific (at around 30°S). With the help of cross-spectral analysis we can illustrate that this inter-hemispheric link becomes dominant only on the very long time-scales of decades and longer, see Fig. 3b.

The question arises, whether the tropical Pacific SSTs cause this link, or does the link exist independent of tropical Pacific SSTs. We can address this question by performing a sensitivity experiment with the ECHAM-OZ model in which we hold the SST in the tropical Pacific (from 20°S to 20°N) fixed to

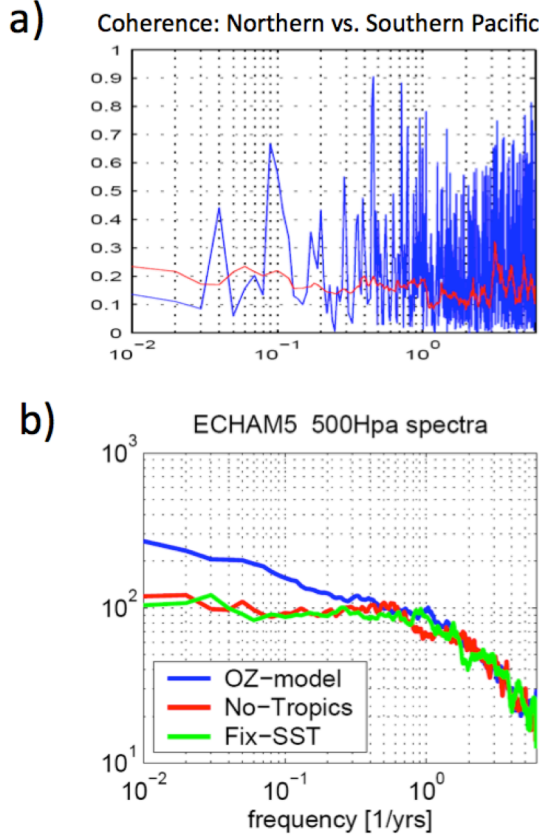


Fig. 4: (a) cross-spectral coherence between the 500hPa geopotential height in the North Pacific box with the mid-latitudes South Pacific as in Fig. 3b, but for the ECHAM-OZ<sub>noeq</sub> simulation. (b) power spectrum of the 500hPa geopotential height in the North Pacific box in the ECHAM-OZ (blue), ECHAM-OZ<sub>noeq</sub> (red) and the ECHAM<sub>FIXSST</sub> (green) simulations.

climatology (no SST variability allowed). The simulation was integrated for 500yrs and is referred to as ECHAM-OZ<sub>noeq</sub>.

Fig. 4a shows the cross-spectral coherence between the 500hPa geopotential heights in the north Pacific box and in the south Pacific box. In comparison to the ECHAM-OZ

simulation (Fig. 3b) we do not see any increase in coherence at any time-scale. The coherence is low on all time scales and gives no indication of coherent variability between the two regions. Thus we can conclude that the tropical SST variability is a necessary link for the inter-hemispheric interactions.

We can go one step further and compare the results to a simulation without any SST variability (climatological SST everywhere; atmosphere only simulation). This sensitivity simulation is also integrated for 500yrs and is referred to as ECHAM<sub>FIXSST</sub>. Fig. 4b shows the power spectrum of 500hPa geopotential heights in the North Pacific box for the three different simulations. Only the simulation that does have tropical SST variability shows an increase in spectral variance for the longer, multi-decadal time-scales. The simulation with extra-tropical SST variability and the one without any SST variability do not differ in the 500hPa geopotential heights power spectrum at all. This suggests that the tropical SST variability does not only cause the link between the hemispheres, but also does cause most of the variance on the multi-decadal time-scales in the atmospheric variability in the extra-tropics.

### The time-scale characteristics of stochastic climate variability

We now like to analyze the time-scale behavior of global-scale climate variability. The aim of this analysis is to understand what causes the multi-decadal time-scale climate variability.

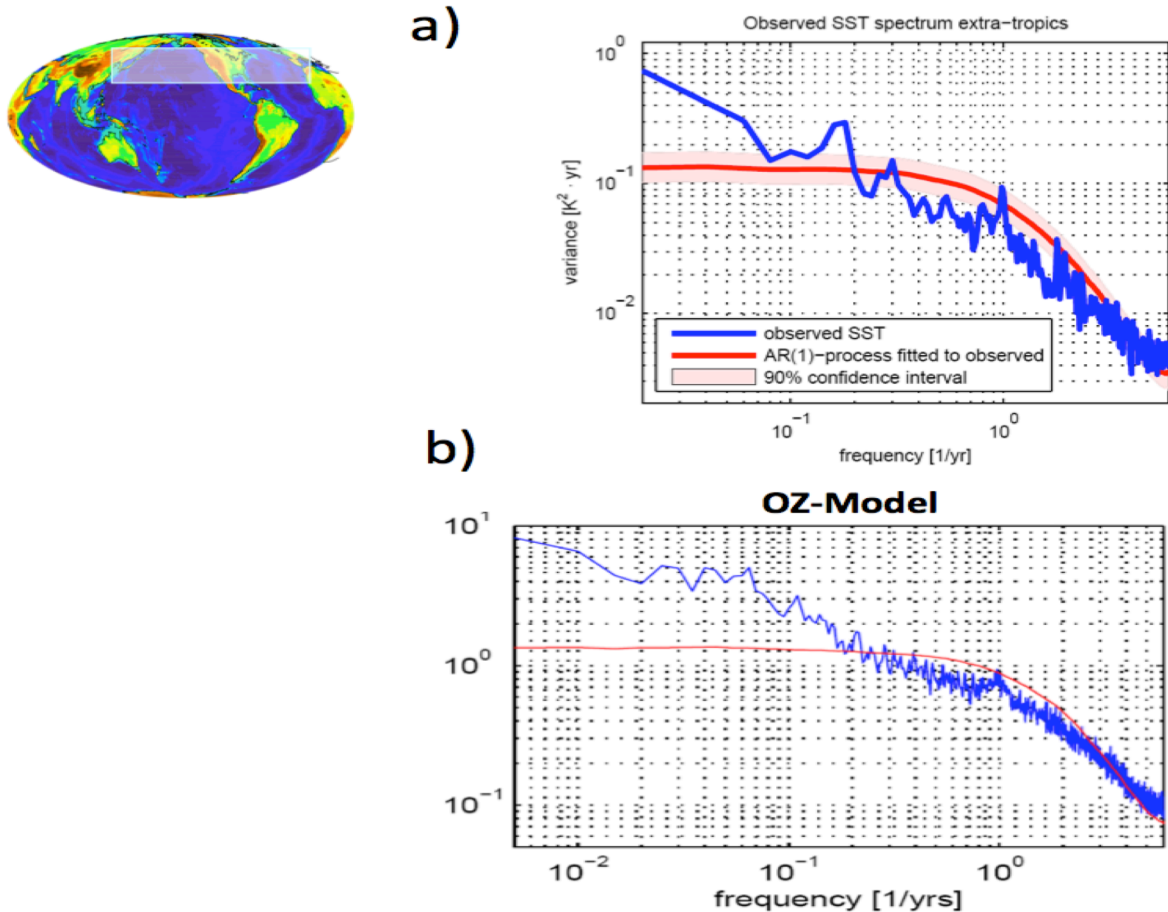


Fig. 5: (a) the average power spectrum of the observed SST (blue line) for all points in the mid-latitudes of the North Pacific and Atlantic (see box in map). The red line is the fitted red noise power spectrum with its 90% confidence interval (light red shading). (b) as (a), but for the 2000yr ECHAM-OZ simulation.

Stochastic climate models will often have a quite clear signature in the power spectrum of the variability. By comparing the observed power spectrum of SST variability with theoretical stochastic models we can gain some insight into the processes that cause the SST variability.

We start with a look at the average power spectrum in the mid-latitudes SST variability of the northern North Pacific and Atlantic, as these regions are known to have relatively strong multi-decadal SST variability. Fig. 5a

shows the mean power spectrum of the northern North Pacific and Atlantic against a fitted red noise power spectrum. The red noise power spectrum represents the simple stochastic climate model that assumes that random weather fluctuations (white noise) are integrated by a fixed heat capacity, such as the ocean surface mixed layer.

We can first of all recognize that the observed mean SST power spectrum increases in variance for increasing periods (smaller frequencies). This increase (the slope of the

power spectrum) is almost constant through out all time-scales and it does not stop at long periods.

This time-scale signature is quite different from the fitted red noise spectrum. The fitted red noise spectrum has a faster increase in variance for decreasing frequencies on time-scales from months to about a year. It then saturates at some variance level and does not increase in variance any more for periods longer than a decade.

The fitted red noise process assumes, by construction, the same lag-1 (mon.) auto-correlation as in the observed SSTs. Thus we can conclude that the time scale behavior of the observed SSTs does not fit to a red noise process. The signature of the observed SST power spectrum is a continuous increase in variance with a slope that is flatter than that of a red noise process, but continues with out any sign of saturation.

The SST power spectrum of the ECHAM-OZ simulation for the North Pacific and Atlantic is quite similar in this respect to the observed power spectrum. The much longer time series of the simulation allows us to extend the power spectrum to longer periods. On the longer periods the ECHAM-OZ spectrum becomes even more clearly separated from the fitted red noise power spectrum. What is also quite remarkable is that the ECHAM-OZ SST variability still increases with no sign of saturation until time scales of 100yrs, despite the fact that this model simulation does not include any ocean dynamics beyond the single column vertical mixing.

The dynamics of the ECHAM=OZ model can be simplified to a simple stochastic model of the SST anomalies,  $T$ :

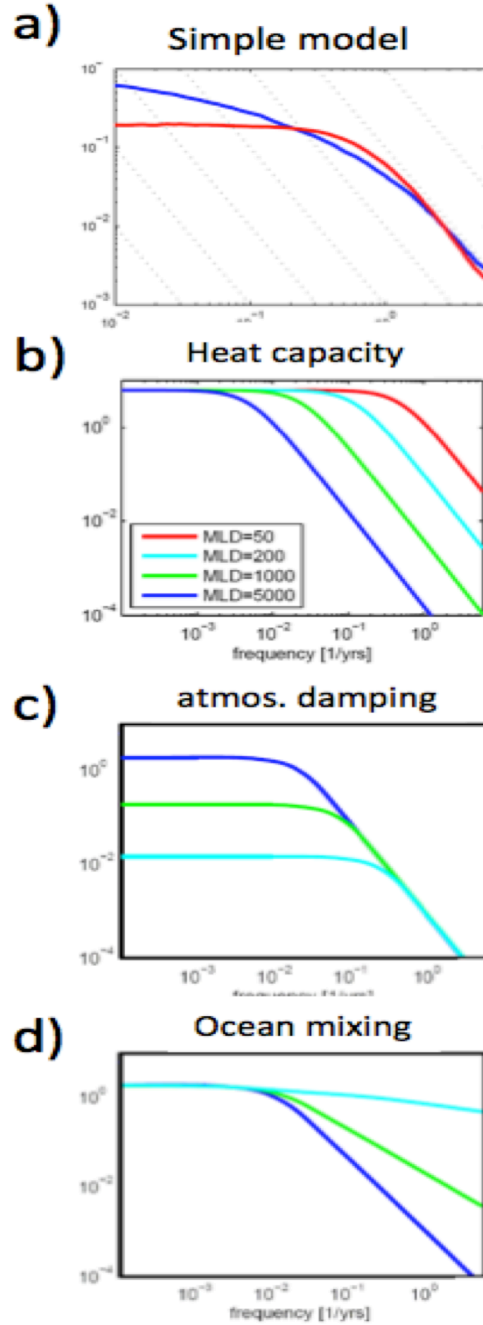


Fig. 6: (a) power spectrum of the SST from eq. [1] with realistic parameters (blue line) compared against a fitted red noise spectrum (red line). (b) red noise power spectra for different heat capacities  $c$ . (c) red noise power spectra for different damping parameter  $\gamma_{surf}$  (dark blue weakest, light blue strongest). (d) the power spectra of the SST from eq. [1] with different mixing profiles for  $K_z$  (dark blue fully mixed ocean, green exponentially decreasing mixing, light blue no mixing thin skin layer ocean).



### Elements of global Hyper Modes

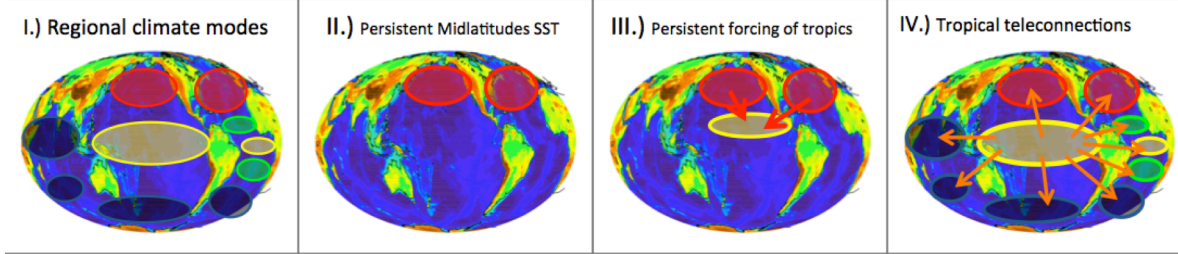


Fig. 7: Sketch summarizing the elements of the global-scale multi-decadal hyper modes.

$$c \frac{dT}{dt} = -\gamma_{surf} \cdot T + \kappa_z \cdot \nabla_z^2 T + \xi_{surf} \quad (1)$$

The heat capacity of the surface layer,  $c$ , is assumed to be a constant. The damping of  $T$  is proportional to the constant,  $\gamma_{surf}$  and the vertical mixing below the mixed layer depth is proportional to  $\kappa_z$  (as a function of the depth underneath the mixed layer). The system is forced at the surface by white noise weather heat fluxes,  $\xi_{surf}$ .

The power spectrum of this simple model, for realistic parameters, is similar to that observed or in the ECHAM-OZ simulation, see Fig. 6a. We can discuss how the time-scale behavior of this model depends on the model parameters. The heat capacity,  $c$ , is damping the high-frequency variability, but does not change the amount of variability on the longer time-scales. It essentially shifts the point in the power spectrum, at which the variance saturates (see Fig. 6b). The damping  $\gamma_{surf}$  shifts the variance at frequency zero (infinitely long periods) down (see Fig. 6c). This also shifts the point in the power spectrum, at which the variance saturates. A zero damping would have infinite power at

frequency zero. Note, that the strength of the damping is mostly an atmospheric characteristic and will depend on the spatial size of the SST variability. A small-scale SST anomaly is more strongly damped than a global scale SST anomaly, because the small-scale SST anomaly is damped by exchanging heat with nearby regions. Thus, the damping  $\gamma_{surf}$  will be spatial scale dependent and it will be weakest for global-scale SST pattern.

Finally, the mixing profile underneath the mixed layer  $\kappa_z$  alters the slope of the power spectrum. In the extreme case of a perfectly mixed ocean (mixed layer goes to the bottom of the ocean) the power spectrum reduces to that of a red noise power spectrum. In the other extreme case of no mixing and a mixed layer of a thin ocean surface skin the power spectrum becomes a white noise power spectrum. The in between realistic cases of an observed mixed layer depth with an exponential decreasing mixing profile underneath the mixed layer gets the power spectrum with the observed slope (Fig. 6a), that is shallower than red noise, but continues to increase through-out all observed time scales.

The question arises: On what time-scales will the power spectrum of this simple stochastic

climate model saturate? For the realistic parameters we have chosen in Fig. 6a it seems to saturate in the 100yrs to 1000yrs time-scales. In the ECHAM-OZ simulation with a 800m deep ocean it seems to be similar, but it is yet not clear, as the 10,000yrs long simulations needed to test this do not yet exist. In the observations it is unclear, but it will very much depend on how much deep ocean mixing and ocean internal or atmosphere-ocean coupled modes, such as ENSO, will affect this stochastic mechanism.

### Summary and discussion

We can summarize the global-scale multi-decadal hyper modes idea by the sketch shown in Fig.7.

1. On the shorter, seasonal to interannual, time-scales most climate variability is essentially regional (e.g. ocean basin, or near continental) with only weak teleconnections to remote regions (Fig. 2 and Fig. 3b).
2. In the higher latitudes of the northern hemisphere and potentially also on the southern hemisphere the SST variability can persist on multi-decadal time-scales due to the deeper mixing in the oceans at higher latitudes (Fig. 5). This SST power spectrum has more variance on multi-decadal and longer time scales and a different slope than a simple red noise process (Fig. 5).
3. These high latitudes SST modes seem to interact with the subtropical Pacific (Fig. 2).
4. The tropical Pacific or the tropical SST in general appear to be the central link that connects global SST modes across both hemispheres and across ocean basins (Fig. 4).
5. On the multi-decadal time scales the variability in all ocean basins is linked via the tropics to have synchronized variability leading to the global scale hyper modes (Fig. 1).

### Acknowledgment

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### References

1. Dommenget, D. and M. Latif, 2008: Generation of hyper climate modes. *Geophysical Research Letters*, 35, -.
2. Hasselmann, K., 1976: STOCHASTIC CLIMATE MODELS .1. THEORY. *Tellus*, 28, 473-485.
3. Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research-Atmospheres*, 108, -.
4. Dommenget, D., 2007: Evaluating EOF modes against a stochastic null hypothesis. *Climate Dynamics*, 28, 517-531.
5. Monahan, A. H., J. C. Fyfe, M. H. P. Ambaum, D. B. Stephenson, and G. R. North, 2009: Empirical Orthogonal Functions: The Medium is the Message. *Journal of Climate*, 22, 6501-6514.
6. Dommenget, D., 2010: The slab ocean El Nino. *Geophysical Research Letters*, 37, -.
7. Clement, A., P. DiNezio, and C. Deser, 2011: Rethinking the Ocean's Role in the Southern Oscillation. *Journal of Climate*, 24, 4056-4072.