Chapter 11

Global-Scale Decadal Hyper Modes

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This article discusses the idea of stochastic global-scale multi-decadal Hyper Modes. The chapter will first illustrate the spatial pattern and time-scales of the leading mode of global-scale multi decadal climate variability in observations and model simulations. It is further shown that the main characteristic of the leading mode of global-scale multi-decadal variability can be simulated in the absence of any ocean dynamics and by atmospheric teleconnections only. In a simple stochastic model for the Hyper Modes, local (basin-wide) modes of variability act mostly on interannual time-scales forced by atmospheric white noise. Most of these modes have a weak link to the tropical regions via atmospheric teleconnections, which on longer (decadal) time-scales become more dominant. The tropical link provides a synchronization of the local modes to near global multi-decadal Hyper Modes. 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.

1. Introduction

The climate varies on all time and spatial scales. The processes that cause the variability on different time and spatial scales can be either 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 basic idea of Hyper Modes was first mentioned by Tim Barnett in the 1990s (personal communications; not published), proposing that on longer time-scales some large-scale (near global) teleconnections may be hidden in the climate variability that connects most of the local modes, which act on shorter time-scales. The name 'Hyper' is somewhat in analog to the "Hyper Space" used in space science, but it should not be seen as indication of a "Hyper Space" in climate variability.

The study present here is based on Dommenget and Latif (2008) 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 (1976). Here the chaotic weather fluctuations are integrated by the slow systems of the climate (oceans) leading to reduced short time climate fluctuations and increased low-frequency (decadal) variability.

The Hasselmann climate model thus describes mostly a time scale behavior, but gives little to no insight into the spatial organization of low-frequency variability.

Dommenget and Latif (2008) 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 and spatial 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 the next section 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.

2. 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 from 1870–2004 (Rayner *et al.*, 2003). The SST for this analysis has been filtered by a 10-year 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 ocean basins. Here it needs to be noted that PCA does have some constraints that do enforce global patterns (*e.g.*, Dommenget, 2007; Monahan *et al.*, 2009). In particular a spatial red noise processes, such as isotropic diffusion,

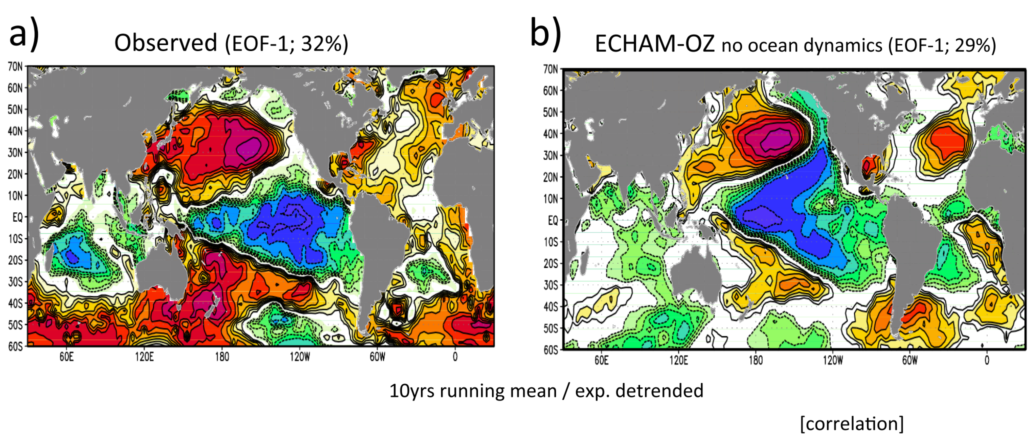

Fig. 1. (a) The leading EOF-mode of observed 10 yrs running mean exponentially detrended SST. (b) the leading EOF-mode in the ECHAM-OZ simulation of 40 yrs running mean SST. The percentage values in the headings are the explained variance for each mode.

would result into a monopole as the leading EOF-mode followed by dipoles (Dommenget, 2007). The fact that we have a quite significant multi-pole structure is a strong support for a non-trivial global-scale teleconnections on the multi-decadal time-scale that is significantly different from a simple spatial red noise process or the geometrical constraints of PCA.

- 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.
- It resembles more a central Pacific El Nino pattern than a east Pacific El Nino. This may indicate that the central El Nino type of variability may have more of a low frequency nature than the east Pacific type of El Nino, which was also discussed in other studies (Yu and Kim, 2011).
- 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 (Bretherton *et al.*, 1999), 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 relatively 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}., even though these gaps are interpolated in the HADISST data.

Given the interesting observational findings and knowing about the limitations of these observations we would like to confirm the existence of 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° × 3.75°) resolution coupled to the simple single column ocean mixed layer model OZ, which does not simulate any lateral interaction in the ocean (Dommenget and Latif, 2008). Each column of the OZ model has 19 levels and goes to 500 m depth. The model is dirven at the surface by heat fluxes and mechanical wind mixing following Niiler and Kraus (1977). The vertical mixing is thus a function of the wind input and decreases with depth. The density is a function of temperature and salinity, but only temperature is variable in this model, whereas salinity is kept at climatological profiles. The temperature of the lowest layer at a depth of 500 m is restored to the observed climatology.

The overall structure of this model is similar to other mixed layer models (*e.g.* Alexander and Penland, 1996), however it seems no other study has used such a model for studying longer (multi-decadal) time-scales.

The model is integrated over 2000-yr 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 2000-yr 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 (Fig. 1b) with the observations (Fig. 1a), 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 $N_{\text{spatial}} = 9$, but still larger than the observations, which could suggest that the much shorter observations period does have some sampling problems. Note that $N_{\text{spatial}} = 20$ 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 (Dommenget, 2010; Clement *et al.*, 2011).

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.

3. Limitations of Coupled General Circulation Model (CGCM) Simulations

In Fig. 1 we illustrated that the observed leading mode of global multi-decadal SST variability is well simulated in its spatial structure by the simple ECHAM-OZ model. It therefore seems reasonable to assume that state of the art CGCM simulations should also be capable of simulating the leading mode of global multi-decadal SST variability. Figure 2 shows the leading EOF-1 of the combined multi-model SST variability of seven CMIP3 preindustrial control simulations with each being 340-yr long (2380-yr in total). Although some of the features of the observed pattern are present in this leading EOF-1 mode, the pattern is not as close to the observed as in the ECHAM5-OZ simulation. It is mostly focused on the Indo-Pacific sector, it is missing most of the Atlantic pattern and it is much smaller in its explained variance.

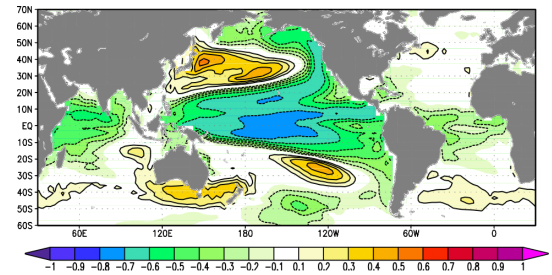

Fig. 2. Correlation maps of the leading EOF mode of detrended multi-decadal global sea surface temperatures (SSTs) as in Fig. 1, but for the CMIP3 multi-model ensemble. From Dommenget and Latif (2008).

This opens up the question: Why do the more sophisticated CGCM simulations have less skill in simulating the leading mode global multi-decadal SST variability? To some extent this is related to the fact that fully coupled climate models, CGCMs, have much more degrees of freedom than the simplified ECHAM5-OZ simulation. The ECHAM5-OZ simulation is flux corrected and therefore the SST climatology stays close to the observed. In the fully coupled CGCMs the small imbalance in the coupled ocean-atmosphere-land-ice interactions lead to substantial model errors that lead to substantially (up to 5°K) different SST climatologies. Furthermore, the CGCMs have ocean dynamics

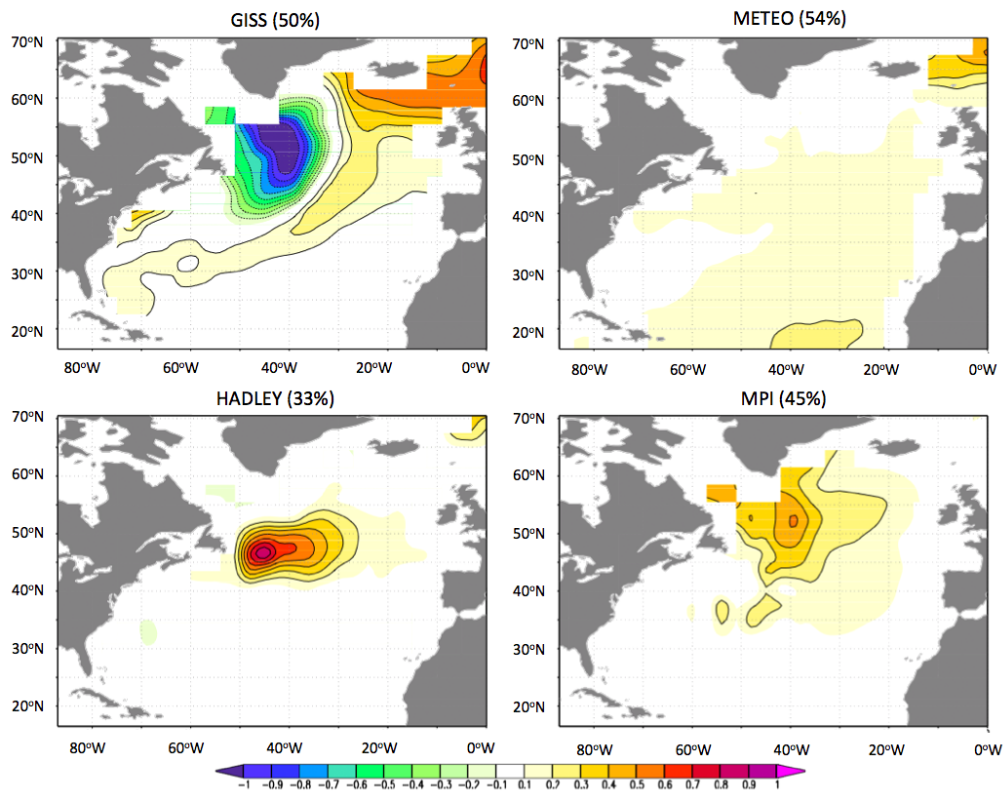

Fig. 3. Correlation maps of the leading EOF modes of detrended multi-decadal global sea surface temperatures (SSTs) as in Fig. 1, but for the CMIP3 multi-model ensemble.

interacting with the atmospheric dynamics, whereas the ECHAM5-OZ simulations do not have any lateral ocean dynamics. Thus the ocean dynamics in CGCM with substantially different SST climatologies can cause quite different modes of SST variability.

This can be illustrated by looking at the leading EOF-modes in different CGCM simulations. In Fig. 3 we show the EOF-1 mode in the North Atlantic for 4 different CGCM preindustrial (no-external forcings) for 5-yr running mean SST variability as an example.

It can be noted that they are quite different from each other and from the observed (not shown). It is also notable that they have quite distinct amplitudes at some locations, but these locations are different in each model. So the models do have quite significant decadal models of variability that are quite local, but different in each model. These local modes are most likely caused by ocean dynamics, as atmospheric dynamics tend to be on larger spatial scales and the AGCM coupled to slab ocean or the ECHAM5-OZ simulations do not capture such local modes. The results are similar for the other extra tropical oceans (North Pacific and Southern Ocean).

In summary, this suggests that the CGCMs simulations strongly disagree on the structure of global Hyper Modes mainly, because they all have different ocean dynamics forcing different SST modes. The global EOF-1 mode (Fig. 2) is only the common structure in all the models and the low explained variance value and the missing Atlantic pattern indicate strong disagreement between the models.

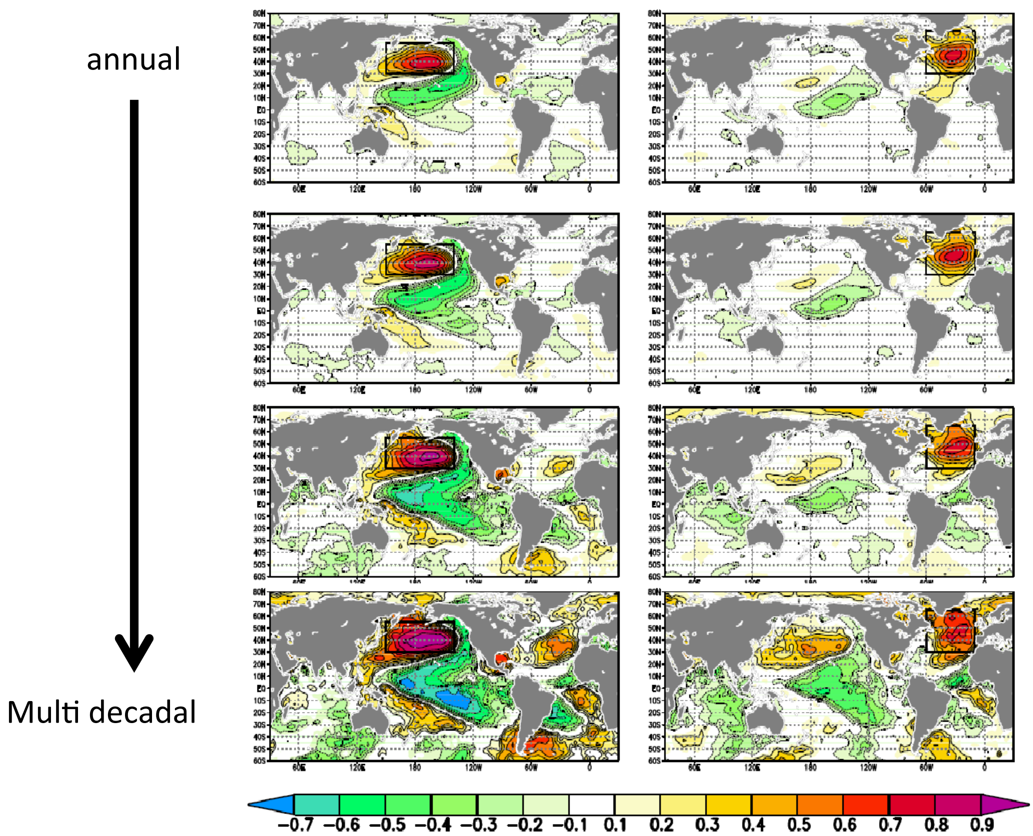

Fig. 4. Left column: The correlation of the SST in the 2000 yrs ECHAM-OZ simulation averaged over the North Pacific box with the SST in all regions of the world. Upper panel for high-pass 5 yrs filter annual mean SST, second from the top for 5 yrs to 10 yrs filtered SST, third from the top for 10 yrs to 40 yrs filtered SST and lower panel for low-pass 40 yrs SST. Right column the same as left, but for the SST-box in the North Atlantic.

4. The Tropical Link of the Inter-Hemispheric Teleconnections

In the previous section we already indicated that the global modes of variability on the shorter, inter-annual, time-scales are much more complex ($N_{\text{spatial}} = 20$). 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. 4) and correlate the mean SST in these boxes with the SST in all parts of the oceans. Figure 4 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 regionp may be a central element to create the global link to remote regions. Several other studies have also suggested that the North Pacific is linked or forcing the tropical Pacific by the subtropical region (Vimont *et al.*, 2001; Yu and Kim, 2011).

To illustrate, that multi-decadal atmospheric variability in the northern and southern hemisphere are indeed linked we can analysis the global correlations of the 500 hPa geopotential heights in the north Pacific with the rest of the world, see Fig. 5a. We find remarkable high correlations all over the world and in particular in the southern extra-tropical Pacific (at around

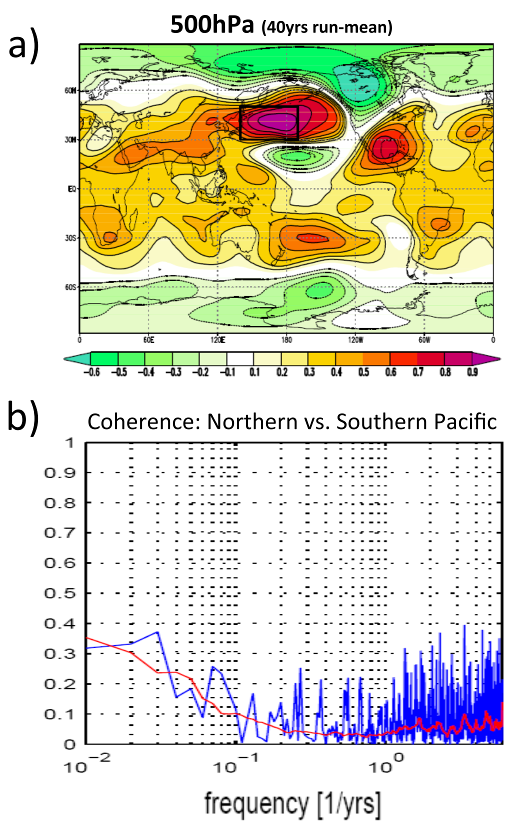

Fig. 5. (a) Correlation of the 500 hPa geopotential height in the ECHAM-OZ simulation in the box over the western North Pacific with the geopotential height globally for 40 yrs low-pass filter data. (b) cross-spectral coherence between the 500 hPa geopotential height in the North Pacific box with the 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.

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. 5b.

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 climatology (no SST variability allowed). The simulation was integrated for 500-yr and is referred to as ECHAM-OZ$_{\mathrm{noeq}}$.

Figure 6a shows the cross-spectral coherence between the 500 hPa geopotential heights in the North Pacific box and in the South Pacific box. In comparison to the ECHAM-OZ simulation (Fig. 5b) 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 500-yr and is refereed to as ECHAM$_{\mathrm{FIXSST}}$. Figure 6b shows the power spectrum of 500 hPa 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 500 hPa 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.

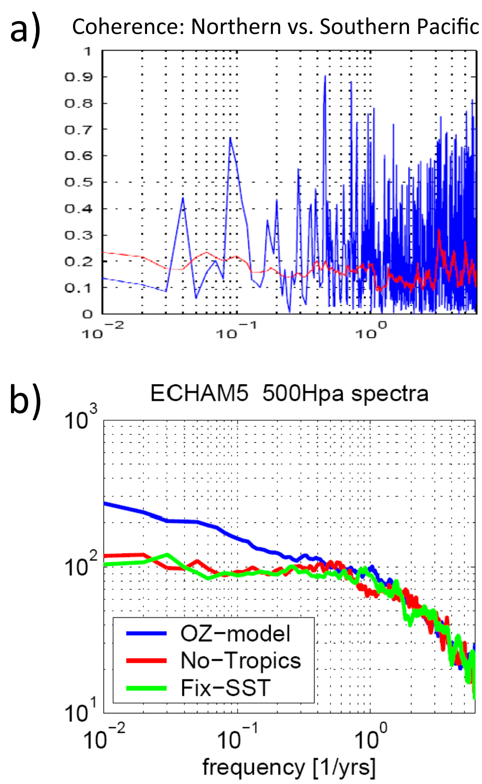

Fig. 6. (a) Cross-spectral coherence between the 500 hPa geopotential height in the North Pacific box with the mid-latitudes South Pacific as in Fig. 5b, but for the ECHAM-OZ$_{\text{noeq}}$ simulation. (b) power spectrum of the 500 hPa geopotential height in the North Pacific box in the ECHAM-OZ (blue), ECHAM-OZ$_{\text{noeq}}$(red) and the ECHAM$_{\text{FIXSST}}$ (green) simulations.

5. 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.

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 case 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. Figure 7a shows the mean power spectrum of the northern North

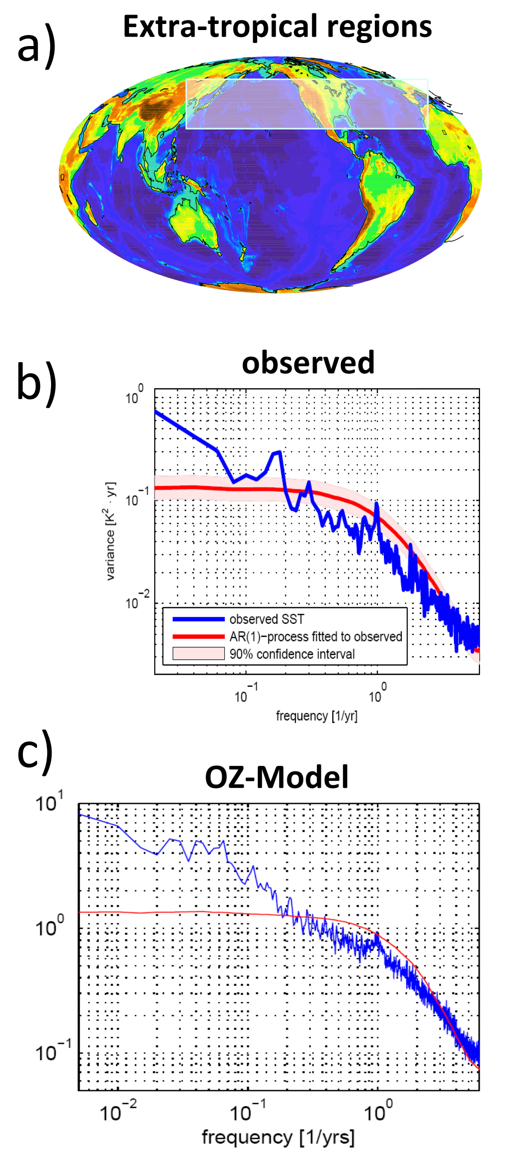

Fig. 7. (a) Region of the mid-latitudes box (b) the average power spectrum of the observed SST (blue line) for all points in the mid-latitudes of the North Pacific and Atlantic (see (a)). The red line is the fitted red noise power spectrum with its 90% confidence interval (light red shading). (c) as (b), but for the 2000 yrs ECHAM-OZ simulation.

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 (month) autocorrelation 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 100-yr, 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:

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

The heat capacity of the surface layer, c, is assumed to be a constant. The damping of T is proportional to the constant, γ_{surf} and the vertical mixing below the mixed layer depth is proportional to κ_z (as a function of the depth underneath the mixed layer) and the vertical temperature curvature $\nabla_z^2 T$. The system is forced at the surface by white noise weather heat fluxes, ξ_{surf}. So the extension to the Hasselmann red noise hypothesis is the inclusion of the vertical mixing term.

The power spectrum of this simple model, for realistic parameters, is similar to that observed or in the ECHAM-OZ simulation, see Fig. 8a. 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. 8b). The damping γ_{surf} shifts the variance at frequency zero (infinitively long periods) down (see Fig. 8c). 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 extend of the SST anomalies: 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 γ_{surf} will be spatial scale dependent and it will be weakest for global-scale SST pattern.

Finally, the mixing profile underneath the mixed layer κ_z alters the slope of the power spectrum. In Eq. (1) the mixing parameter κ_z

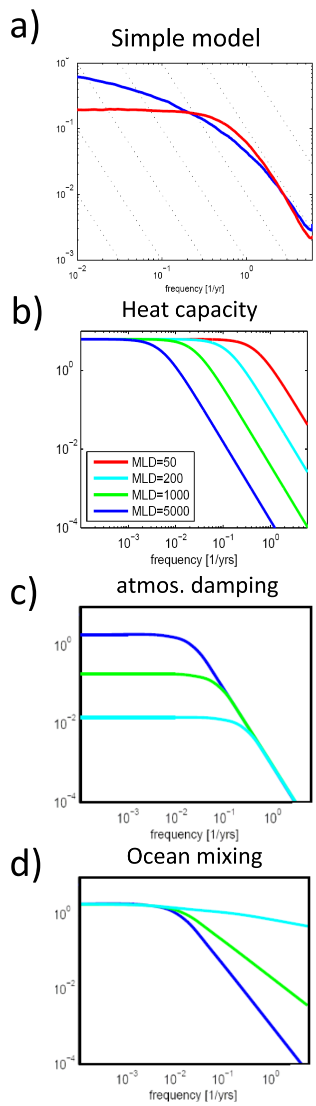

Fig. 8. (a) Power spectrum of the SST from Eq. (1) with realistic parameters (blue line) compared against a fitted red noise spectrum (red line). (b) red noise power spectra for different heat capacities c. (c) red noise power spectra for different damping parameter γ_{surf} (dark blue weakest, light blue strongest). (d) the power spectra of the SST from Eq. (1) with different mixing profiles for κ_z (dark blue fully mixed ocean, green exponentially decreasing mixing, light blue no mixing thin skin layer ocean).

is a function of depth. It is largest at the surface due to the wind input and decreases with depth. In the extreme case of a perfectly mixed ocean (κ_z is very large in all depth; 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 (κ_z is very small) 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 κ_z mixing profile underneath the mixed layer gets the power spectrum with the observed slope (Fig. 8a), 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. 8a it seems to saturate in the 100-yr to 1000-yr time-scales. In the ECHAM-OZ simulation with a 800 m deep ocean it seems to be similar, but it is yet not clear, as the 10,000-yr 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.

6. Summary and Discussion

We can summarize the global-scale multi-decadal Hyper Modes idea by the sketch shown in Fig. 9.

I. 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 (Figs. 4 and 5b).

II. 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. 7). 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. 7).

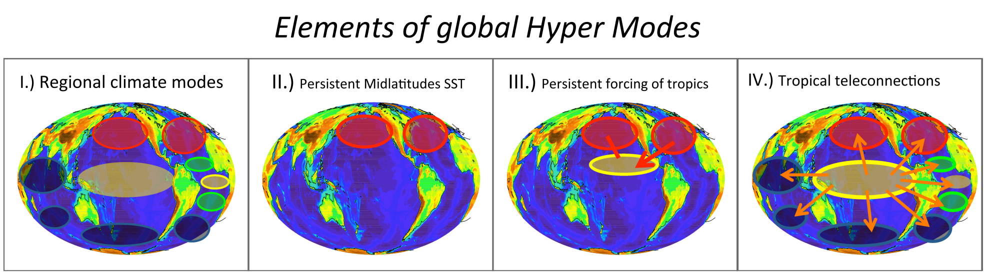

Fig. 9. Sketch summarizing the elements of the global-scale multi-decadal hyper modes.

III. These high latitudes SST modes seem to interact with the subtropical Pacific (Fig. 4).
IV. 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. 6).
V. 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).

Thus the idea of Hyper Modes can be summarized as near global-scale climate modes that connect local mode of variability on longer time scales via atmospheric teleconnections. They can therefor be considered as being a teleconnection in the climate system that is on top of or hidden from the dominant local and shorter time-scale mode, but are probably the dominant modes of internal natural climate variability on time scales longer than decades.

Acknowledgments

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References

Alexander, M. A., and C. Penland, 1996: Variability in a mixed layer ocean model driven by stochastic atmospheric forcing. *J. Climate*, **9**, 2424–2442.

Bretherton, C. S., M. Widmann, V. P. Dymnikov, J. M. Wallace, and I. Blade, 1999: The effective number of spatial degrees of freedom of a time-varying field. *J. Climate*, **12**, 1990–2009.

Clement, A., P. DiNezio, and C. Deser, 2011: Rethinking the ocean's role in the Southern Oscillation. *J. Climate*, **24**, 4056–4072.

Dommenget, D., 2007: Evaluating EOF modes against a stochastic null hypothesis. *Clim. Dyn.*, **28**, 517–531.

———, 2010: The slab ocean El Niño. *Geophys. Res. Lett.*, **37**, L20701.

———, and M. Latif, 2008: Generation of hyper climate modes. *Geophys. Res. Lett.*, **35**, L02706.

Hasselmann, K., 1976: Stochastic climate models Part I. Theory. *Tellus*, **28**, 473–485.

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. *J. Climate*, **22**, 6501–6514.

Niiler, P. P., and E. B. Kraus, 1977: One dimension models of the upper ocean. *Modeling and Prediction of the Upper Layers of the Ocean*, E. B. Kraus, Ed., Pergamon, New York, 143–172.

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. *J. Geophys. Res. Atmos.*, **108**, 4407.

Vimont, D. J., D. S. Battisti, and A. C. Hirst, 2001: Footprinting: A seasonal connection between the tropics and mid-latitudes. *Geophys. Res. Lett.*, **28**, 3923–3926.

Yu, J. Y., and S. T. Kim, 2011: Relationships between extratropical sea level pressure variations and the central Pacific and eastern Pacific types of ENSO. *J. Climate*, **24**, 708–720.