Extratropical climate variability: PNA, NAO, annular modes and the ocean circulation

Notes for Fall 2004 mini-series

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Based on the modern climate record and a hierarchy of coupled climate models, we will discuss the following issues: (i) What are the 'modes' of climate variability in the extra-tropics (Northern and Southern Hemispheres) and how do we single them out in climate records? (ii) What are their timescales and spatial patterns and why are they so? (iii) Is the ocean involved in their fluctuations?

Contents

Chapter 1

Background on observed teleconnections

One experiences every day the changing and hardly predictable nature of weather events. If it seems relatively easy to characterize the spatial ($\simeq 1000\ km$) and temporal ($\simeq$ day) scales of the latter, it is only relatively recently (early 1980s) that, building upon earlier work done in the 1930s, observational studies could investigate thoroughly other structures of atmospheric variability. These were referred to as *teleconnections*. Recent climate changes (and perhaps past and future) seem to be closely related to those teleconnections.

1.1 Teleconnections

The wave-like background

Playing with (monthly) 500 mb geopotential height field (Z_{500}) [1], there seems to be significant correlation between anomalies at a given reference point (seen as the bull's eye with correlations close to unity) and anomalies at a distance of several thousands of kilometers (Figs. 1, 2). Such patterns bear a strong

[1]see Matlab programs at /u/u0/czaja/TEACHING/FALL04/HANDSON

qualitative resemblance with forced waves emanating from the reference point. Indeed, one usually thinks of such teleconnections as providing a background of waves, presumably forced by smaller scale storms, akin to surface ocean waves constantly excited by the wind.

PNA, NAO, SAM

Among the myriads of such teleconnections, are there a few which

(i) Stand out above the backgound?

(ii) Might carry some predictive skill?

If the answer is not yet clear for (ii), it is a YES for (i). After looking at all possible maps like Figs 1 and 2 several authors have become convinced that only a few patterns emerge above the background 'noise' (e.g., Wallace, 1996). Such teleconnections are the Pacific North American (PNA), the North Atlantic Oscillation (NAO) or Northern Annular Mode (NAM) and its Southern Hemisphere counterpart, the Southern Annular mode (SAM). -see Figs. 3, 4 and 5. To add a 3D perspective, note that all patterns shown in Figs. 1 to 5 are essentially the same from the surface to the tropopause ($\simeq 10\ km$).

There are several other ways to 'find' these structures than correlation maps. A common way is to proceed through Empirical Orthogonal Functions (EOFs). More advanced techniques exist, like rotated EOFs, maximum covariance analysis (so-called 'SVD'), etc... (e.g., Bretherton et al., 1992). As recently shown for the Northern Hemisphere winter (Quadrelli and Wallace, 2004), more and more of the variance of temperature, pressure etc, is contained in only EOF1 (=NAO) and EOF2 ($\simeq$ PNA) as one goes from monthly to seasonal to decadal timescales.

Maybe more importantly than being 'revealed' by their statistical signatures, PNA, NAO-NAM and SAM are closely related to important changes in climate. That's where the excitement comes from.

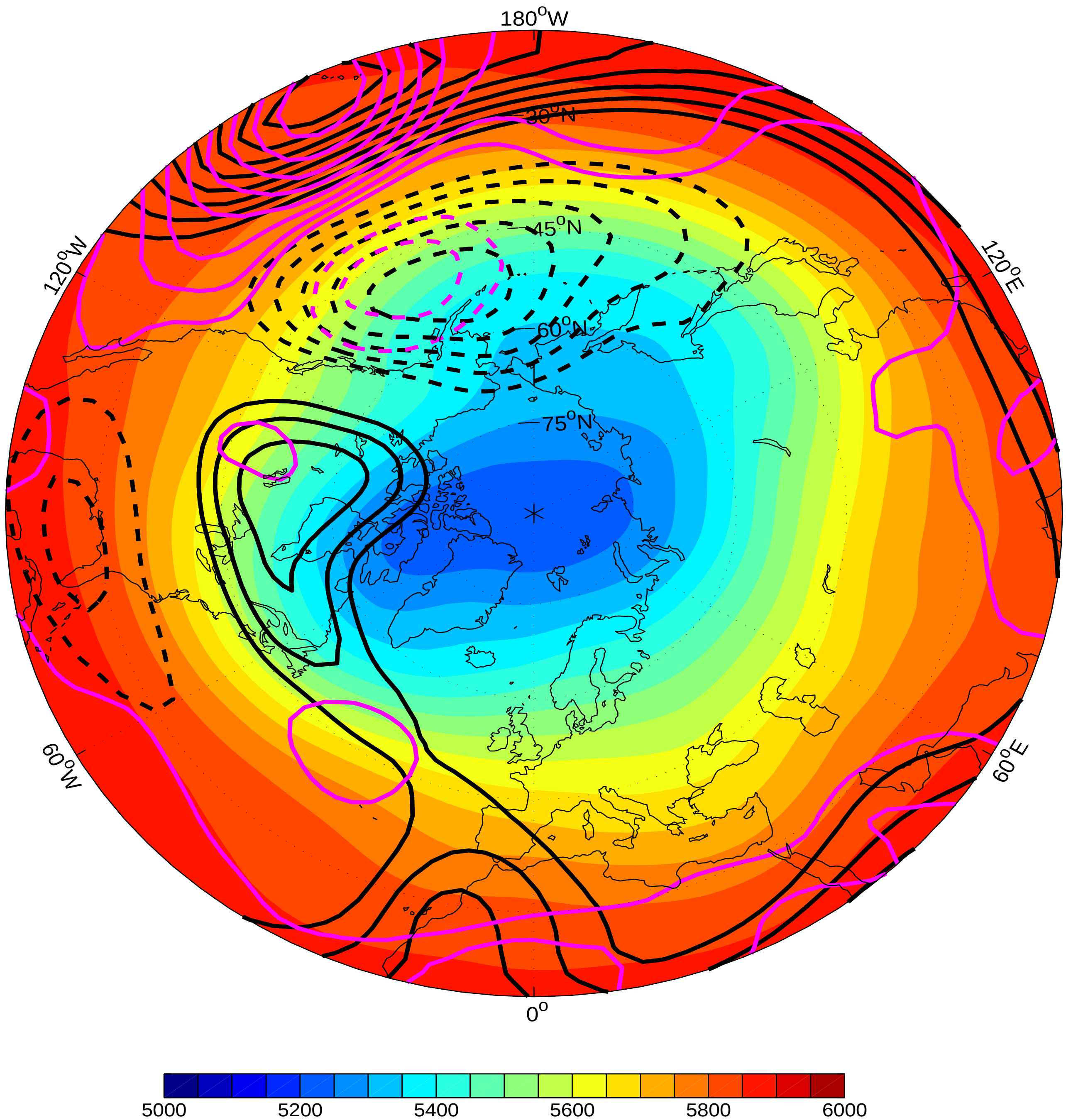

Figure 1.1: Long term mean Z_{500} (color) and winter and summer correlation maps (N-D-J-F-M in black, J-J-A-S-O in magenta) between a reference point at $25°N$ in the eastern Pacific and Z_{500} anomalies everywhere else. Based on monthly anomalies from NCEP-NCAR renalysis (1980-2003). Correlations are only shown when stronger than 0.2.

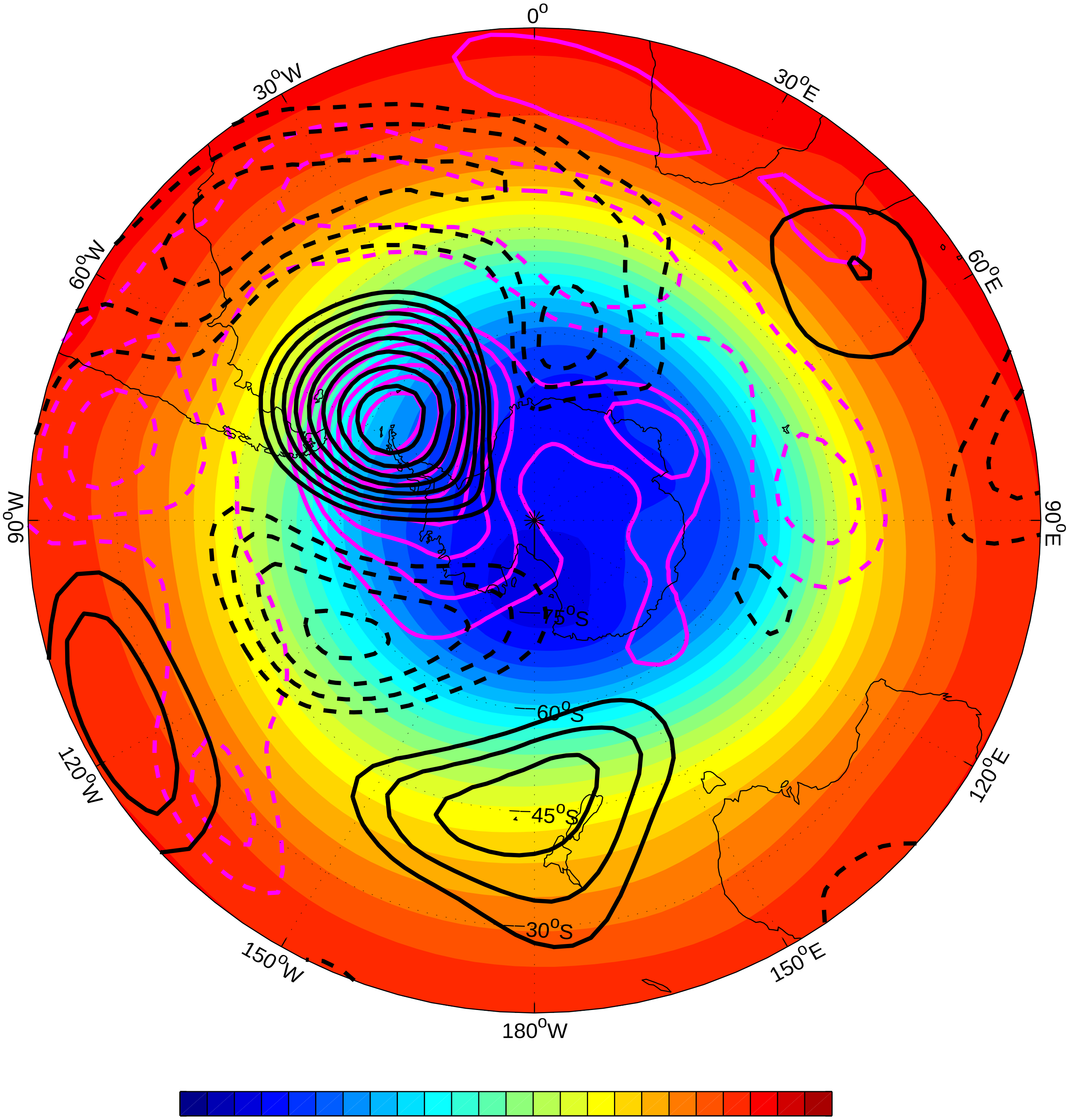

Figure 1.2: Same as Fig. 1.1 but for a reference point at Drake Passage.

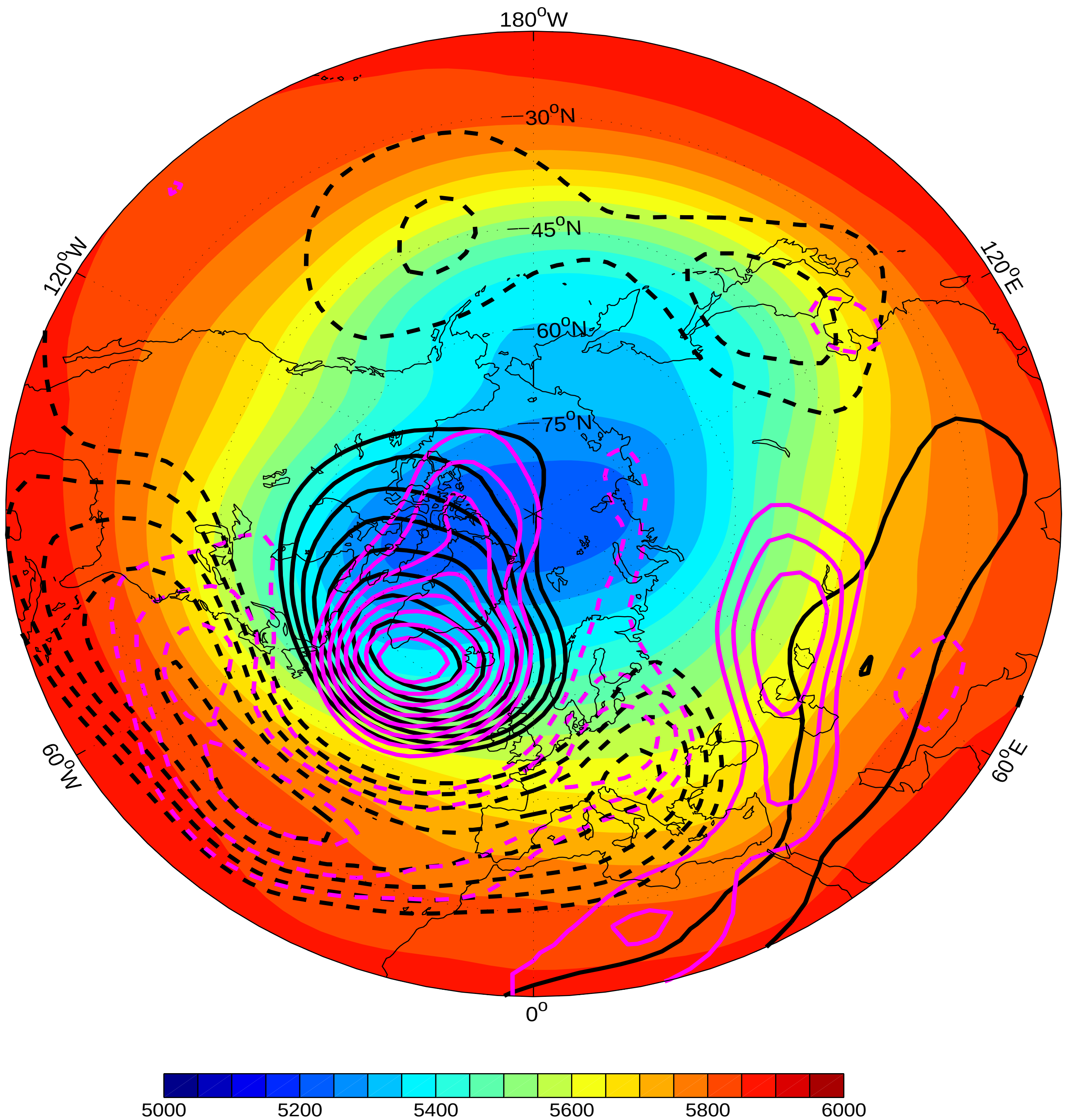

Figure 1.3: Same as Fig. 1.1 but for a reference point on the Southern tip of Greenland. This map is one way to illustrate the North Atlantic Oscillation in the Z_{500} field.

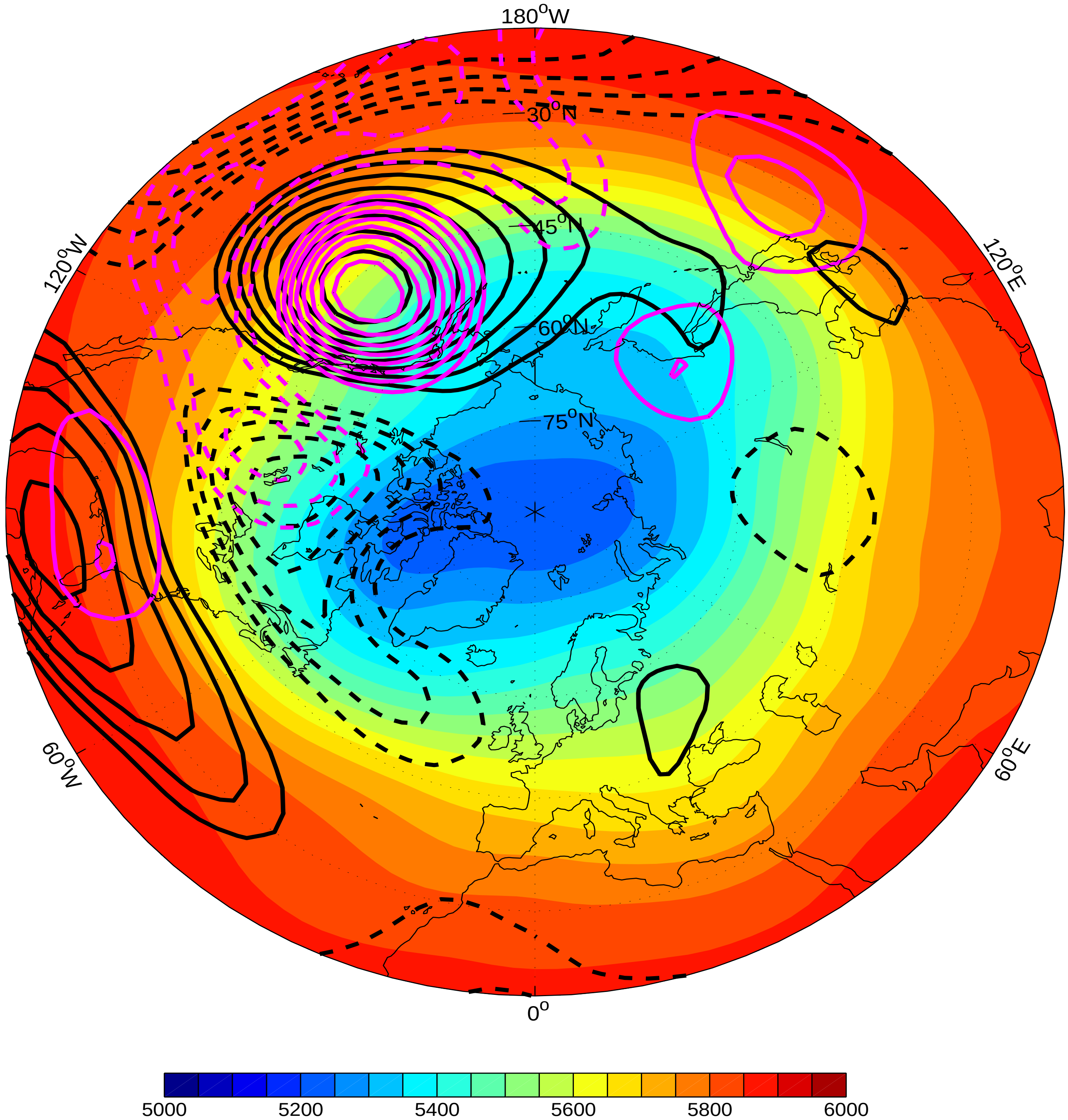

Figure 1.4: Same as Fig. 1.1 but for a reference point in the Gulf of Alaska. This map is one way to illustrate the Pacific North American in the Z_{500} field.

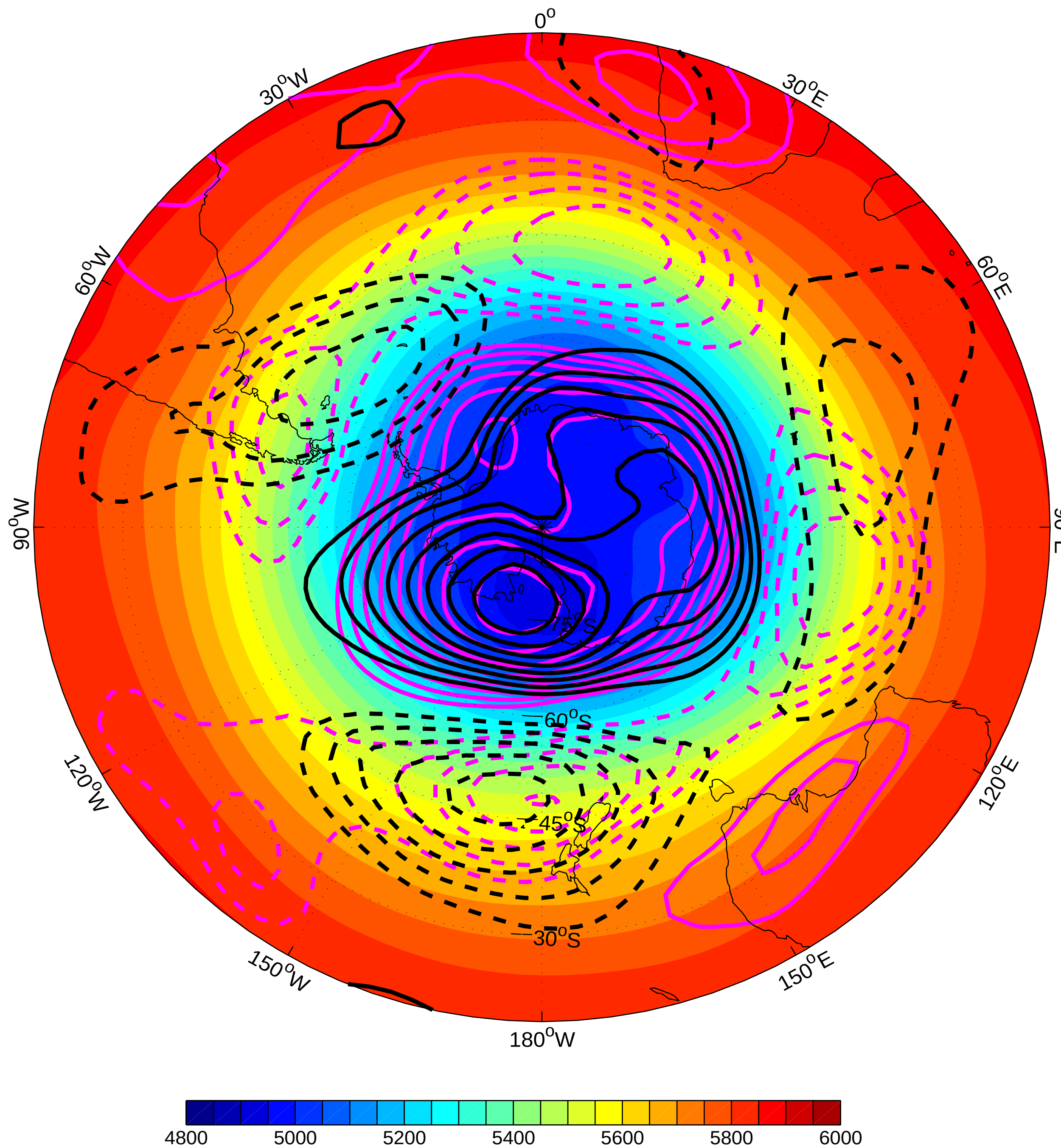

Figure 1.5: Same as Fig. 1.1 but for a reference point in the Ross Sea. This map is one way to illustrate the Southern Annular Mode in the Z_{500} field.

1.2 Climate impacts of teleconnection patterns

To name only a few for the NAO-NAM and SAM

- the distribution of precipitation: stronger subpolar westerlies (positive phase of the NAO-NAM) are associated with a poleward shift of the storm track and wetter climate over Northern Europe.
- surface temperature, both regional and global
- ozone loss at high latitudes
- oil consumption in Norway
- ...

Actually, one essential aspect of the Northern annular mode which has made it so popular recently is its close connection with the recent rising in global surface temperature: 30 % of the January through March (JFM) warming over the Northern Hemisphere as a whole over the past 30 yrs is explained by the NAO-NAM (Thompson et al., 2000).

Similarly in the Pacific, the PNA signature is seen in interdecadal changes of various fields, including the so-called 'climate shift' from 1976 to 1977 (Zhang et al., 1997). This low-frequency component has been relabelled 'Pacific Decadal Oscillation' (PDO), and is also associated with large changes in marine ecosystems, Alaska salmon production... (e.g., Mantua et al., 1997).

1.3 Open questions

- What is the timescale of NAO, SAM & PNA?

- What is fundamentally driving these teleconnections?
- Do they have oceanic analogs?
- Are they predictable?
- We talked a lot about long (decadal) timescales. Could the ocean be involved in NAO, SAM & PNA fluctuations?
- How do they respond to increased CO_2 concentrations?
- Were they dominating past climate variability?
- ...

We will address a few of those issues in the following.

1.4 References

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Chapter 2

What drives the teleconnections?

From recent (and active!) research over the past few years, a simple picture emerges where PNA, NAO and SAM are essentially phenomena intrinsic to the atmosphere. There is little doubt that they would exist in absence of ocean circulation or tropical forcing associated with ENSO. Their timescale is short (about 10 days) and they appear in a wide range of atmospheric models.

2.1 Timescales

You can easily build daily timeseries of the teleconnections from simple indices. For instance, a daily NAO index is readily obtained by substracting the timeseries of sea level pressure fluctuations at Rekjavik (Iceland) from those observed in Lisbon (Portugal). Figure 2.1 displays a 6-months slice of such daily NAO (top), SAM (middle) and PNA (bottom) indices [1].

[1] They were obtained in a slightly more complicated way than simply from two points (from EOF analysis of mid-level geopotential height anomalies) - see http://www.cpc.ncep.noaa.gov/products/precip/CWlink/ENSO/verf/new.teleconnections.shtml

One observes persistence of positive and negative anomalies over several weeks for all indices. Zooming over a larger (5 year) slice (Fig. 2.2) we also observe prominent year to year fluctuations. The astute observer will also notice indications of stronger NAO and PNA events in boreal winter. Such seasonality is less pronounced for SAM. Finally, Fig. 2.3 diplays a long slice (1979-2004) of the record with a low-pass version superimposed in green. Fluctuations over five years and longer timescales can be seen. Such low - frequency fluctuations, and even longer timescales are present in the multi-decadal instrumental records of NAO or PNA indices (Hurrell, 1995; Mantua et al., 1997).

It is crucial (and hard!) to realize that such year-to-year and even decades-to-decades variability primarily reflect physical changes occuring on a much shorter timescale. In Fig. 2.4 we display the autocorrelation function of the daily indices. A typical e-folding time is about 15 days for SAM and about 10 days for NAO and PNA, consistent with visual impression from Fig. 2.1. This 'noise'-driven 'climate' variability (that associated with year-to-year, decadades-to-decades changes) is referred to in the literature as *climate noise* (e.g., Madden, 1981).

Probably the simplest way to convince yourself of the power of climate noise is to play with a mathematical software such as Matlab. Consider the following evolution model for an index $I(n)$ of say, NAO, at day n,

$$I(n+1) = aI(n) + \xi \tag{2.1}$$

where a measures the memory of I from one day to the next and ξ is a random variable (normally distributed). Running the model forward from a given initial condition, one can then apply to I the same procedure we used in Figs. 2.1, 2.2 and 2.3. For instance, Fig. 2.5 displays 6-month (upper), 5-year (middle) and 30-year (bottom) slice of I simulated using $a = 0.9$ (this choice means a 10-day memory for I). The similarity with the observed curves is striking. Feldstein (2000) has shown convincingly

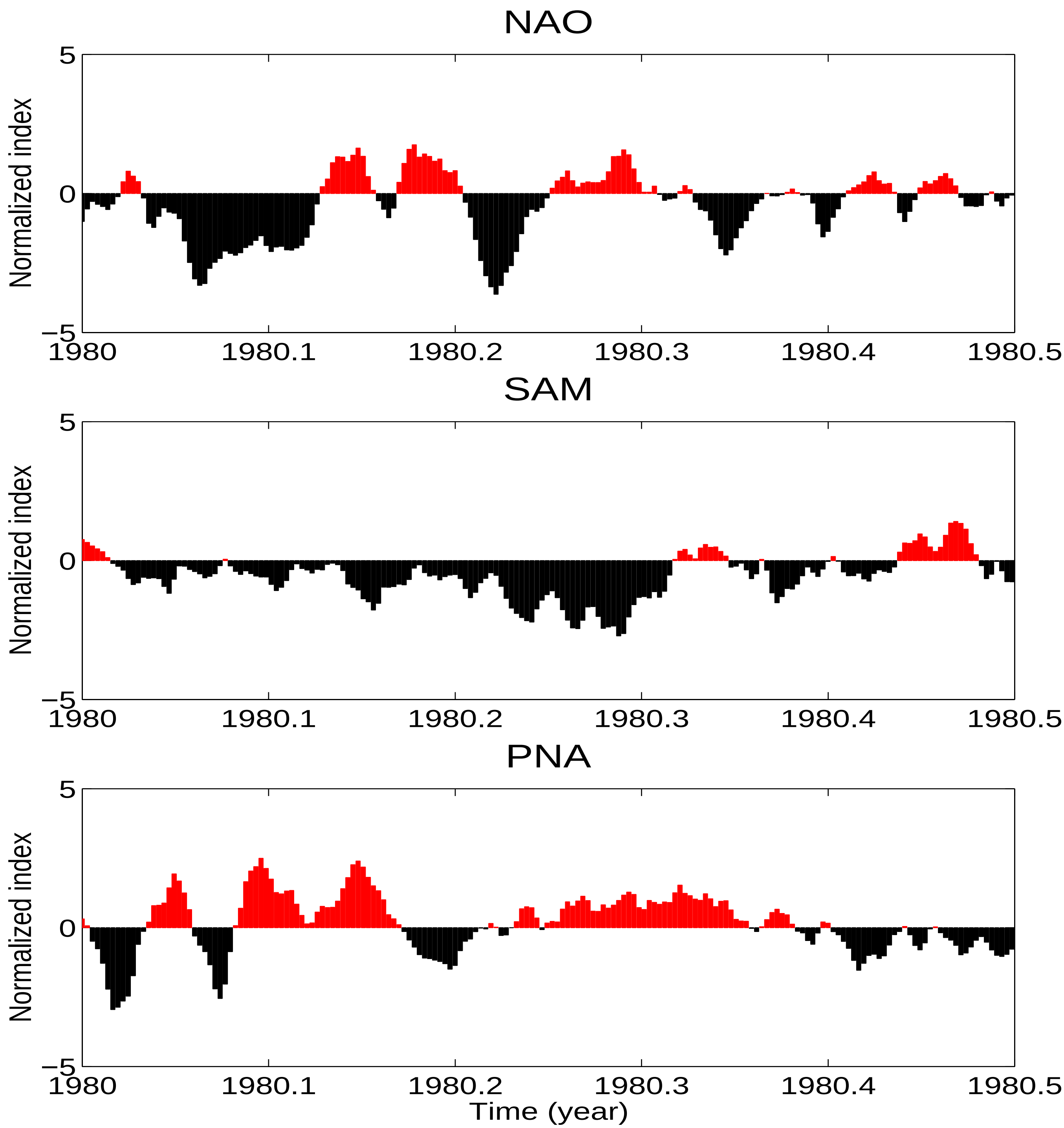

Figure 2.1: Daily timeseries of NAO, SAM and PNA indices. All indices have daily variance set to unity, i.e. are normalized. Positive (negative) values are in red (black).

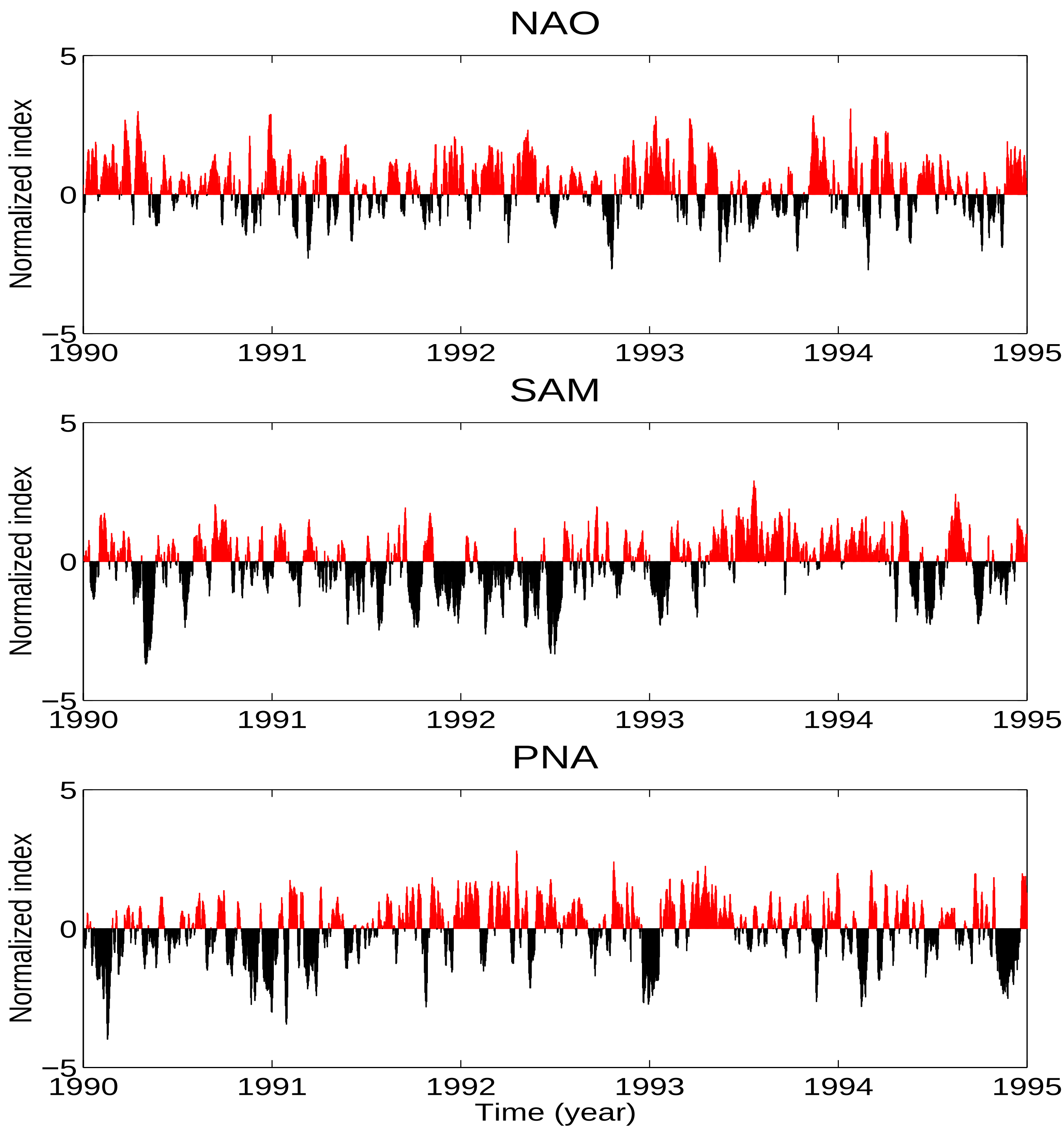

Figure 2.2: Same as Fig. 1, but over a 5 year slice.

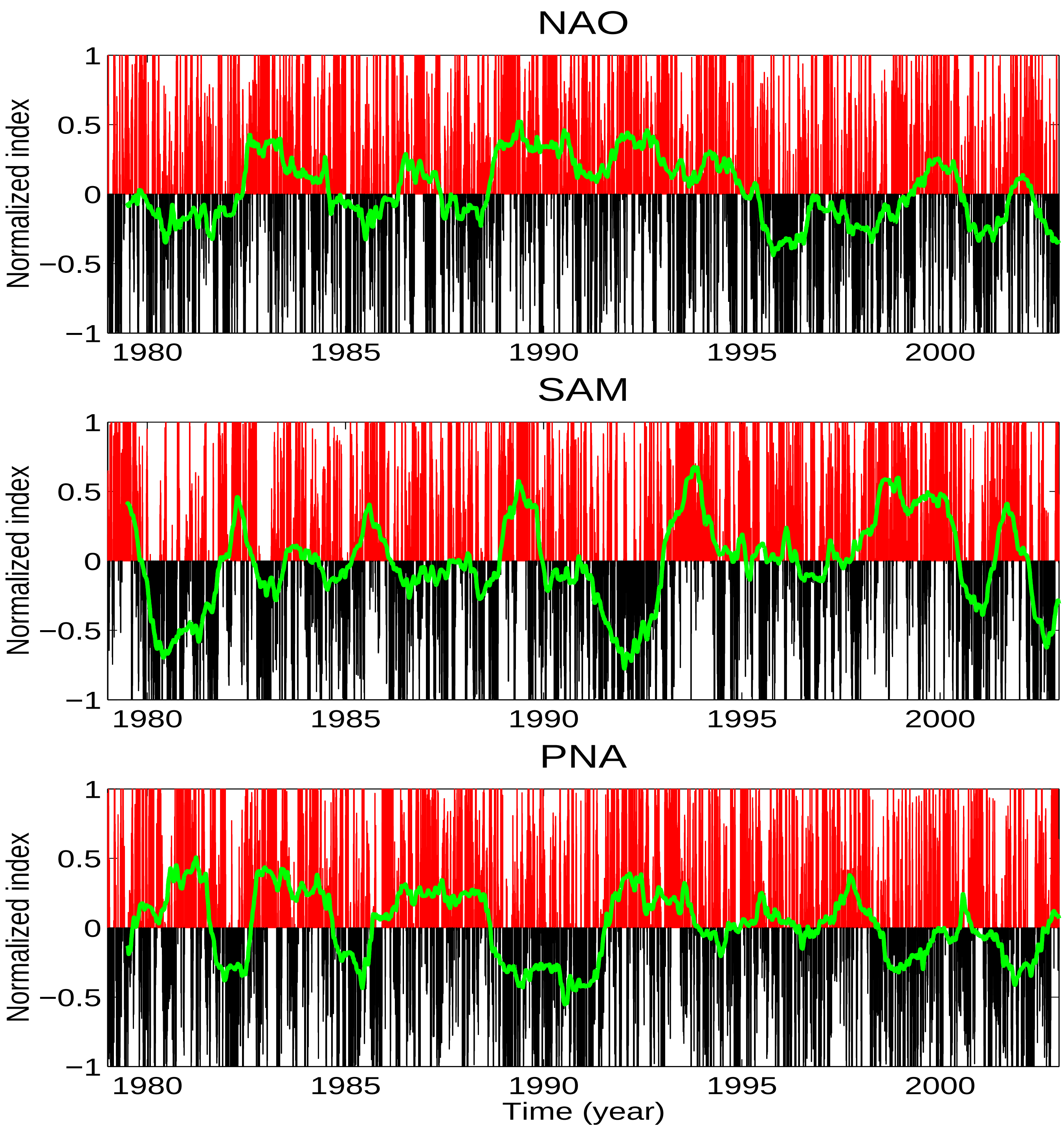

Figure 2.3: Same as Fig. 1, but with a 1-yr low pass version of each index (green) superimposed. Note the change of scale on the y-axis.

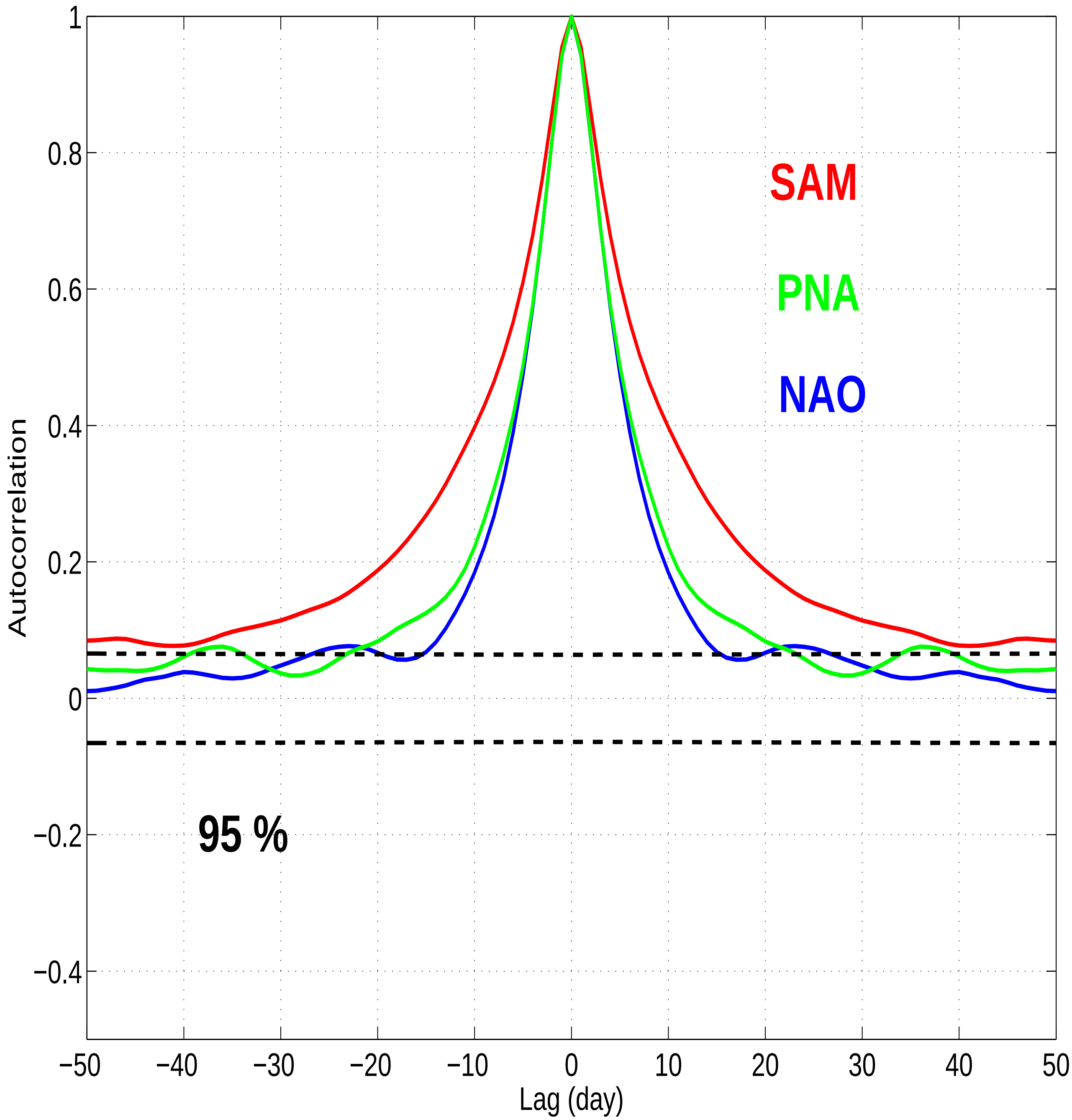

Figure 2.4: Autocorrelation of the daily NAO, SAM and PNA indices over 1979-2004. An approximate 95% confidence level is indicated assuming that every 10 day - chunk of data is independent from its predecessor and its successor.

that such a simple model as (2.1) is actually qualitatively correct for NAO and PNA.

2.2 Teleconnections in atmospheric models

Are current atmospheric General Circulation Models (GCMs) able to reproduce the patterns and timescales of the teleconnections? The answer is a clear YES, and without the need of coupling to the ocean or the tropical forcing associated with ENSO. Have a look for instance at the results of Limpasuvan and Hartmann (2000) for the Southern Annular mode and NAO. Using the GFDL atmospheric model forced with a prescribed seasonally varying sea surface temperature (SST) climatology (thus without any oceanic or ENSO-like boundary forcing), they reproduce the 10 day timescales and the strength and location of the 'centers of action' of SAM and NAO. Several authors have reproduced this result with different models, showing that this is robust (e.g., Saravanan 1998 with the NCAR model; Cassou and Terray, 2001 with ARPEGE, etc...). This also applies to PNA (e.g., Straus and Shukla, 2002).

The essential dynamics of NAO and SAM is the interaction between the jetstream and the storms. Thus even the simplest model for the midlatitude atmosphere (one layer forced by prescribed random storms) is able to reproduce the typical NAO and SAM patterns! This is shown for instance in Vallis et al. (2004).

2.3 References

-*Cassou and Terray, 2001:* Oceanic forcing of wintertime low-frequency atmospheric variability..., J. of Clim., vol 14, 4266-4291.

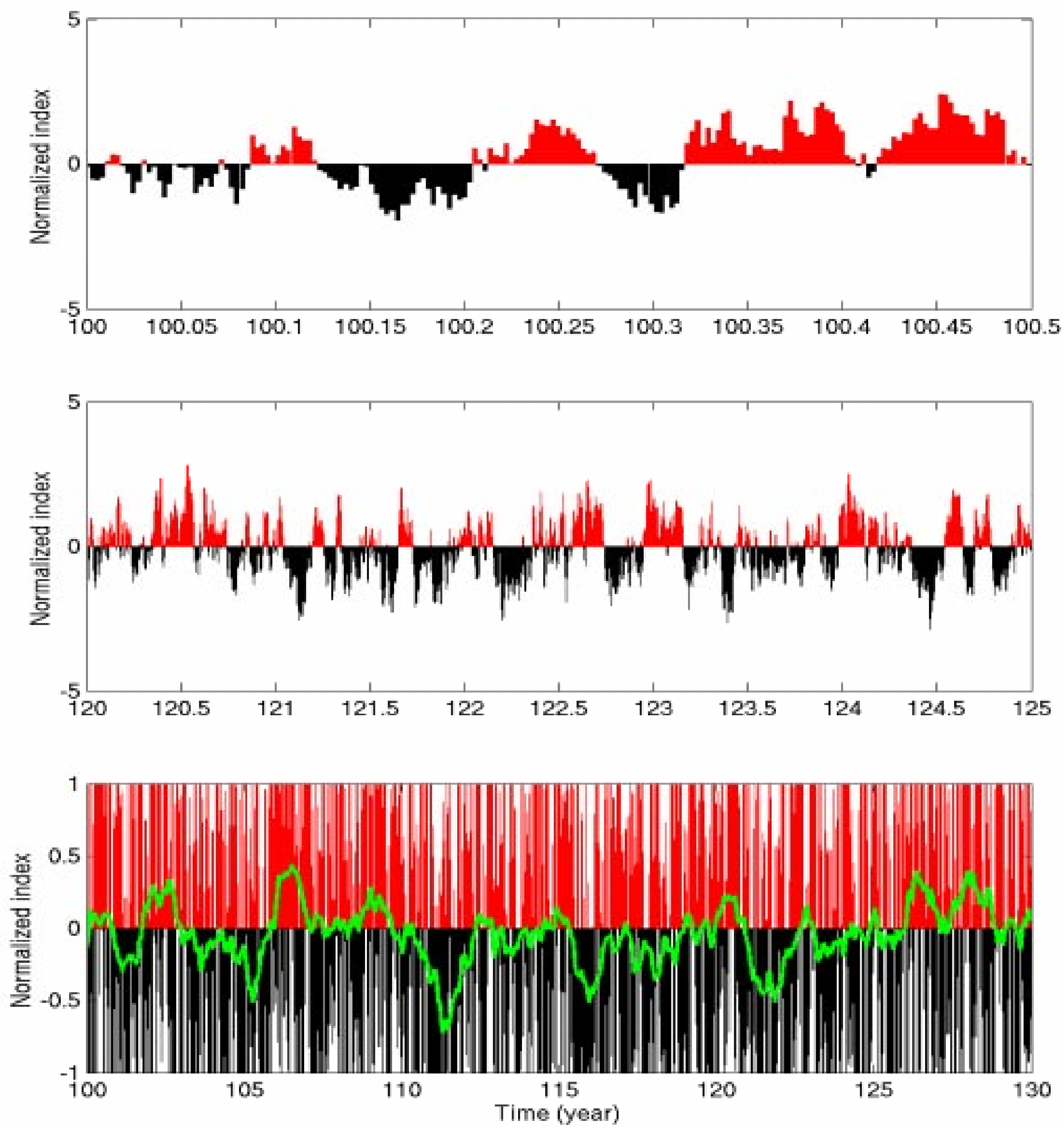

Figure 2.5: Timeseries simulated with model (2.1) and $a = 0.9$ in a similar format as Fig. 2.1, 2.2 and 2.3.

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Chapter 3

The response of the ocean to atmospheric forcing

The variability of the jetstream / storm track system is felt by the ocean through changes in surface winds and surface heat loss. This day-to-day, high-frequency forcing, is a major source of variability for the ocean. Observations and numerical models have suggested that all ocean components (mixed layer, horizontal gyres and meridional overturning cell) are impacted, although with different timescales.

3.1 The surface mixed layer

The fastest (and the simplest to understand!) ocean component to respond to atmospheric forcing is the ocean mixed layer. Focusing here on sea-surface temperature (SST), we write a simple model for departures T' from the mean as,

$$\rho C_p h[\frac{\partial T'}{\partial t} + U_o \frac{\partial T'}{\partial x}] = Q'_s + Q'_{Ek} \tag{3.1}$$

where $h \simeq 100\ m$ is the mixed layer thickness, ρ and C_p are the density and heat capacity of seawater, respectively. In (3.1), $U_o \simeq 10\ cm/s$ is a mean surface velocity and x is a coordinate along the current. Temperature anomalies are generated by the right hand side, i.e., either the surface heat flux anomalies Q'_s (latent+sensble) or the anomalous Ekman advection Q'_{Ek}. They are subsequently advected by the mean flow U_o. Both Q'_s and Q'_{Ek} are essentially in phase with the changes in atmospheric circulation and are often lumped together in a single forcing term $Q'_{tot} = Q'_s + Q'_{Ek}$. Figure 3.1 and 3.2 display typical Q'_{tot} forcing patterns driven by the Northern and Southern Annular modes. As described in details by Cayan (1992), such forcing patterns can be explained by considering changes in windspeed and advection of cold-dry or warm-moist air induced by atmospheric teleconnections.

A striking feature we observe in these figures is the large scale and spatial coherence of the forcing. SST anomalies of a size of thousands of kilometers can be created this way and the characteristic shape or patterns of SST anomalies forced by Northern Annular mode (or NAO) have been given names, like the 'Atlantic SST tripole'. That such imprint can be seen in SST observations is shown in Fig. 3.3, where the SST anomaly distribution for November 1980 is shown. The NAO imprint (warm SST below high atmospheric pressure and cold SST below low atmospheric pressure) can readily be seen by comparing this figure with Fig. 3.1. Note that the model (3.1) is indeed quite successful in hindcasting the observed month to month and yr to yr variability of large-scale SST patterns (e.g., Seager et al., 2000).

What is the timescale of such SST anomaly pattern? From Figs 3.1 and 3.3, we guess that a typical amplitude for SST anomaly is 0.5 K and that for Q'_{tot} is 30 Wm^{-2}. For a 100 m thick mixed layer, eq. (3.1) suggests that this corresponds to a timescale of about $T'\rho C_p h/Q'_{tot} \simeq 2 - 3$ months. Such timescale is rather short compared to any dynamical processes (waves, advection) in the ocean. It is

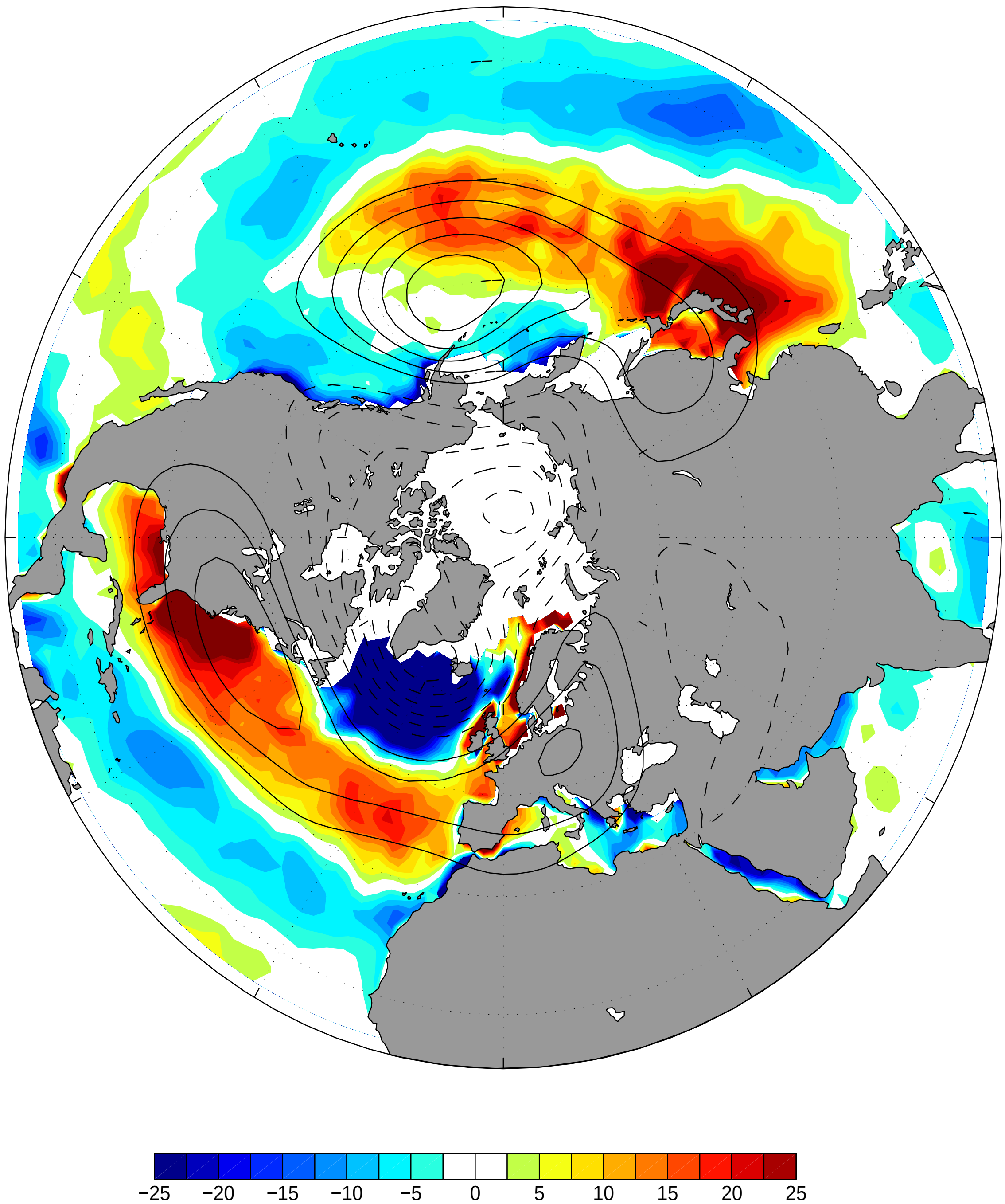

Figure 3.1: Observed wintertime anomalies in 500 mb geopotential height (contoured every 10 m) and surface warming of the ocean (latent + sensible + Ekman heat flux, colored in Wm^{-2}; red, warming of the ocean; blue, cooling of the ocean) associated with the positive phase of the Northern Annular mode.

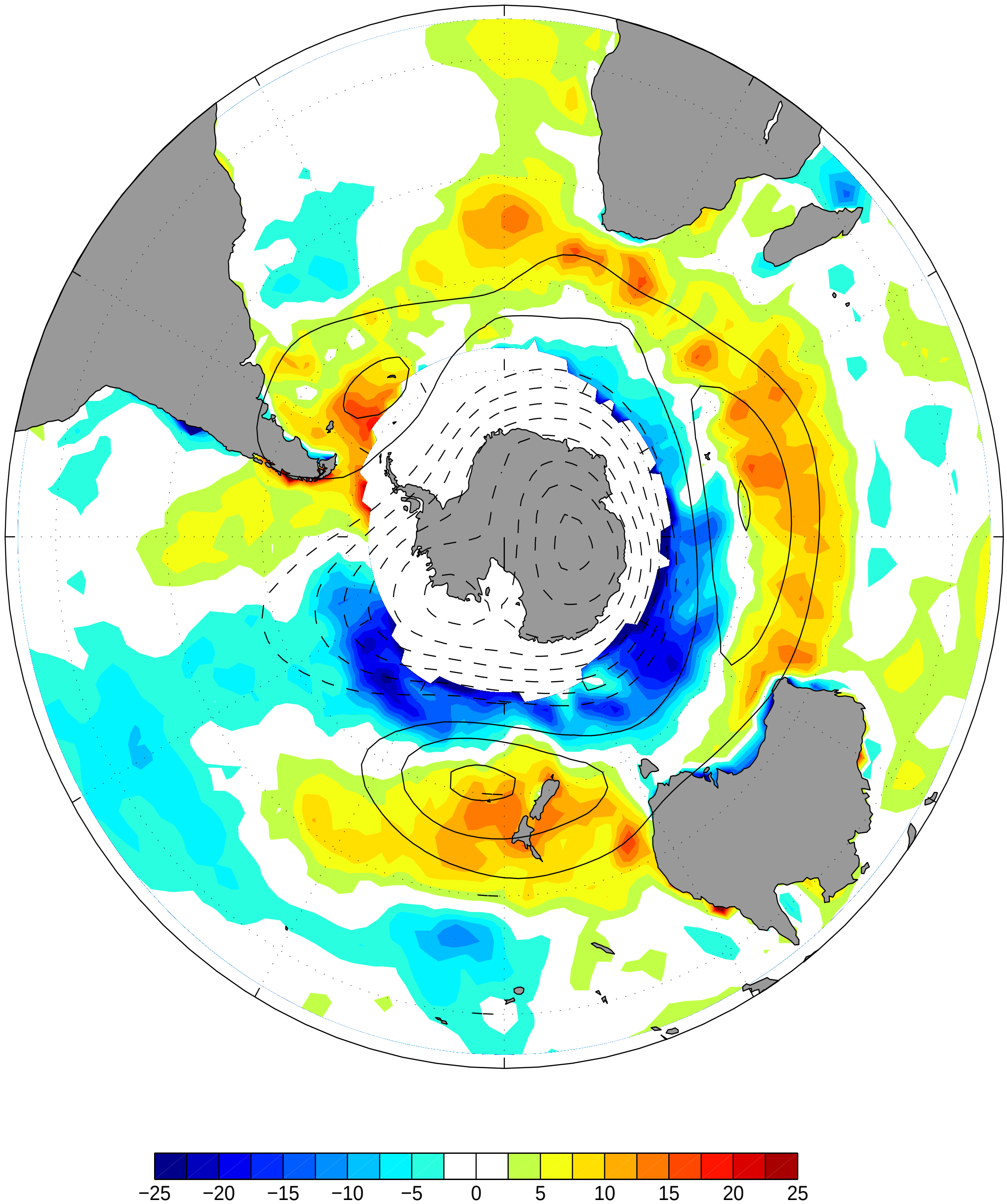

Figure 3.2: Same as Fig. 3.1 but for the Southern Annular mode

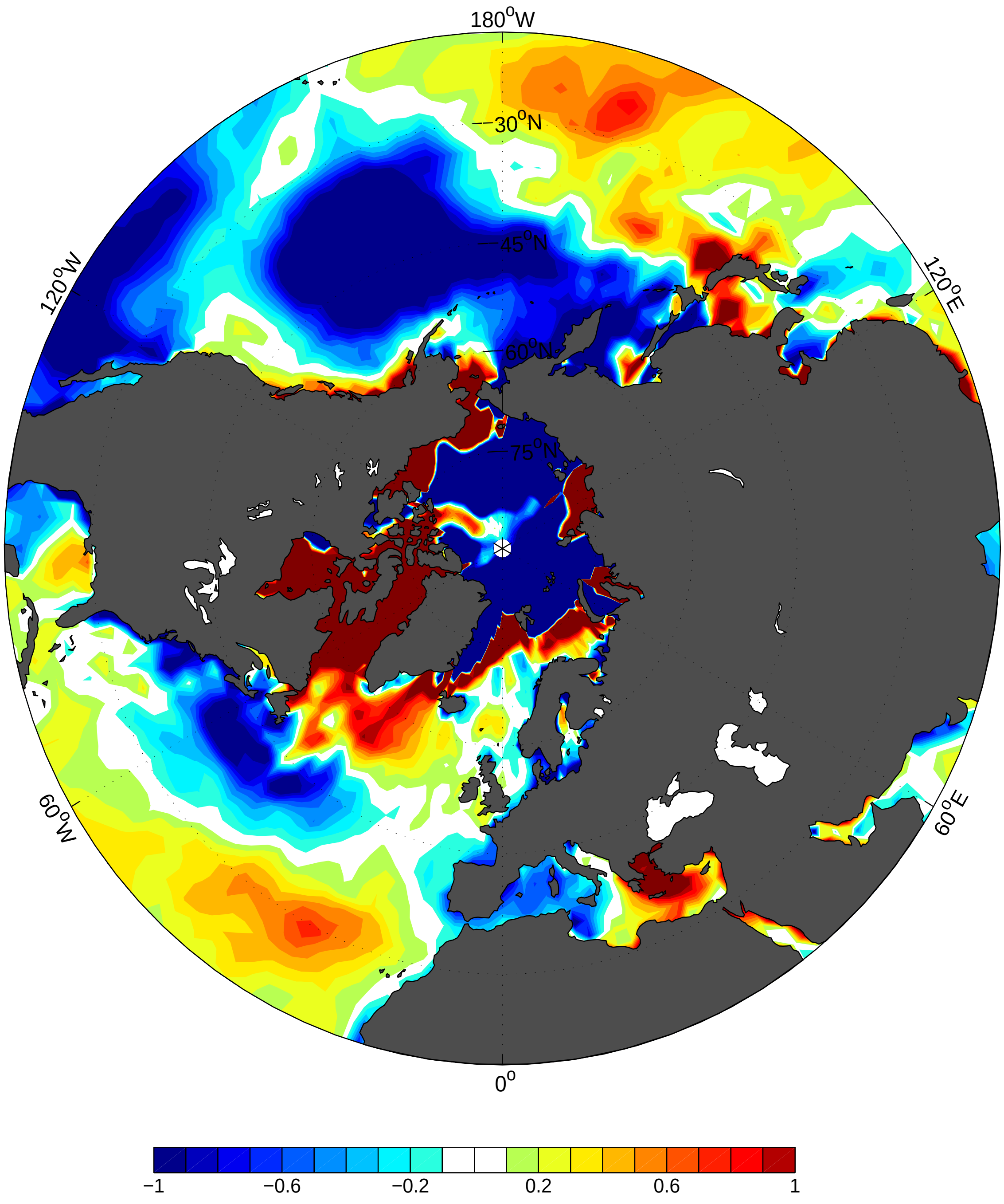

Figure 3.3: Departure of November 1980 SST from the long term mean (in K). This pattern bears a qualitative resemblance to Fig. 3.1 but with reverse signs (i.e., associated with a negative NAO phase).

observed when playing with SST teleconnection maps akin to those of chapter 1 (e.g., Frankignoul, 1985).

The mixed layer / SST system also feels longer timescales introduced by changes in ocean circulation (the term U_o in eq. (3.1)). These are studied below.

3.2 The horizontal gyres

A characteristic feature of the ocean circulation is the so-called subtropical and subpolar gyres, readily visible in sea surface height (SSH) maps like the one displayed in Fig. 3.4. Despite the lack of continuous, global, records of velocity changes, several studies were able to detect significant changes in the strength of the subtropical and subpolar gyres of the North Atlantic and Pacific basins.

Consider first the North Pacific (Deser et al., 1999). We show in Fig. 3.5 an estimate of the change in strength of the gyres (black contours) estimated from a simple dynamical model (Sverdrup balance) forced by surface wind changes between 1977-88 and 1968-76 (the so-called climate shift of the 1970s, linked, as we discussed in chapter 1 to the PNA/PDO teleconnection). The calculation predicts a strengthening of both the subpolar and subtropical gyres, i.e. of the Kuroshio, the current separating them (compare with Fig. 3.4), a few years after the winds have strenghtened. This is confirmed by in - situ temperature changes (shown in color) and current meter records (not shown).

Similar results have been observed very recently for the North Atlantic subpolar gyre by Hakkinen and Rhines (2004). These authors have argued that the strength of the subpolar gyre has decreased since the early 1990s (from observed SSH and current meter changes). However, rather than being caused by NAO surface wind forcing, they speculate that the causes of the slowing down are the NAO surface heat loss forcing (see Fig. 3.1), with less cooling of the subpolar gyre since the early 1990s.

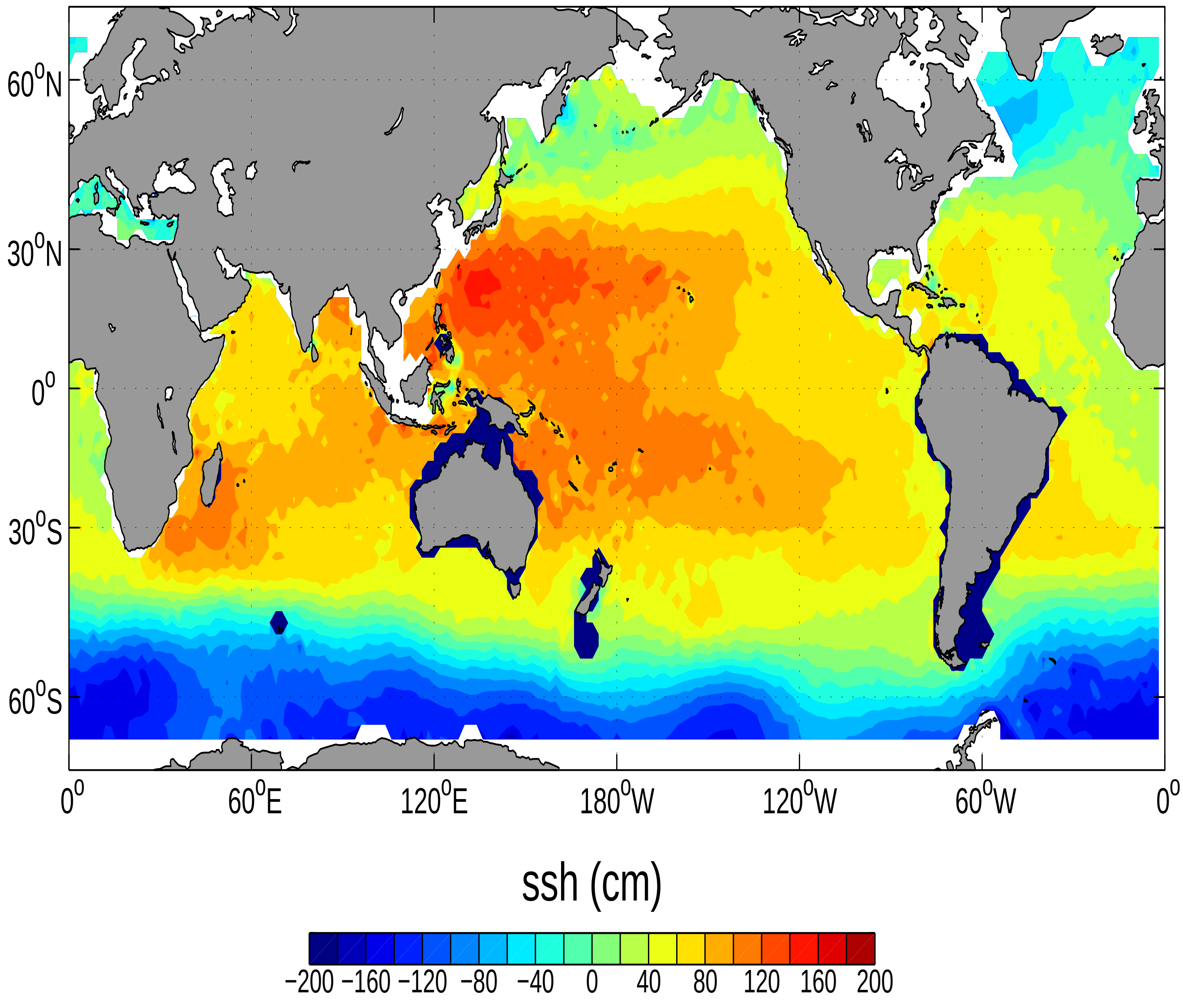

Figure 3.4: Mean sea surface height (in *cm*) from the Topex-Poseidon altimeter. Higher sea level is associated with subtropical (anticyclonic) circulation while lower sea level is associated with subpolar (cyclonic) circulation. This map is the oceanic equivalent of atmospheric surface pressure maps.

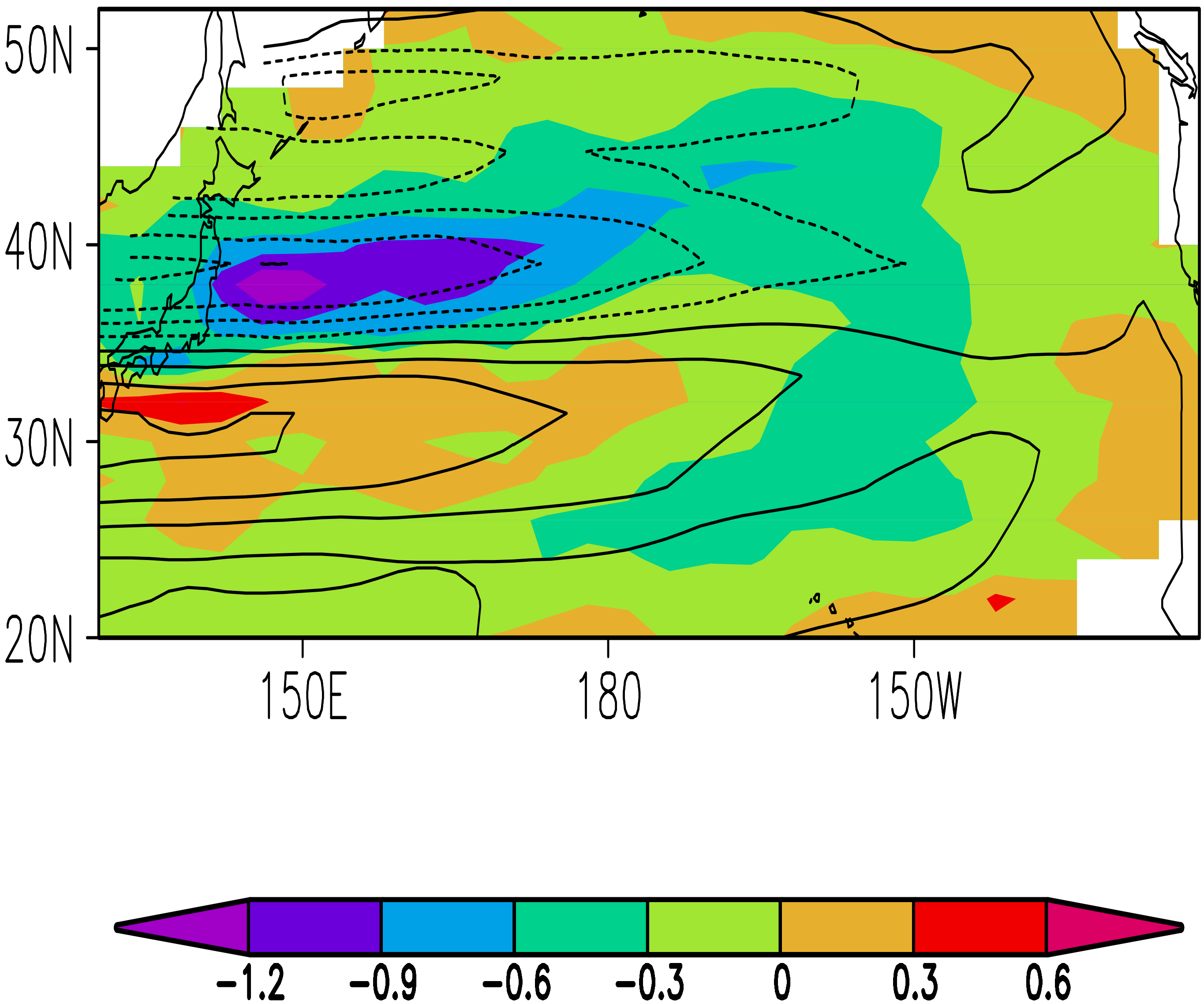

Figure 3.5: Predicted change in horizontal gyre strength (contoured every 2 Sv, 1 $Sv = 10^6 m^3 s^{-1}$) and observed depth averaged ($0 - 450$ m) temperature change (in K) between 1970-80 and 1982-90, i.e. a few years after the surface wind changes. From Deser et al. (1999).

3.3 The overturning circulation

The slowing down of the subpolar gyre hinted at in the study by Rhines and Hakkinen might be accompanied by a slowing down of the circulation in the meridional (latitude-depth) plane, the so-called overturning (or thermohaline) circulation Ψ. An estimate of Ψ is given in Fig. 3.6 for the Atlantic basin, from a simulation of an ocean model which has been constrained to observations over the last decade (Wunsch, 2002). Its essential features are the downward flow at high latitudes (related to North Atlantic Deep Water -NADW- formation) and the subsequent equatorward flow in deep layers balanced by a northward flow at intermediate (Antarctic Intermediate Water -AAIW) and upper (the Gulf Stream) levels.

Changes in the Atlantic overturning circulation in response to NAO forcing (surface wind+heat loss) have been hinted at in several modelling and observational studies (see the recent review by Visbeck et al., 2003). Eden and Jung (2001) for instance, suggest a basin scale anomaly in the heat transport by the overturning circulation lagging the NAO forcing by 10-20 yrs. It is not clear yet whether such changes are able to feedback on the atmosphere. This will be discussed in the last chapter.

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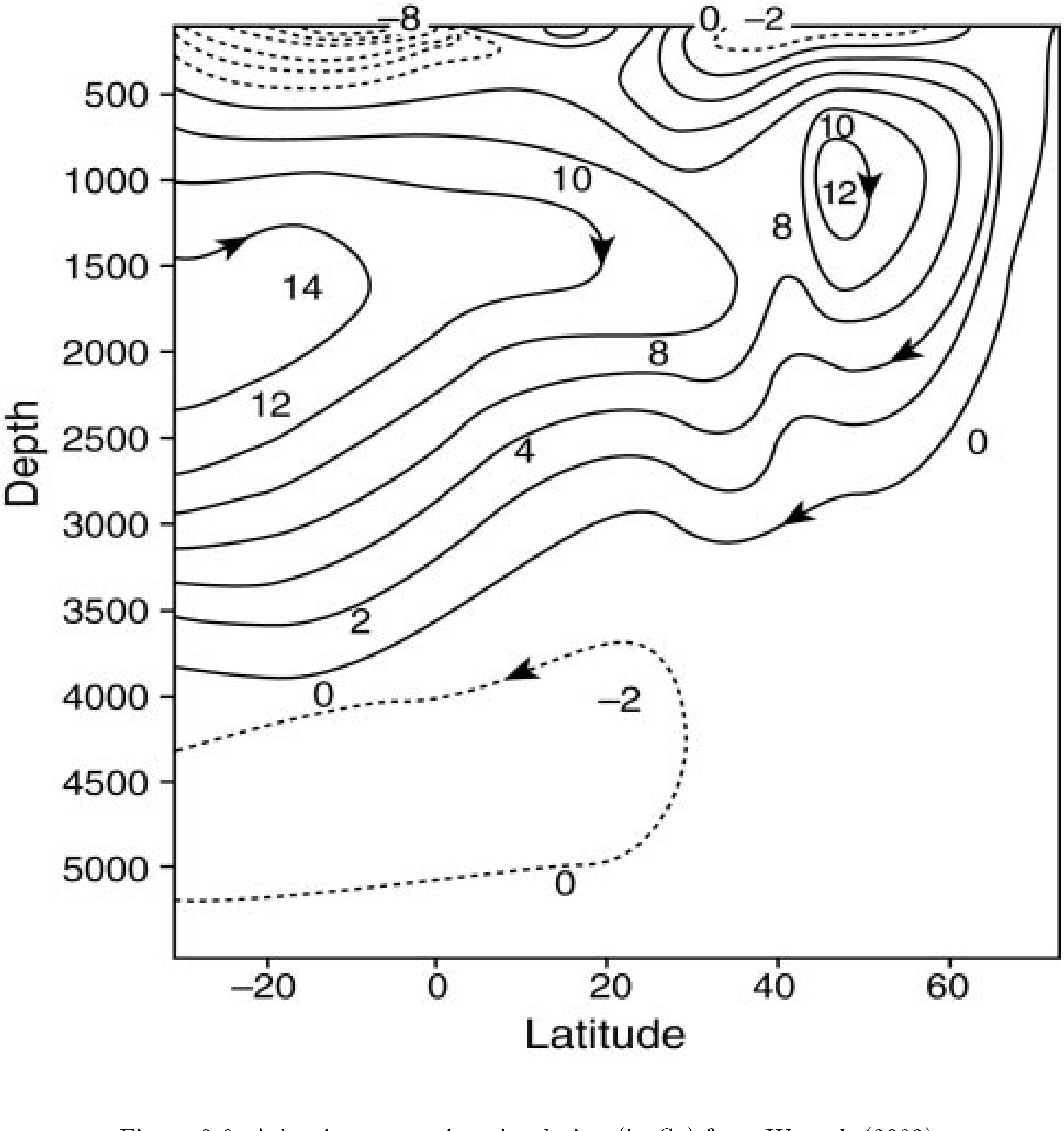

Figure 3.6: Atlantic overturning circulation (in Sv) from Wunsch (2002).

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Chapter 4

Feedback of the ocean on the atmosphere

We have seen in the last chapter that there is a large variability of the ocean circulation induced by atmospheric variability. In addition, as emphasized in the second chapter, there is little doubt that NAO, PNA and SAM would exist if there was no Gulf Stream and no meridional overturning circulation in the ocean. In other words, unlike in an El Nino event in which *both* the ocean and the atmosphere are key players, the extra-tropical atmosphere can "do it alone", even though we observe changes in ocean circulation.

This nevertheless does not rule out an oceanic influence, or feedback, on atmospheric teleconnections. Since this influence is likely to carry predictive skill, owing to the slow oceanic timescales (months and longer), it has been widely investigated.

4.1 The case against an oceanic influence in midlatitudes

Before looking at indications of such oceanic impact on the atmospheric circulation, let us first analyze the reasons for the general skepticism.

The latter is indeed quite strong, especially in the atmospheric community, and stems from many disappointing numerical experiments with atmospheric general circulation models (AGCMs) forced by prescribed SST anomalies. To summarize the latter, here is a dialog quite often heard in meetings:

> **(A)**: 'Do you think the midlatitude atmosphere cares about Gulf Stream SST anomaly?'
>
> **(B)**: 'Well, not really. Look at all these experiments with AGCMs. Whether or not you put an SST anomaly does not seem to change the model's NAO. This situation is very different from the tropics where SST anomalies have a much bigger impact.'
>
> **(A)**: Why is it so?
>
> **(B)**: I do not think anybody knows... the response of the jetstream to extra-tropical SST anomalies is weak and complicated. Slight changes in the background flow seem to lead to significant changes in the response. The response of the tropical atmosphere is more robust and we can understand it from simple dynamical models like Gill's 1980 solution. There is no such thing in midlatitudes...

It is indeed easy, looking at the huge literature, to understand (B)'s reaction. Consider first the equatorial Pacific region. A shown in Gill and Rasmusson (1983), one can simulate the surface winds anomaly in an intense El Nino event (that of 1982-83 here) from the diabatic heating, itself closely linked to SST anomaly. The atmospheric model used by Gill and Rasmusson is extremely simple, so simple that it is hard to imagine simpler! But it works!

Was it just by chance that the model succeeded in reproducing the 1982-82 changes in atmospheric circulation from SST changes? A recent and provocative study (Chen et al., 2004) showed that this is unlikely. Chen et al. are even able to go further and show that the same atmospheric model coupled to a simple ocean model can successfully reproduce all major ENSO events since the 1850s... Impressive!

Let's now look at the midlatitude region. If you were to force an AGCM with a given Gulf Stream SST anomaly and then redo the experiment starting from a different initial condition, chances are large that you would find a different atmospheric response than you had found in the first experiment. Why is it so? Simply because the atmosphere has a large variability of its own which masks any other signals. In other words, ensembles of experiments with different initial conditions rather than a single experiment are needed.

A vivid illustation of the above was given by Rowell (1998), who conducted ensemble of AGCM experiments with different initial conditions but same SST forcing (observed SST anomlies since the 1950s). Rowell shows maps of percentage of precipitation and sea level pressure which can be attributed to oceanic forcing (SST anomalies) over the last few decades (his Figs. 1, 2). Large values are found in the Tropics (with values close to 100 %), but as one moves towards higher latitudes the percentage falls to at best 30 %.

4.2 The case for an oceanic influence

Hopefully for oceanographers, maps like those of Rowell do not rule out a signal but merely suggest that the influence of the ocean must be weak. Even better, if the focus is on teleconnections instead of local (at each gridpoint) precipitation or sea level pressure anomalies as Rowell did, maybe there is even a stronger signal.

Focusing on NAO in this section, there seems indeed to exist a systematic influence of the lower boundary (SST, sea-ice, snow cover) on its behaviour over the last few decades. Consider the study by Rodwell et al. (1999), who again used ensemble of AGCMs forced by global lower boundary conditions anomaly over the last few decades. His key result is shown in Fig. 4.1. One observes that the ensemble mean, simulated, NAO index (dotted line) compares well with the true, observed NAO index (continous black). It does so better when low pass (bottom panel, correlation of 0.74) than when plotted each year (top panel, correlation of 0.41). This is remarkable, especially when thinking about the large intrinsinc variability we expect from the atmosphere. Does this mean we can predict the NAO ten years in advance from SST? And if yes, what is the physical mechanism behind the predictive skill?

It turns out that there are several caveats in Rodwell's analysis which must temper our excitment! First of all, look at the y-axis. It is non dimensional, which means that we are only comparing the phase of the two NAO indices. The amplitude of the simulated NAO index is actually much lower than the observed NAO. Second, it assumes that SST can be predicted. If the SST themselves are forced in an unpredictable way, we are short of any predictive skill! Third, SST anomalies were prescribed globally and it is not clear if North Atlantic SST (as Rodwell argue in the paper) or tropical Pacific SST, or sea-ice (!) anomalies are responsible for the good simulation.

Rodwell's results nevertheless have stirred a lot of interest and hopes that something exciting (not simply a passive response of the ocean to atmospheric forcing) might happen in extra-tropical ocean atmosphere interactions. It has been hard however to find as clear indications as Rodwell's experiments (and his successors who have been able to reproduce his results with differents AGCMs) in observations or coupled climate models. There are hints however.

Consider Fig. 4.2, which displays a time sequence of the Atlantic SST tripole (the SST pattern interacting with the NAO) from a long observational record (1854-2000). There is indication of a damped decadal oscillation which could be interpreted as reflecting a weak coupled mode of interaction between the Atlantic ocean gyres and the atmospheric jetstream (Czaja and Marshall, 2001).

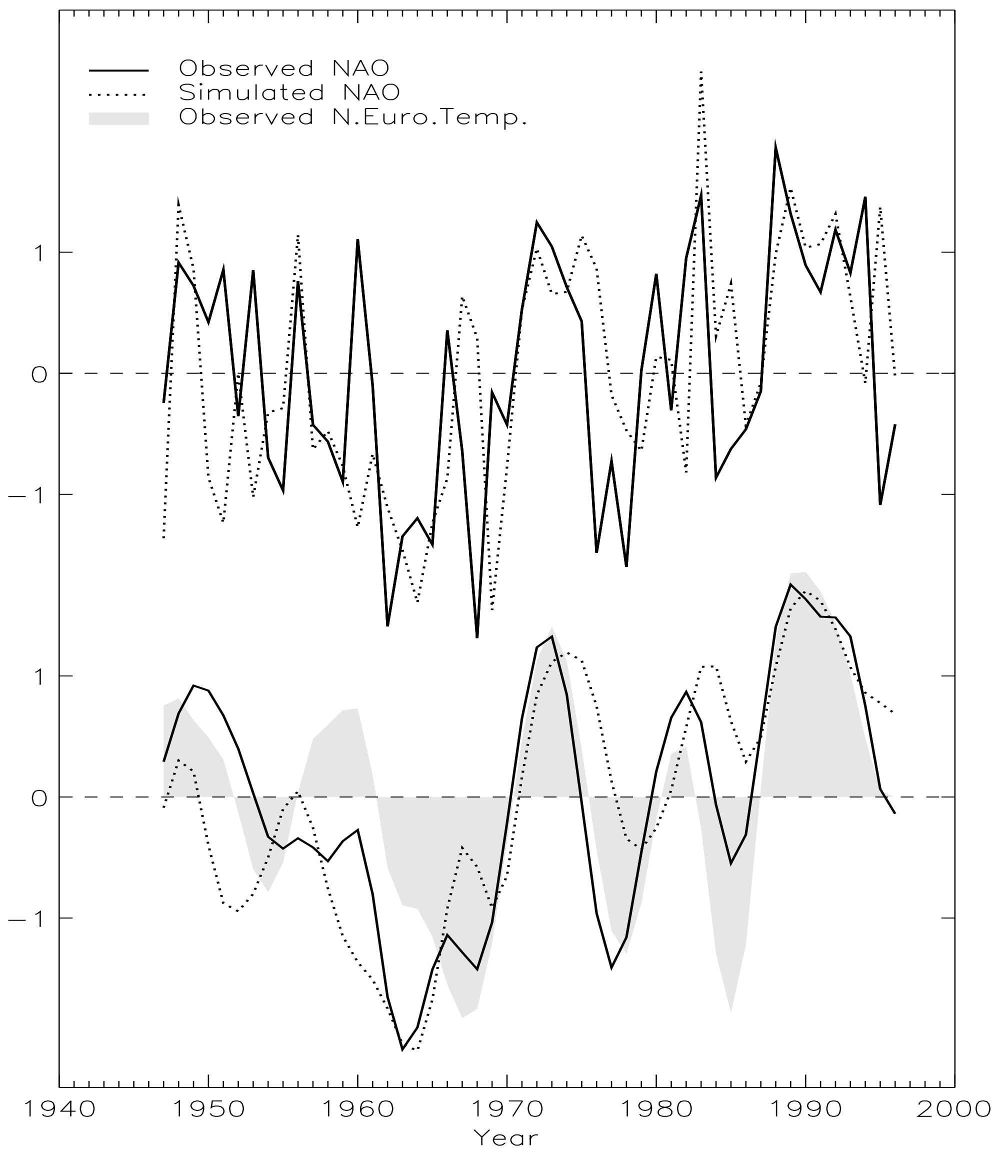

Figure 4.1: Observed (solid line) and modelled ensemble average (dotted line) winter (DJF) NAO index. The shading in the upper graph shows ±1 standard deviation about the ensemble mean, calculated from the normalized six model simulations for each individual year. The lower graph shows the NAO index timeseries after they have been filtered to pass variations with periods greater than 6.5 years. Shading in lower graph is the normalized filtered timeseries of observed North European surface temperature (averaged over $5-50°E, 50-70°N$). The year corresponds to December for each DJF season.

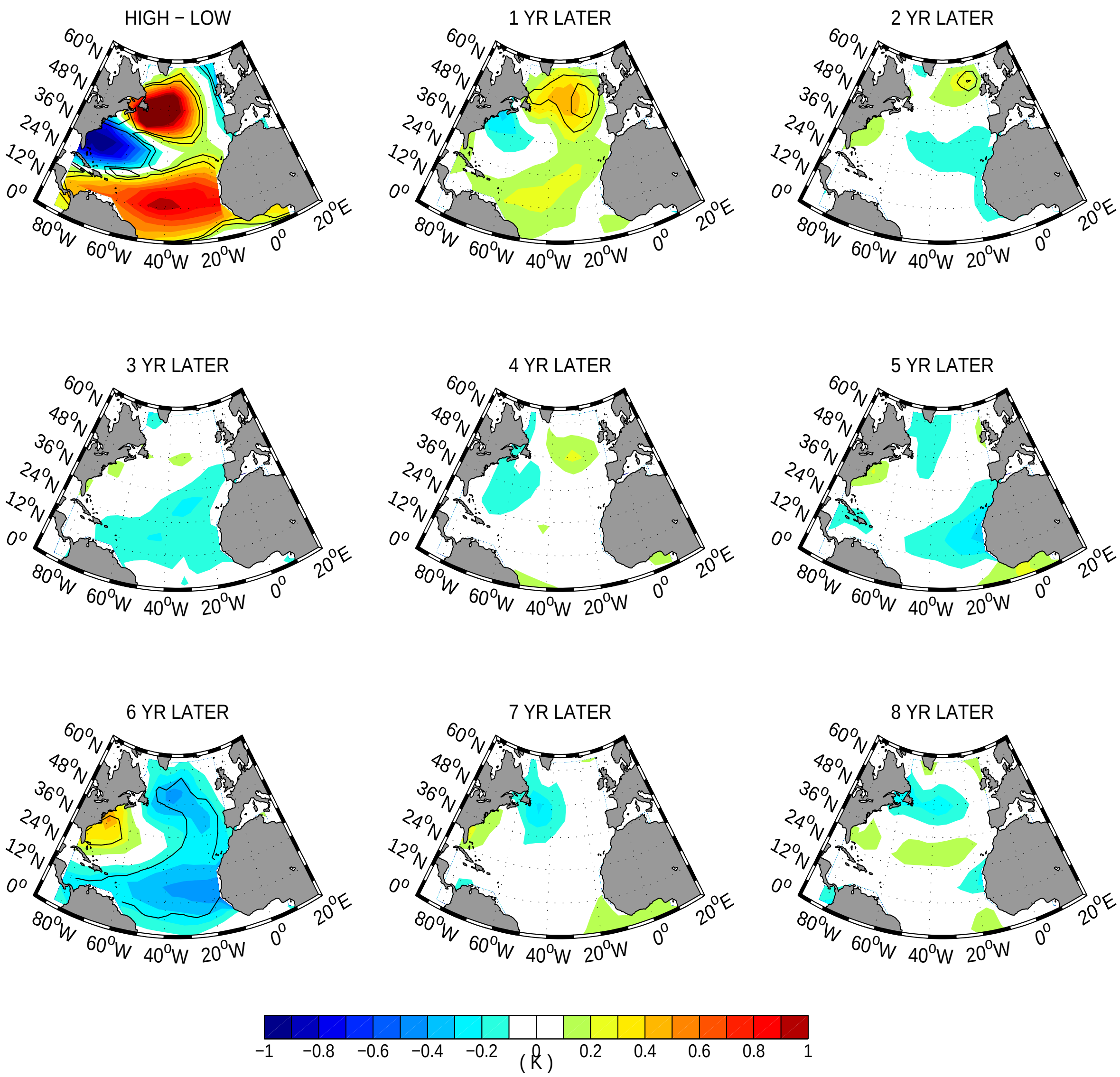

Figure 4.2: Composite of SST anomaly (color) based upon a cross Gulf Stream SST index (north of Gulf stream minus south of Gulf Stream). The SST pattern appears to persist for a couple of years, then disappears, then reappears with *opposite sign* after about 6 years. The black lines indicates where the maps are significant at the 95 % and 99 % confidence levels.

The hunt for such midlatitudes 'oscillations' has been intense among climate modellers. Perhaps the best example of one comes from Timmerman et al. (1998), who argue, by analyzing a long integration of the Max Planck Climate model, for a coupled (decadal) 'mode' between the Atlantic meridional overturning circulation (see chapter 3) and the midlatitude jetstream.

4.3 Open issues

(i) There is no equivalent to Gill's tropical solution in midlatitudes. This is crucially missing and the large spread of behaviour in AGCMs response to changes in ocean circulation and SST is still puzzling and at the same time very challenging! What is the dynamics by which a teleconnection such as NAO feels the surface boundary, as suggested in Fig. 4.1?

(ii) As the Paleo-community is bringing more and more basic observations of how climate has fluctuated in the past, there is a need for understanding the role played by the ocean in more basic problems than (i) such as what sets the pole-to-equator temperature gradient, or the position of the sea-ice margin, or the partitioning of the total poleward heat transport between the ocean and atmosphere. It now becomes possible to investigate these issues in idealized -yet realistic- settings, owing to the development of simple, 'intermediate' complexity, coupled climate models. This is a very exciting prospect!

4.4 References

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