Mechanisms of low-frequency SST variations in GFDL CM2.1: atmospheric forcing and delayed ocean response

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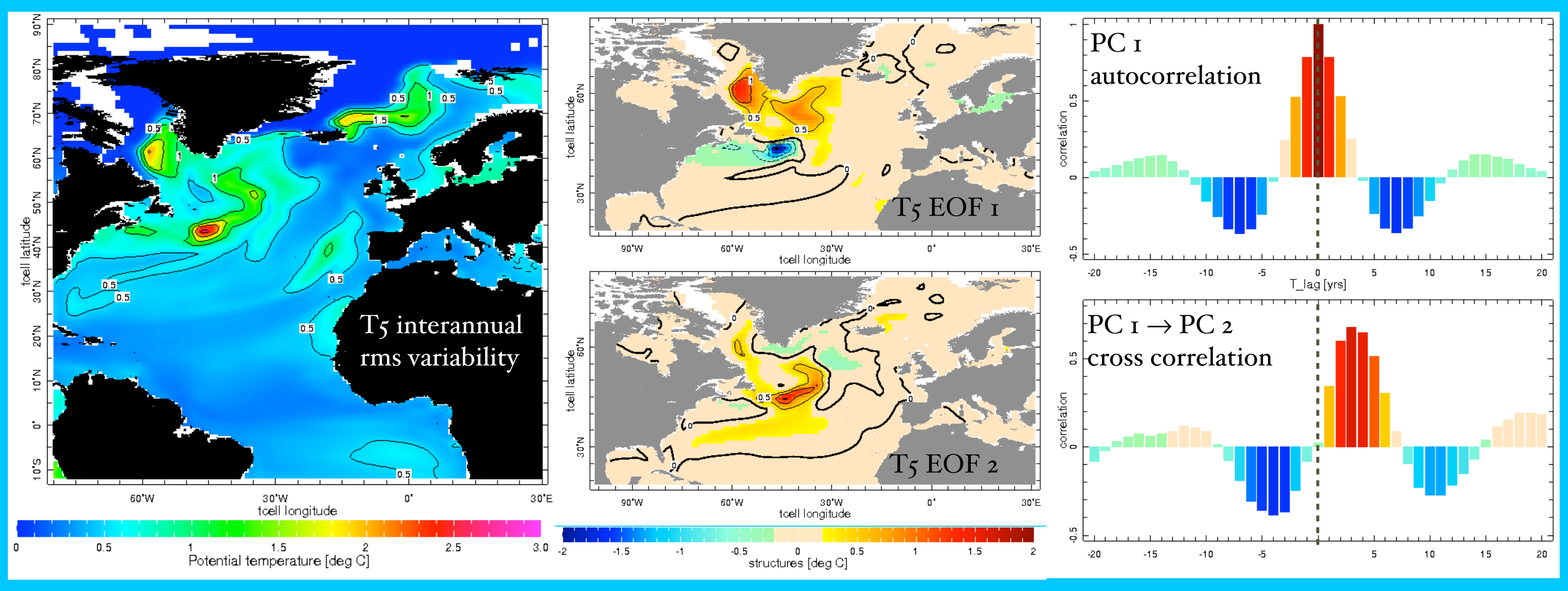
Abstract: The GFDL CM2.1 exhibits a prominent quai-periodic, decadal oscillation in subpolar North Atlantic SST and upper ocean heat content (OHC). The variability is forced by stochastic atmospheric variations in windstress and A/O surface heat flux exchange, both associated with the interannual variability of the wintertime North Atlantic Oscillation (NAO). The NAO forces upper SST and OHC anomalies such that when it is in a positive (negative) phase, subpolar SST anomalies are negative (positive) and anti-phase thermal anomalies in the subtropics. At the same time the NAO forces a delayed baroclinic meridional mass and heat transport that set up a slow process of northward ocean heat transport, which acts as a negative feedback on the contemporaneous, forced thermal anomalies. This interaction generates a quasi-periodic, stochastically driven oscillation.

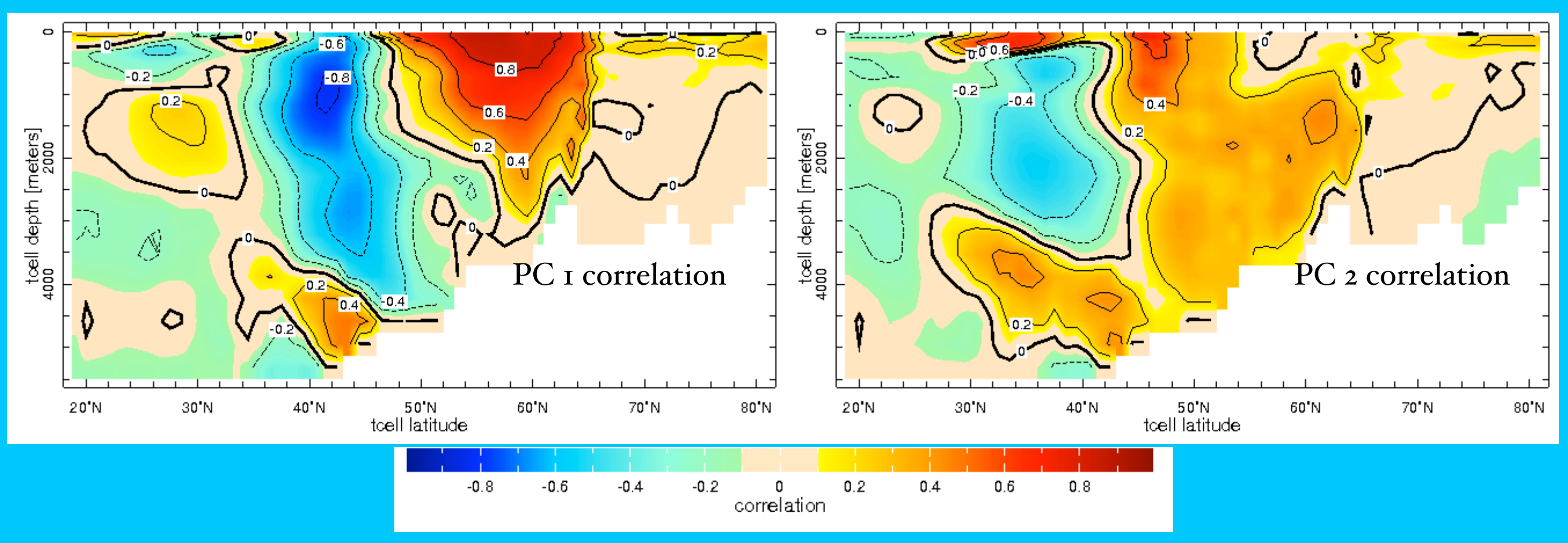
500-years of CM2.1 North Atlantic 5 m temperature variability

- T5 displays larges rms values in the subpolar gyre and along the North Atlantic Current. There is also a local maximum at the sea ice boundary in the Greenland Sea (left panel).
- The variance field is lead by two EOFs (middle panels), explaining 18 and 10% of the total domain variance, respectively.
- The respective time series (PCs) are quasi periodic, oscillating at 15-20 years (see acf of time series 1 in upper right panel).
- The times series of EOF 1 and 2 are in quadrature (the cross correlation figure in lower right panel) that implies a progressive movement of warmer/colder than normal water from the subpolar region to the subtropics.



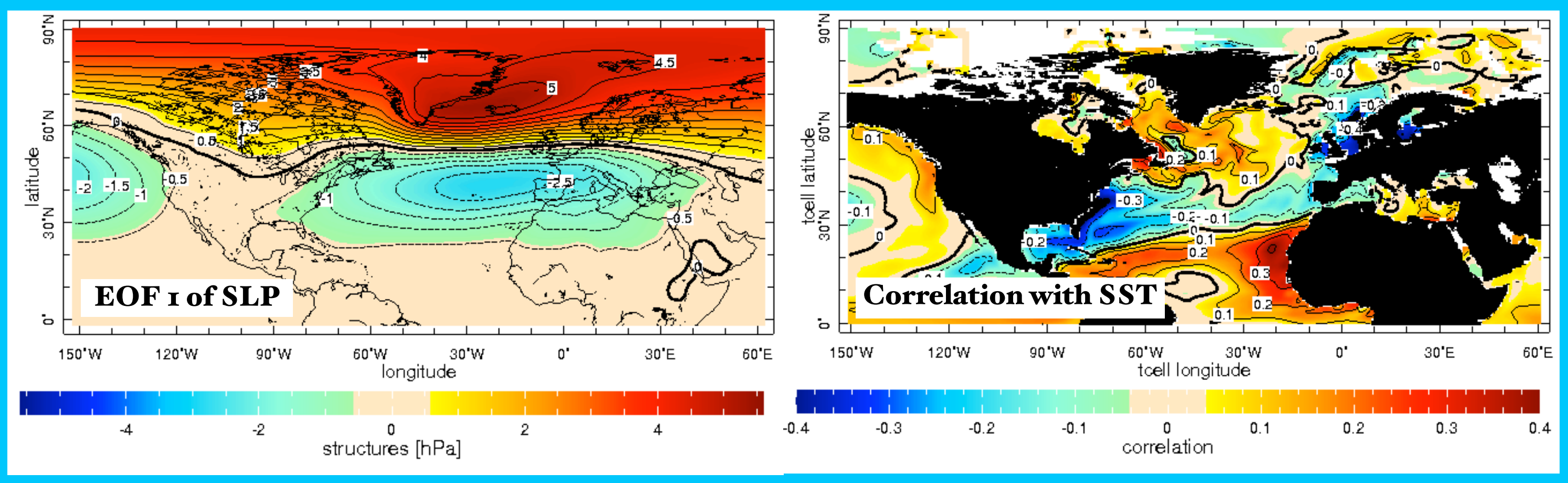
Vertical structure of ocean thermal anomalies

- The T5 temperature anomalies are the surface expression of a deep, coherent pattern of variability as seen from the correlation between the leading PCs and the zonally-averaged vertical thermal anomalies.
- Regression patterns (not shown) indicate that variance is confined to the top -1000 m.



The North Atlantic Oscillation and its SST footprint

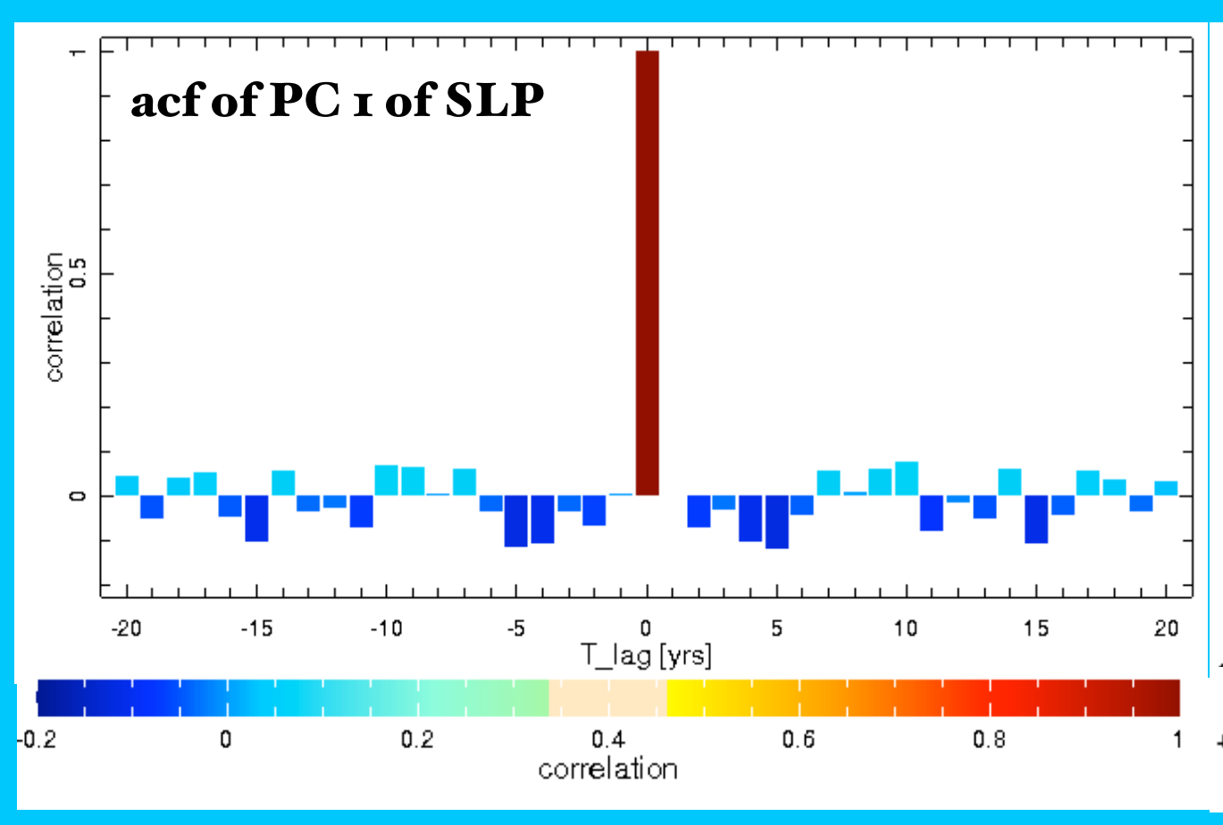
- North Atlantic Dec-Feb sea level pressure (SLP) variability is dominated by an annular mode pattern (NAO/AO) explaining 36% of total domain variance.
- The NAO ocean footprint is similar to observed one. The NAO related, North Atlantic SST pattern resembles the T5 leading EOF in the anti-phase relation between the subpolar and subtropical regions.

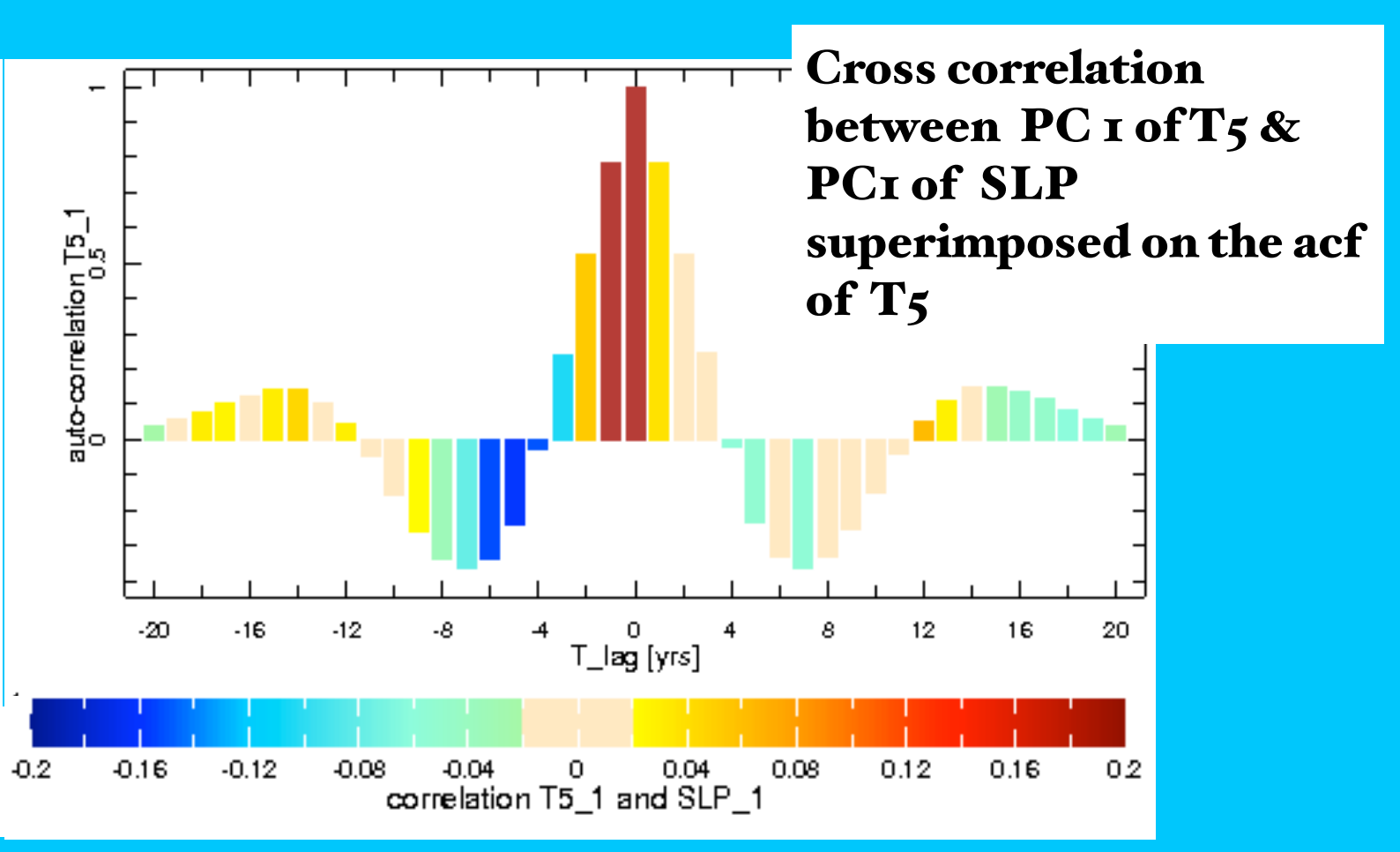


NAO driving the ocean thermal anomalies

- The NAO time series is largely "white" with no indication of the decadal timescale that dominate the upper ocean temperature variability (see SLP PC1 autocorrelation below left).
- The cross-correlation between PC1 of T5 and the NAO (below right) indicates that the NAO is driving the ocean thermal anomalies the impression of NAO persistence may largely be due to the T5 acf.
- There is indication of a weak positive feedback between the ocean and the atmosphere that may be important for the interaction though that too might be a statistical artifact due to the T5 persistence.

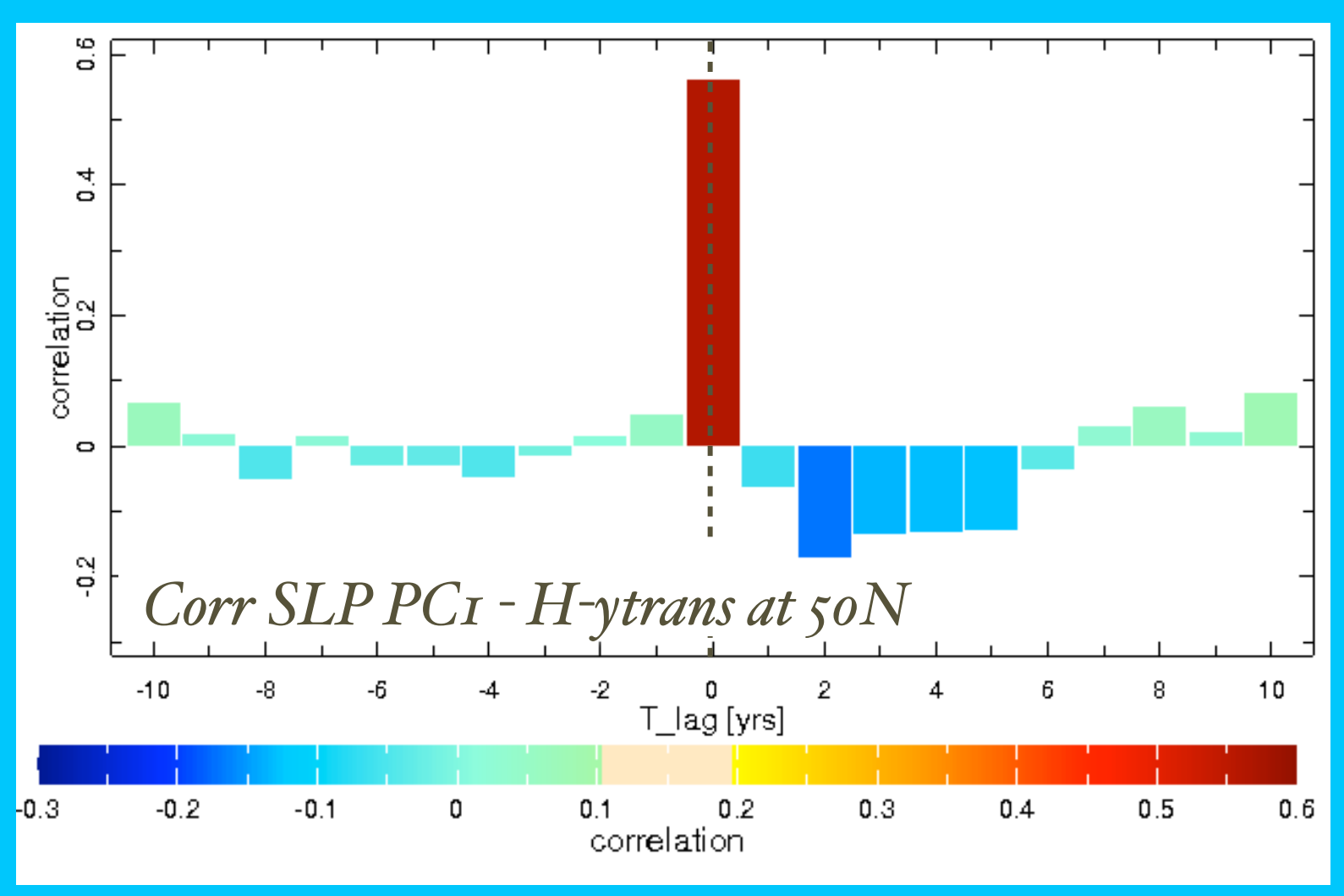
(In the diagram on the right the autocorrelation of PC1 of T5 is depicted by the length of the bars and the colors indicate the correlation between T5 and SLP. The significance of the low values of the cross correlation was confirmed by correlating PC1 of T5 and SLP from two different sets of 500 years)

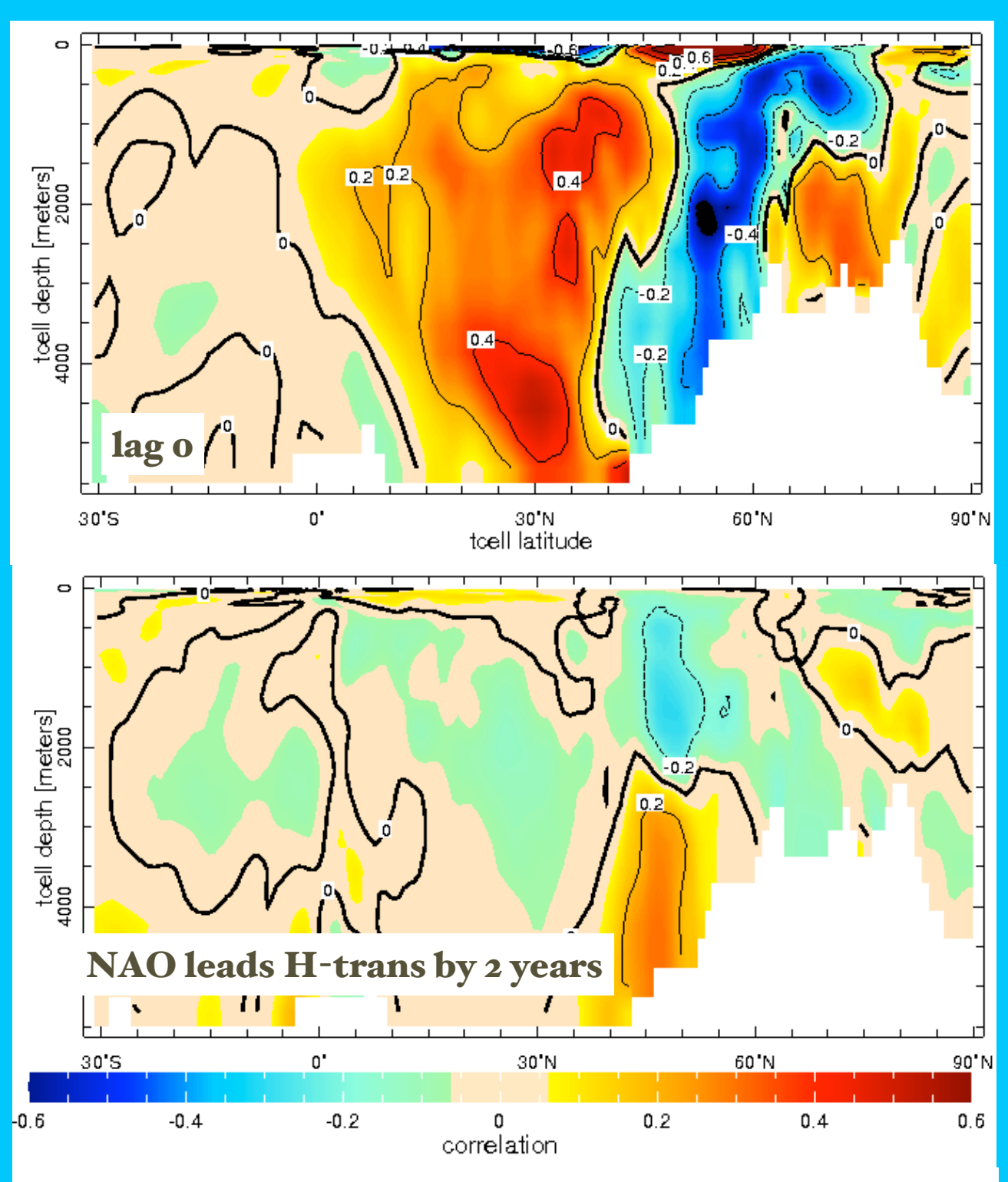



Cross correlation between PC 1 of T5 & PC1 of SLP superimposed on the acf of T5

NAO impact on the ocean meridional heat transport

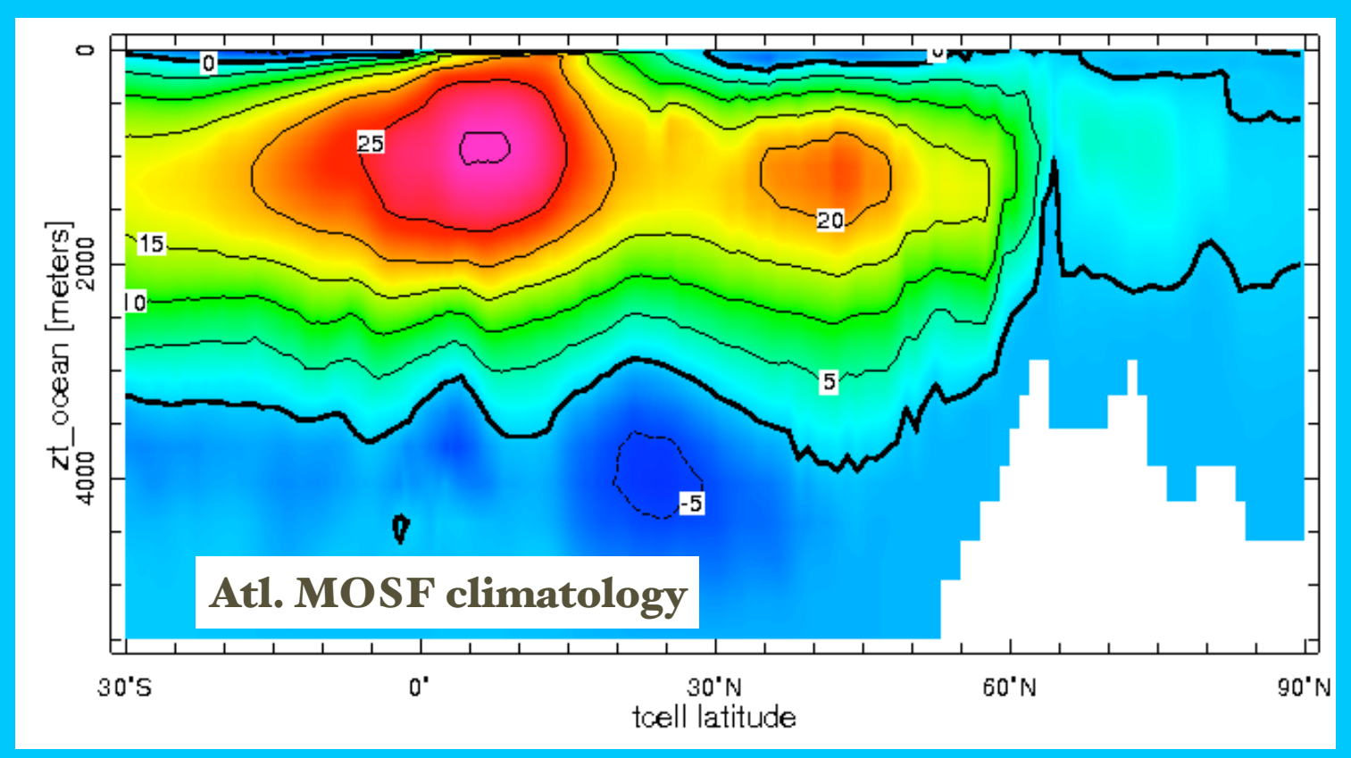
- The NAO related surface windstress field drives an ocean circulation response which affect the ocean heat transport in the North Atlantic.
- The concomitant seasonal impact of the windstress is to force an Ekman flow, which creates a surface warming (cooling) in the subpolar region, when the NAO is in its negative (positive) phase (in the same sense as the NAO-related surface heat flux response).
- The deep ocean circulation also responds to the windstress forcing, counteracting the shallow surface response.
- While the shallow upper ocean Ekman effect is short lived, the deep ocean response sets in motion a delayed negative impact on the ocean thermal field.

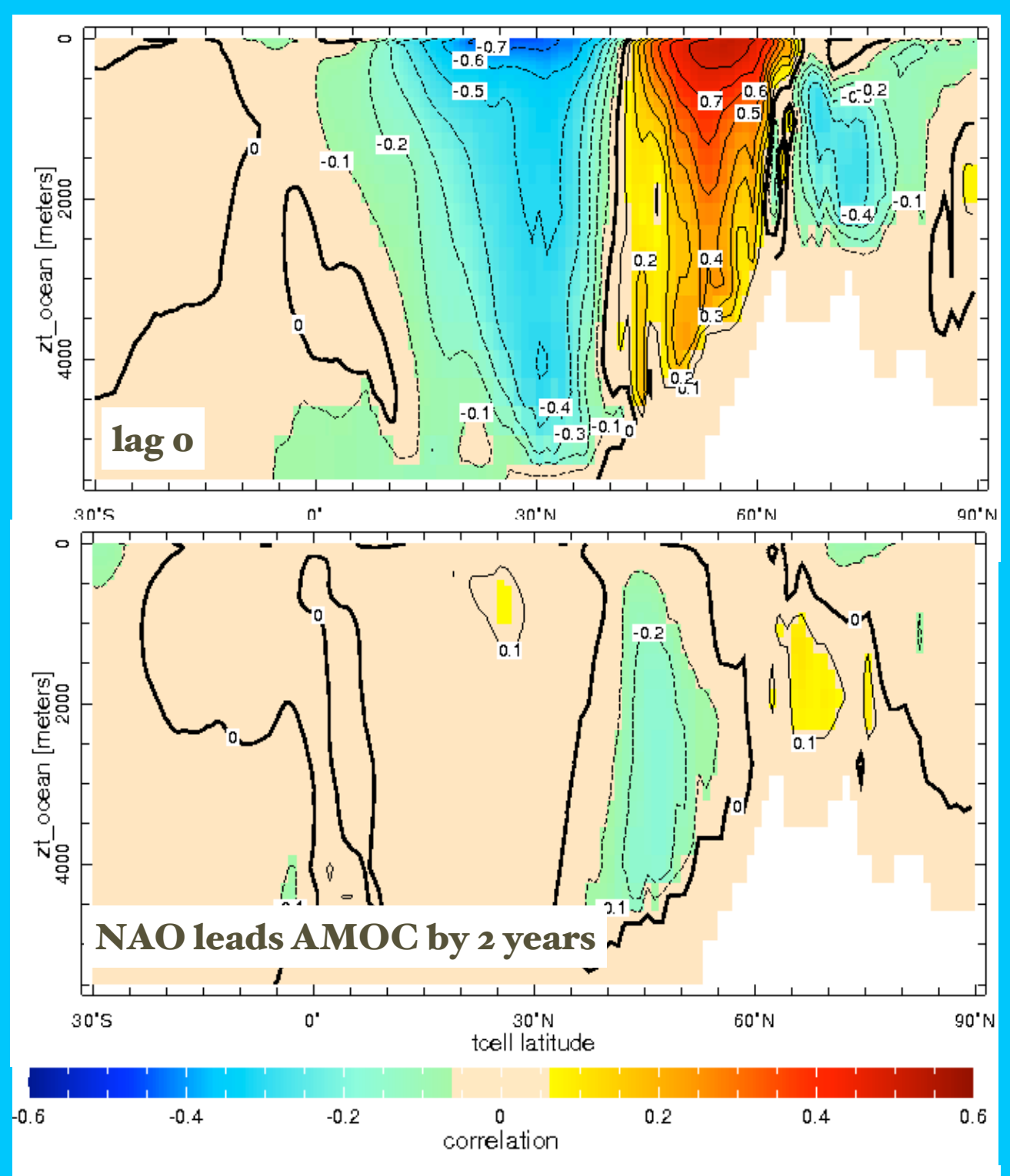



Corr SLP PC1 → meridional heat transport

NAO and AMOC

- The NAO impact of meridional ocean heat transport is connected with its impact on the Atlantic meridional overturning circulation (i.e., the circulation anomaly is important for the heat transport).
- The concomitant season response is a strengthening of the overturning in the subpolar region and a weakening in the subtropical region, consistent with the meridional heat transport response.
- As in the case of the meridional heat transport, the NAO sets up a delayed effect which will eventually weaken the overturning stream function strength in the subpolar region and lead to the the damping of the thermal anomalies there, setting the motion for the reversal of the thermal response.

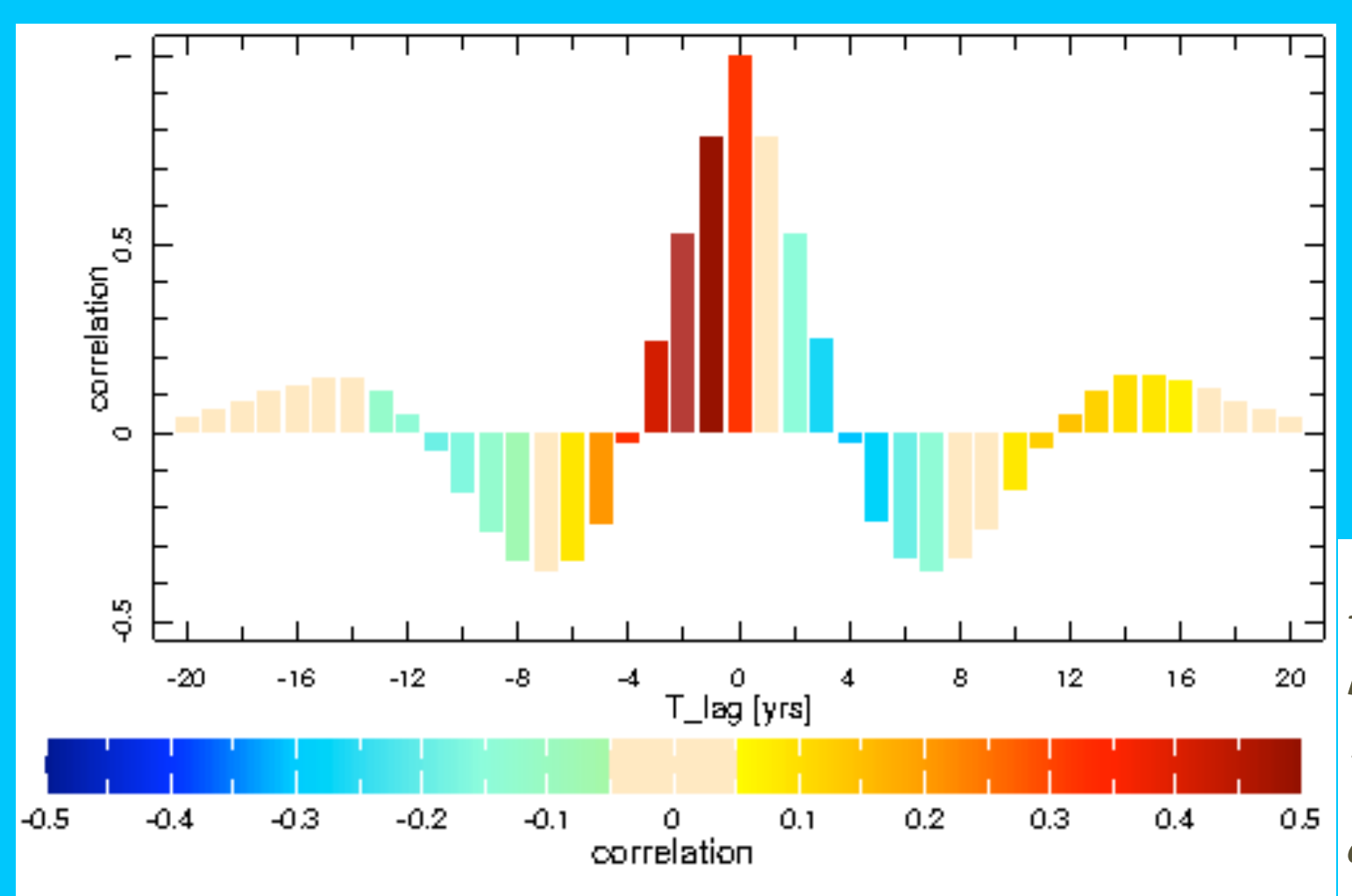



Corr SLP PC1 → meridional strem function

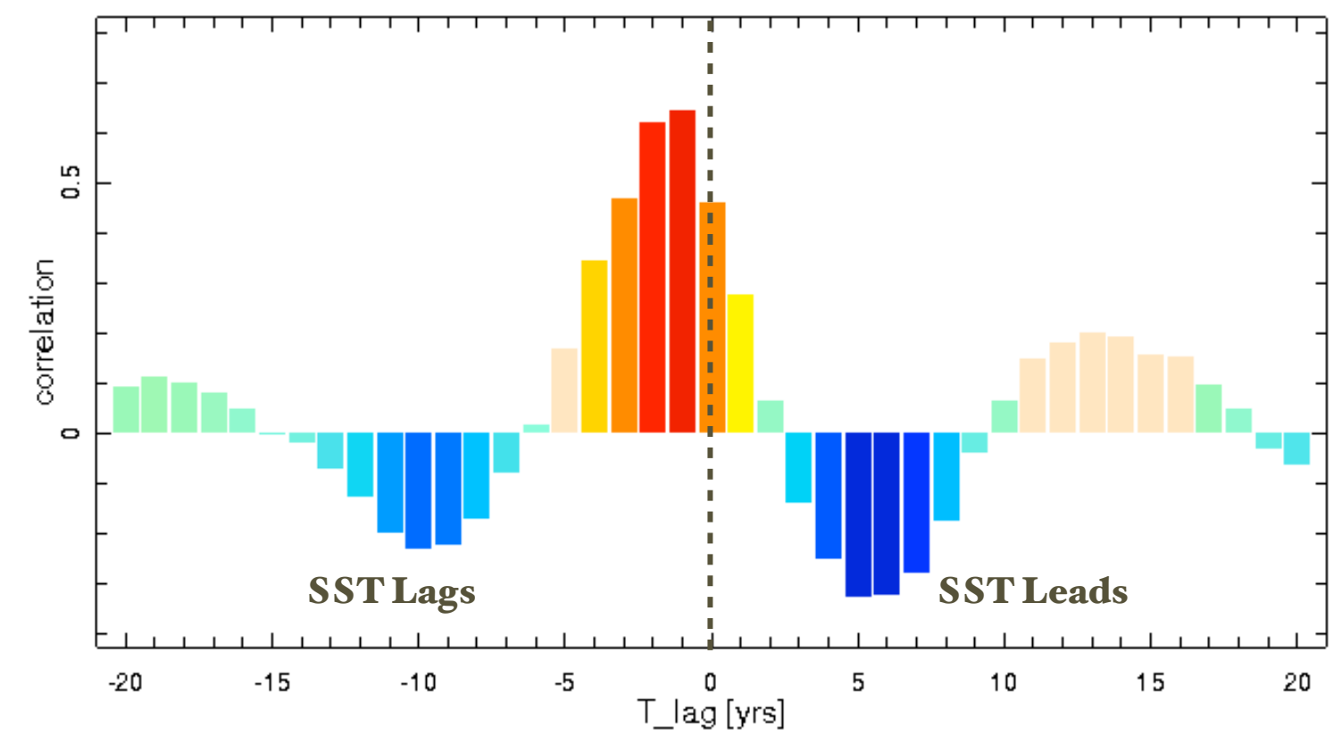
The ocean circulation and OHC anomalies

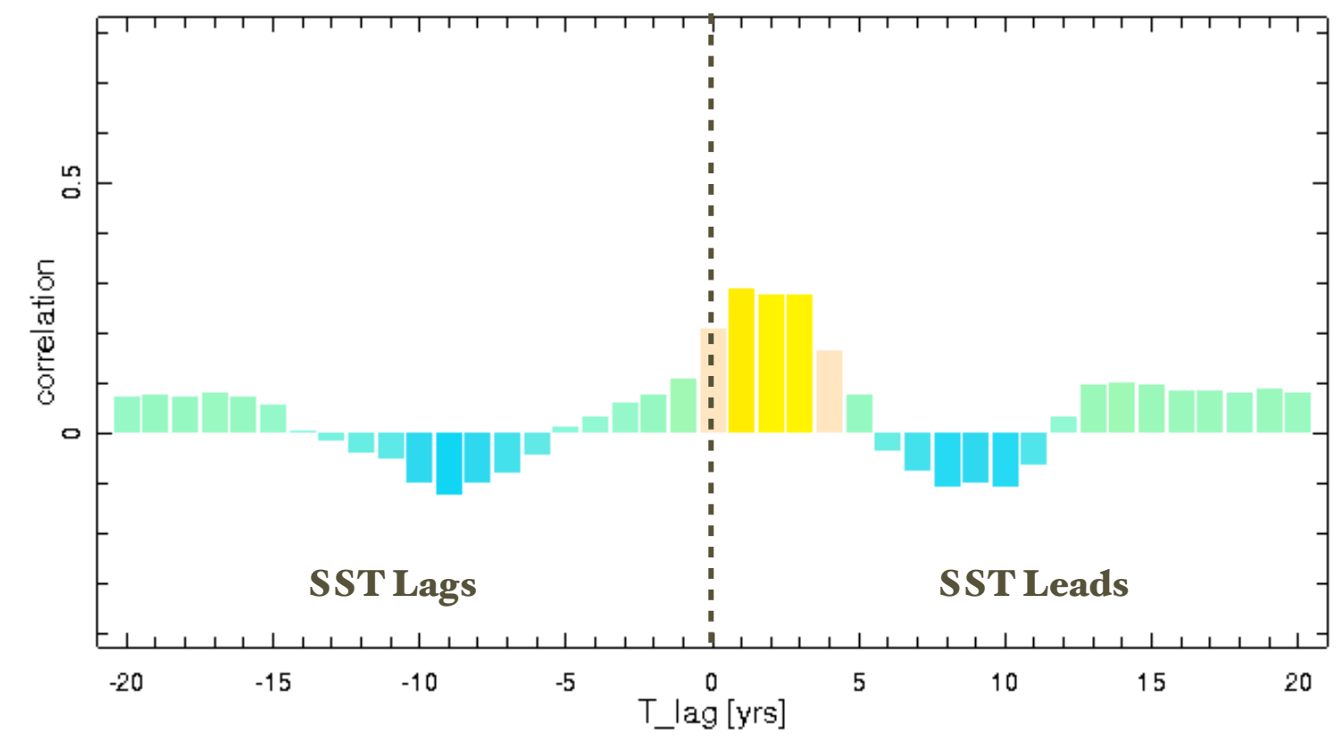
The relationship between upper ocean thermal anomalies and the action of the meridional heat transport and mass circulation is revealed in the figures below.

- Meridional ocean heat transport at 50°N leads the subpolar ocean thermal anomalies.
- This is due to mean overturning circulation anomalies that correspond to the alternating expansion and contraction of the overturning cell towards and away from the subpolar gyre.



In colors: corr. T5 PC1 → meridional ocean heat transport in the upper 1000 m.
The length of the bars represents the autocorrelation of PC1.


Corr T5 PC1 → MOSF 40-60°N 500-5000m


Corr T5 PC1 → MOSF 0-60°N 500-5000m

Oscillating of North Atlantic thermal anomalies driven by stocastic atmospheric forcing

The delay between the NAO forced heat content anomalies and its forced AMOC response is generating a damped oscillation, which is continually fed by the stochastic variability of the atmosphere. This "mode" of oscillation emerges also from a linear inverse model (LIM) fitted to the 3D ocean T and S anomaly fields of CM2.1. Upper ocean thermal anomalies generated by this process appear to propagate slowly (compared to the fast fluctuating atmosphere) from north (subpolar region) to south (subtropics) as the overturning circulation cell contracts and expands, respectively, controlling ocean northward heat transport and its convergence.

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