



Mechanisms of Interannual Thermal Variability in the North Atlantic During 1950-1999: An Ocean GCM Study

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Surface Interannual Thermal Variability

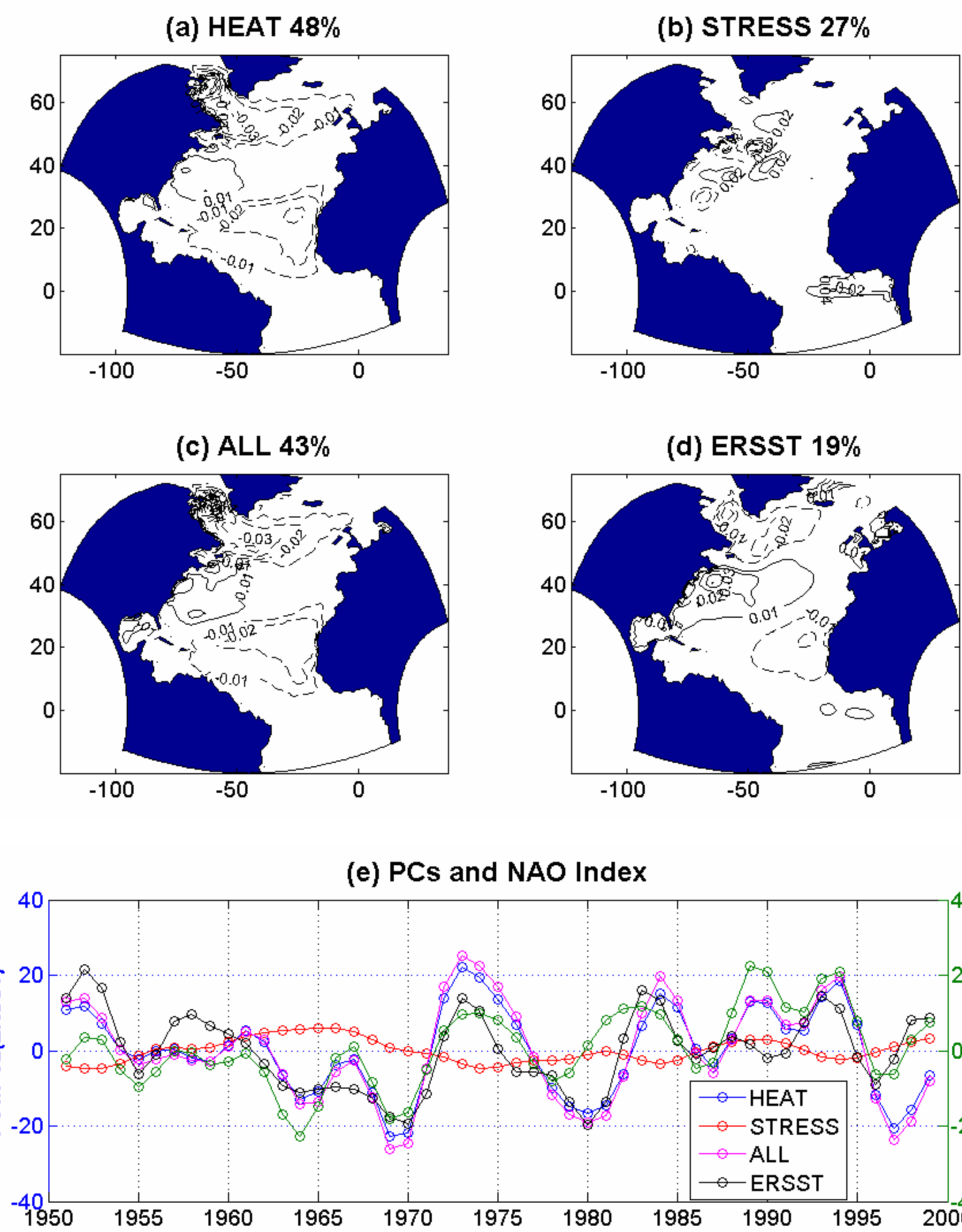


Figure 1. Spatial pattern of the leading EOF of the winter-time (JFM) SST anomalies for experiment (a) HEAT (b) STRESS and (c) ALL. The data are low pass (4-yr) filtered before calculating the EOFs. The percentage of variance explained is shown in captions. Experiments HEAT and ALL exhibit the familiar North Atlantic SST tripole, seen in (d) which shows the second EOF of extended reconstructed global sea surface temperature (ERSST) (the leading EOF of ERSST is a monopole associated with a long-term trend). There is strong variance in Baffin Bay in experiments HEAT and ALL, which, presumably, is due to the lack of a sea ice model in that region. Experiment STRESS shows a totally different pattern from HEAT and ALL, with strong variability concentrated along the Gulf Stream and its extension. The whole picture suggests that winter-time SST changes are predominantly forced by the air-sea heat flux anomalies, mainly the turbulent part induced by wind and air temperature changes (Cayan, 1992). Specifically, in the western North Atlantic, cold air outbreaks in winter can explain a significant part of the variance. Wind stress can change SST by modifying gyre circulation, and thus the heat transport, especially in the Gulf Stream extension. (e) The principle components (PCs) for the corresponding SST EOFs of HEAT, ALL and ERSST all show a significant correlation with the NAO index, suggesting that the atmospheric forcing of the SST tripole is coordinated by the NAO. The PC for STRESS is uncorrelated with the NAO and shows a long term change, however.

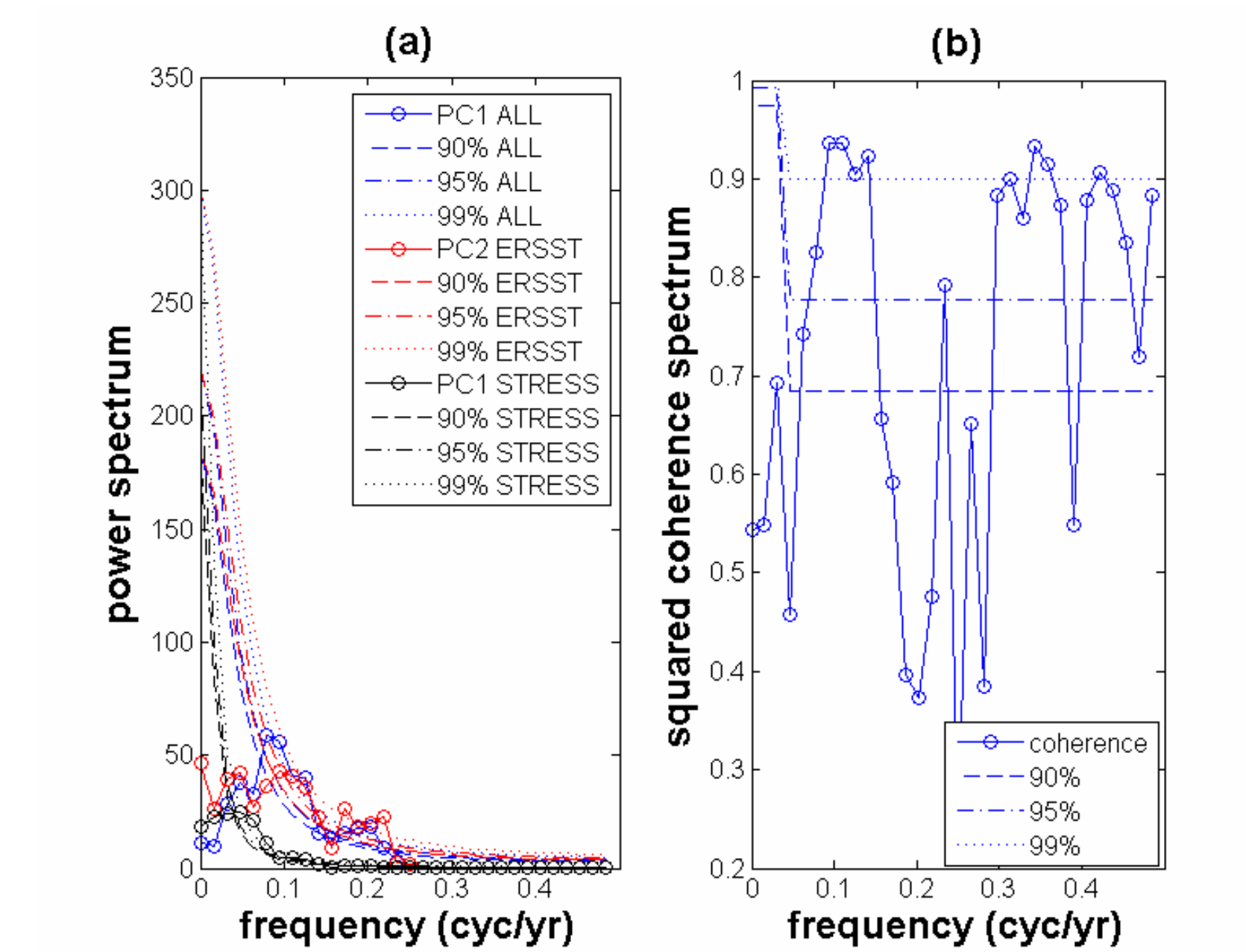


Figure 2. (a) Multi-taper power spectrum for PC1 of Experiments ALL and STRESS, and PC2 of ERSST with 90%, 95% and 99% confidence level above a red noise fit. PC1 of HEAT has very similar shape to that of ALL (not shown). PC1 of ALL shows peaks around periods of 5 yr and 10 yr. They are 99% significant above the red noise, indicating the interannual and decadal nature of the SST variability. The observation (ERSST) also shows a peak around 10 yr, but not so significant (only above 95%) as ALL, maybe due to the noise in the data. ERSST PC2 also has strong variability over 4-7 yr period. STRESS PC1 has a peak above 99% level at 16 yr. This suggests that the gyre response to the mechanical forcing by the atmosphere is a slow process. (b) Squared coherence between PC1 of ALL and PC2 of ERSST. At a significant level, the two time series are well correlated with each other in the interannual to decadal band.

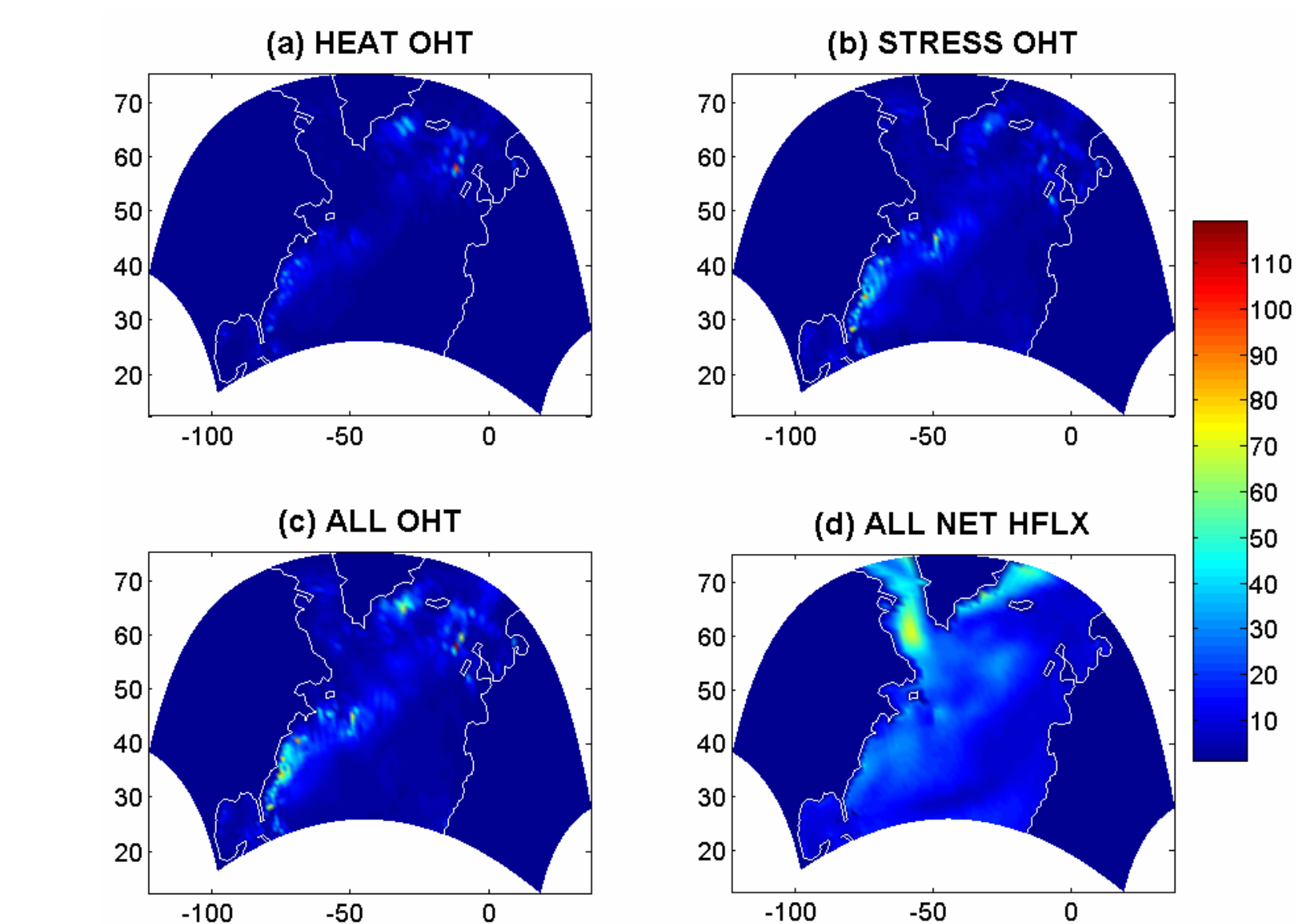


Figure 3. Standard deviation of the winter-time oceanic heat transport (OHT; shown in the flux form, Wm^{-2}) by anomalous currents advecting SST climatology in the mixed layer for experiments (a) HEAT (b) STRESS and (c) ALL. (d) standard deviation of the winter-time net air-sea heat flux for experiment ALL. There is little OHT variability in experiment HEAT, because most gyre circulation anomalies are caused by the wind stress changes, as shown in STRESS and ALL. Most of the wind-stress-induced OHT variance is in the western subtropics and the Gulf Stream extension. Its spatial scale is small, but the magnitudes can match or exceed those of the surface heat fluxes. In contrast, OHT by the mean advection carrying SST anomalies are less important (not shown). This finding is consistent with altimetric derived horizontal advection data (Scott and Qiu, 2004). An estimate of OHT by Ekman currents components (not shown) is also performed and it is generally found to be small ($10-20 Wm^{-2}$) and concentrated in the region where the gradient of the climatological SST is the greatest.

Introduction

Interannual thermal variability in the upper layer of the North Atlantic during the last 50 years is studied using a 1 degree resolution ocean GCM. When forced with monthly-varying NCEP fields, the model reproduces the observed SST variability moderately well. The variability appears to exhibit power on periods of 5 and 10 years, which is significantly different from a red noise spectrum. Other experiments show that surface thermal variability is dominated by air-sea heat fluxes. Ocean circulation changes induced by wind stress anomalies play a secondary role. In some regions, such as the western subtropics, circulation changes can cause similar variability to the air-sea fluxes, however. Heat budget analysis shows that SST anomalies from heat transport changes - mainly anomalous currents - are smaller in lateral scale than those caused by surface heat flux perturbations, and are concentrated in the Gulf Stream and its extension. Upper ocean heat content anomalies show a different EOF pattern from that of SST with much longer time scales. Heat and momentum forcing contribute almost equally in mid-latitudes. Wind stress anomalies dominate at lower latitudes via wind stress curl driven long Rossby waves. Heat flux anomalies play a dominant role at higher latitudes through their control on deep convective processes. Anomalies in the western subtropics are hinted to be advected by the Gulf Stream and North Atlantic Current into the subpolar region.

Model and Experiments Description

The ocean model (without sea ice) is a 1° configuration of the MITgcm on a rotated spherical polar coordinate grid. There are 21 levels in the vertical with 4 levels in the upper 100m. The model is spun up for 20 yrs forced with NCEP/NCAR reanalysis climatology from the Levitus (1994a, b) climatology. All the experiments start from the state at the end of the spin-up run. The forcing fields are the monthly NCEP/NCAR reanalysis (1950-1999) surface wind, air temperature, air specific humidity, downward long-wave and short-wave radiation, and precipitation, which are then used to calculate the surface flux terms in the model. Four experiments are performed as summarized in Table 1. The only difference among these experiments is the time-varying components in the forcing. In experiment CONTROL, all forcing fields are climatology. Monthly turbulent heat flux and wind stress anomalies are added in experiment HEAT and STRESS respectively. Experiment ALL has all the monthly flux anomalies. By setting up experiments this way, we can have a clear look at the ocean's response to mechanical and thermal forcing by the atmosphere.

Experiment	Latent Hflx	Sensible Hflx	Wind Stress	Radiative Fluxes	E-P-R
CONTROL	C	C	C	C	C
HEAT	V	V	C	C	C
STRESS	C	C	V	C	C
ALL	V	V	V	V	V

Table 1. Surface flux forcing for numerical experiments.
C: Monthly climatology over period of 1950-1999
V: Containing time-varying monthly anomalous field for 1950-1999

Surface Thermal Variability: Fig1, 2, 3

Subsurface Thermal Variability: Fig4, 5, 6

Summary

- The model is moderately accurate at capturing the observed 1950-1999 SST variation.
- Interannual to decadal SST anomalies in the North Atlantic arise mainly from surface heat fluxes, modulated by the NAO. Wind-driven gyre changes only produce small-scale SST anomalies in the western boundary currents.
- Upper ocean heat content varies over much longer time scales, with wind stress and heat (buoyancy) fluxes both playing a role. The subsurface anomalies in the western subtropics, which mainly result from oceanic adjustment to surface wind stress curl changes through long Rossby waves, tend to propagate north-eastward into the subpolar region, although the evidence is not very strong.

References

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Subsurface Thermal Variability

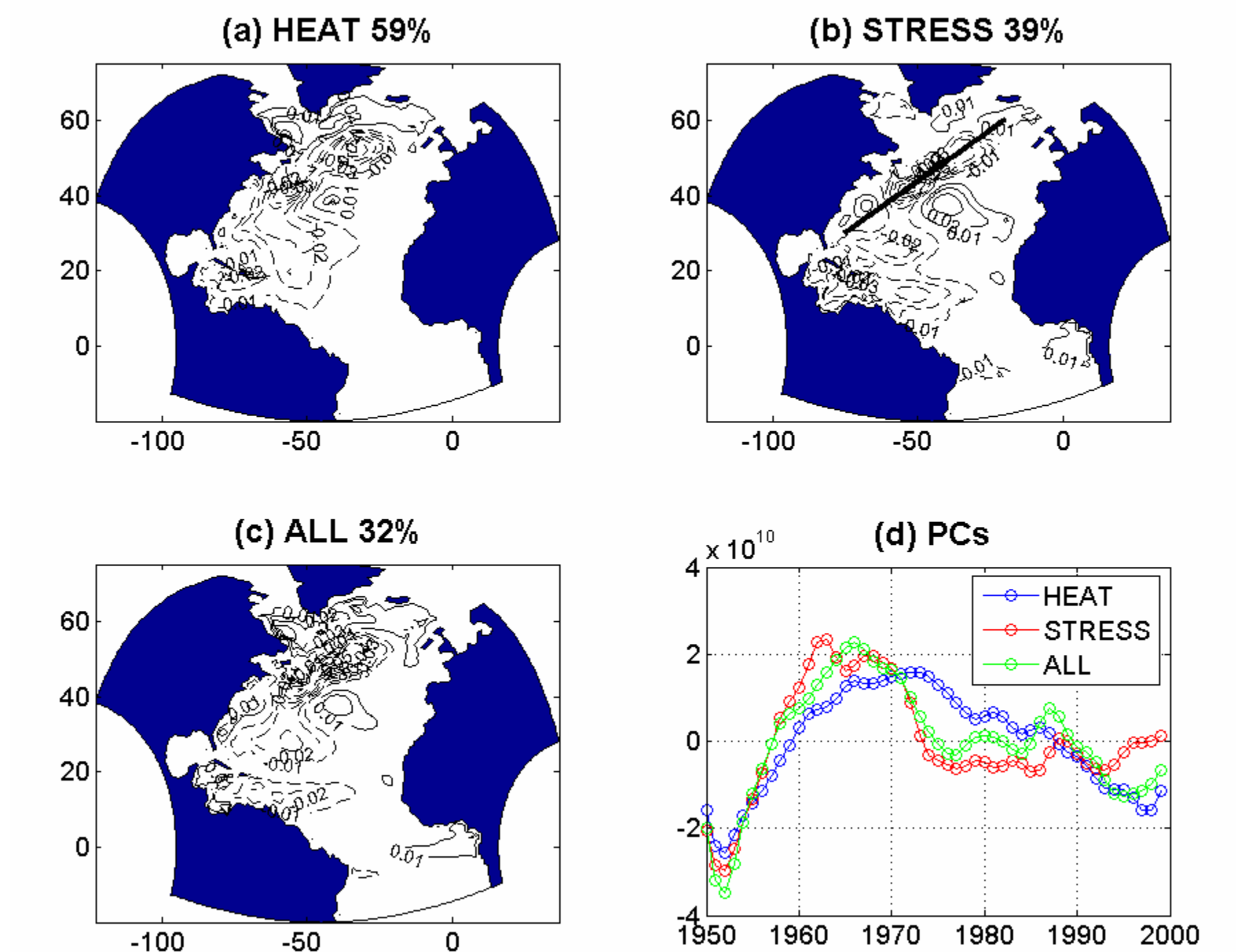


Figure 4. Spatial pattern of the leading EOF of the annual mean upper ocean (0-1000m) heat content anomalies for experiment (a) HEAT (b) STRESS and (c) ALL and (d) their corresponding PCs. The percentage of variance explained is shown in captions. Large variabilities can be seen along the path of Gulf Stream separation and the North Atlantic Current (NAC) in all three experiments. The PCs indicate that the variability is on a much longer time scale than SST (decadal or even longer) such that it can not be resolved robustly in the present 50 year simulation. At low latitudes (south of 20°N) wind-driven response dominates, while heat flux forcing is more important at higher latitudes. Both contribute equally in middle latitudes. Similar features are present in Ezer (1999) although he considered decadal sea surface height (SSH) variability.

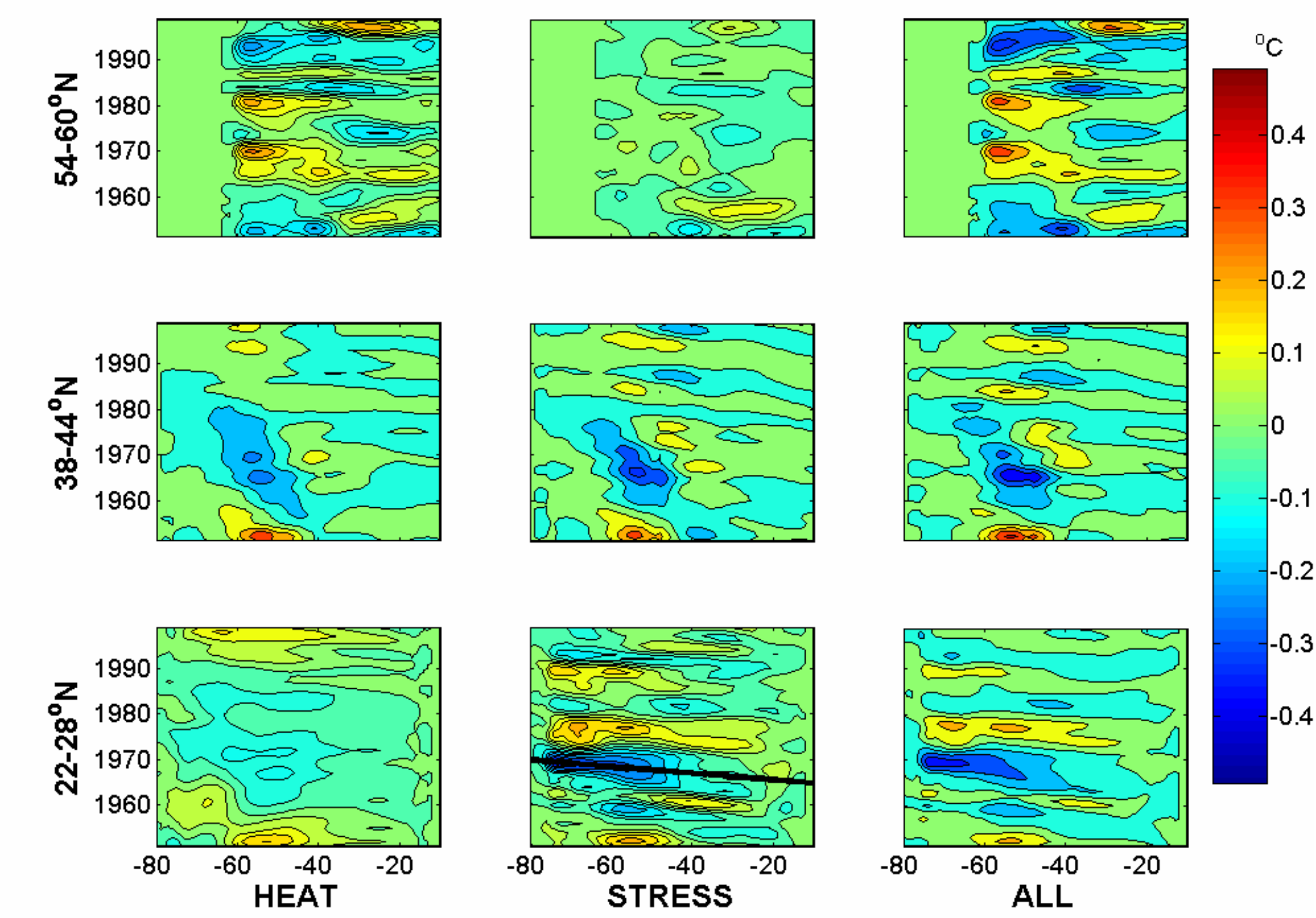


Figure 5. Hovmöller diagram of annual mean temperature anomalies [$^{\circ}C$] over top 1000m (similar to the heat content defined in Figure 4) for experiments HEAT (left column), STRESS (middle column) and ALL (right column) at three latitude bands: 22-28°N (top row), 38-44°N (middle row) and 54-60°N (bottom row). At lower latitudes (bottom row), the pattern of STRESS resembles that of ALL with little signal in HEAT, indicating the dominance of the wind stress. In particular, STRESS shows the propagation of temperature anomalies westward, whose speed is consistent with the long Rossby wave speed at this latitude (bold solid line in the middle of the bottom row). At higher latitudes (top row), the opposite is true. We speculate that this is because of the control of heat flux on the deep convective processes (hence on the meridional overturning circulation) in the western subpolar gyre (Labrador Sea). In middle latitudes, all three experiments show similar features with a strong cooling moving westward slowly from middle of the basin starting at 1960's. The contributions from heat flux and wind stress add much in a linear way, as emphasized by Ezer (1999). Although decadal variability in the subpolar region can be attributed to thermal or buoyancy forcing (Häkkinen, 2000), wind stress does play an important role in other places. Its role in middle latitudes is especially worth further investigation.

As an example, **Figure 6.** shows the Hovmöller diagram of annual mean temperature anomalies [$^{\circ}C$] over top 1000m along an axis (bold solid line in **Figure 4.(b)**). There is a hint that anomalies propagate from western subtropics to the subpolar region in 1950's, 60's, and 90's. The axis lies over the path of the separated Gulf Stream and the NAC, suggesting these anomalies are carried by the upper ocean currents. It has been shown that SST anomalies propagate along a similar path (Sutton and Allen, 1997). Our results show that this could also potentially happen for the subsurface temperature anomalies, although the propagation is less clear.

