UNSTABLE AIR-SEA INTERACTION IN THE EXTRATROPICAL NORTH ATLANTIC

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The possibility of coupled modes in the extratropical North Atlantic has fascinated the climate community since 1960's[1]. A significant aspect of such modes is an unstable air-sea interaction [1,2] , also called positive feedback, where disburbances between the atmosphere and ocean grow unbound. If a delayed response exists [3] before the negative feedback takes effect, an oscillatory behaviour will develop. Here we explore the relationship between heat flux (positive upward) and sea surface temperature (SST). Positive feedback is characterized by a cross-correlation between the two where correlation maintains a negative sign whether SST or heat flux leads [4]. We use model results and observations to argue that in the North Atlantic there exist regions with positive feedback. The two main locations coincide with the well-known north-south SST dipole [5] where anomalies of opposite sign occupy areas east of Florida and north-east of Newfoundland. We show that oceanic dynamics, wave propagation and advection, give rise to oceanic anomalies in these regions. Subsequently these anomalies are amplified by atmosphere-ocean interaction: thus a positive feedback.

Several studies have argued on behalf of negative feedback between atmosphere and ocean on longer time scales in the world oceans away from western boundary current regions [6,7]. These arguments are based on a stochastic model which describes the observed low-frequency SST variations as an oceanic red noise response to the atmospheric white noise forcing [8]. The case for red noise response in the eastern Atlantic Ocean can be considered rather clear, however the western Atlantic and the subpolar gyre have not been subjected to such analyses because of the influence of the strong currents affecting SST variability [6,7]. Comparison of SST and sea surface salinity spectra suggests that the physics in the those areas cannot be described by local white noise-forcing [9]. Since a positive feedback is necessary for the extra-tropical atmosphere to respond to SST anomalies, an atmospheric general circulation model (AGCM) forced with observed SST should produce such a response in a form of specific circulation changes. However, until very recently the various efforts of forcing AGCMs with observed SST or with idealized patterns of specified SST anomalies have been unsuccessful in producing a robust response [10,11] while at least one coupled model exhibits modes that have been interpreted as coupled atmosphere-ocean modes[12]. The study of Rodwell et al.[13] is the first to document a statistically significant signal in AGCM both by using observed SST monthly anomalies (in respect to the climatological monthly average) and by limiting the model SST forcing to the dipole SST pattern from the analysis of Grötzner et al.[12]. In the former case the low frequency North Atlantic Oscillation (NAO) index (periods less than 6 years filtered out) is reproduced using an ensemble of 6 experiments. The use of SST dipole gives a NAO-like sea level pressure (SLP) response based on ensemble of six 20-year simulations.

Here we document existence of positive feedback between heat flux and SST in the extra-tropical North Atlantic based on both observations and numerical ocean model results. While it is expected that the centers of the aforementioned dipole SST would be such regions, the goal is to show that in those regions ocean dynamics produces much deeper anomalies which are coincident with, or lead, heat flux changes. We start with the numerical model results[14] for time evolution of the upper ocean temperatures and surface heat flux in the subtropics. The largest variance in the surface heat flux occurs at the same locations as the SST dipole and is characterized by the leading mode from an empirical orthogonal function (EOF) analysis (Fig. 1; explains 24% of the seasonal variance). The evolution of subsurface temperature anomalies and their arrival near the subtropical center of heat flux EOF1 is depicted in fig. 2 which shows the temperature anomaly at 400 meter depth along the latitude 26N, from west to east for the period, 1951-1993. Also the subtropical heat flux anomalies (80W-50W, 25N-35N) are shown with the (negative of) time series of the heat flux EOF1. Only winter (Nov-April) averages are used which are detrended quadratically and smoothed by one binomial filter. There are 3 warm and 3 cold events propagating across the Atlantic with an apparent quasi-decadal periodicity. These signals are prominent in the subsurface temperatures down to 1000 meter depth and are interpreted as baroclinic Rossby waves due to their westward phase propagation. The observed arrival of warm and cold subsurface temperature anomalies (from 1969 on) at 74W in the latitude band 23N-29N [15] is shown to be rather well matched with the model ones. Comparison of the heat flux and temperature variations in the western Atlantic suggests that the relationship between them appears to be a local one-way forcing by atmosphere: positive heat flux creates negative heat content and vice versa. However, with the information from an ocean GCM, one sees that the local heat flux acts to amplify oceanic temperature anomalies propagating from east; i.e. a positive feedback occurs.

A harbinger for the fate of the heat content anomalies after they reach the US East Coast is a propagation of winter SST anomalies along the Gulf Stream and North Atlantic current [16]. We confirm that the same route is taken also by anomalies in the deeper water column. The winter temperature anomalies at 400 m (Fig. 3) along the path (depicted in Fig. 1) shows advection along Gulf Stream, but the propagation speed varies considerably: a rapid expansion of the anomalies from Cape Hatteras to 40N and then slower propagation towards the northern subpolar gyre. The quasi-decadal events are well defined but bifurcate around 40N. Compared to the subtropics the relationship in the subpolar gyre between the heat flux and oceanic heat anomalies has shifted towards the ocean leading the atmospheric changes: The warm (cold) temperature anomalies arrive to the subpolar gyre at the time when the heat flux tendency reverses from cooling (heating) towards heating (cooling). The subpolar gyre has been noted to be an area of positive feedback in a coupled model[12]. Less strong assessment, lack of damping of subpolar low-frequency SST anomalies, is inferred from observations [17].

Another way to determine areas of positive feedback is to compute cross-correlations between the heat flux and SST fields. To include advective effects to some degree, spatial averaging is applied to both fields. Since atmospheric scale is about 1000km, a natural choice is to form 10degx10deg spatial averages. The upper waters of the western Atlantic travel even longer distances within one to two years, thus the spatial averaging does not cover all of the advective effects. Figure 4. displays the cross correlation between net flux and SST based on ship observations for 1945-1993 [18], and between the model heat flux and 400 meter heat content from period 1951-1993. Besides spatial averaging, linear detrending and one binomial filter have been applied to the winter time series at individual gridpoints. At 95% level, a significant correlation is 0.38 for a 43 year record. For monthly time scales observations suggest a lifespan of 4-6 months for mixed layer temperature anomalies [6,7] which is valid if there are no underlying physical mechanism giving them more persistence. At lower frequencies considered here an existence of such mechanism maintaining long lasting oceanic anomalies should manifest itself as regions of significant negative correlations whether ocean leads or lags. The appearance of significant negative correlations for 0 and +1 year lags when the atmosphere leads is expected since there is some persistence also in the atmospheric forcing on longer time scales. On the negative lags of -1 (and -2 years) when ocean leads atmosphere, there are prominent centers of significant correlations at locations east of Florida and north-east of Newfoundland. We argue that these significant correlations do not occur by chance but there is a physical mechanism, wave propagation or advection, at work as confirmed by Figs. 2-3. The significant cross-correlations carry over to the deeper ocean depending on the location: for a 400m heat content, the subtropics show stronger correlations than the subpolar gyre (Fig.4). In the latter area the largest correlations occur for depths (about 1000 m) typical of deep convection [19]. Stronger correlation values for the deeper ocean than for SST is suggestive of a dynamic link between heat flux and thermohaline circulation.

The locations of positive feedback are associated with the centers of the Atlantic SST dipole pattern [5] similar to the SST anomaly distribution used to produce a robust atmospheric response in an AGCM [13]. We have demonstrated that these are locations where oceanic dynamics contribute to the existence of the SST/upper ocean heat content anomalies in the first place. Aside from the dipole centers, the cross-correlations implicate the Gulf of Mexico and the North Sea to be also regions of positive feedback. All the regions appearing with positive feedback are areas of intense winter storminess. With the knowledge of SST anomalies in these key areas in the North Atlantic and with the understanding of the oceanic role maintaining those anomalies, longer time scale dynamic prediction of winter climate in the eastern US and Europe can gain feasibility.

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FIGURE CAPTIONS:

1. The spatial pattern of the heat flux EOF1 in non-dimensional units. The temperature sections along 26N and along Gulf Stream and North Atlantic Current are also shown.

2. (a) Time evolution of the anomalous heat flux in an area [80W-50W, 25N-35N] (solid line) and heat flux PC1 multiplied by (-0.2) (dashed line), both in units of W/m2. (b) The sign of anomalies arriving at 74W at 300 m from Molinari et al. (1997) after 1969 (time axis is the same as in (a)) and the model simulated evolution of 400 m temperature anomalies (in C) along 26N. The simulated heat flux and temperature anomalies are November-April averages, quadratically detrended and smoothed by one binomial filter.

3. (a) The 400 m temperature anomalies (in C) along the Gulf Stream and North Atlantic Current (path depicted in Fig. 1) versus time. (b) The model simulated evolution of the subpolar heat flux anomalies (solid line) [55W-25W,45N-60N] together with the heat flux PC1 (dashed line), both in units of W/m2. The heat flux anomalies and temperature anomalies are November-April averages, quadratically detrended and smoothed by one binomial filter.

4. The spatial distribution of cross-correlations between (a) heat flux and SST from COADS (daSilva et al 1994) based on 48 year record, (b) model heat flux and 400 meter heat content (Häkkinen 1999) based on 43 year record. At lag -1 year, the oceanic quantities lead, at lag +1 year, the heat flux leads. The fields are November-April averages, linearly detrended and smoothed by one binomial filter. Correlations (absolute value) above 0.38 are significant at 95% level using Student t-test. Only negative correlations are shown and areas with correlation greater (i.e. weaker) than -0.3 are shaded, interval is 0.1.

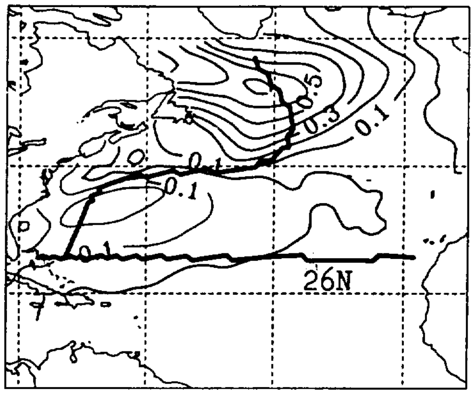
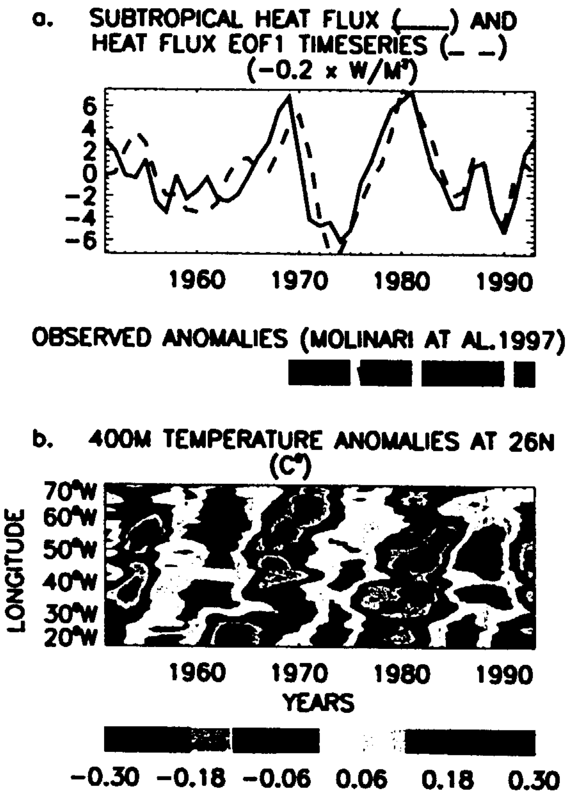
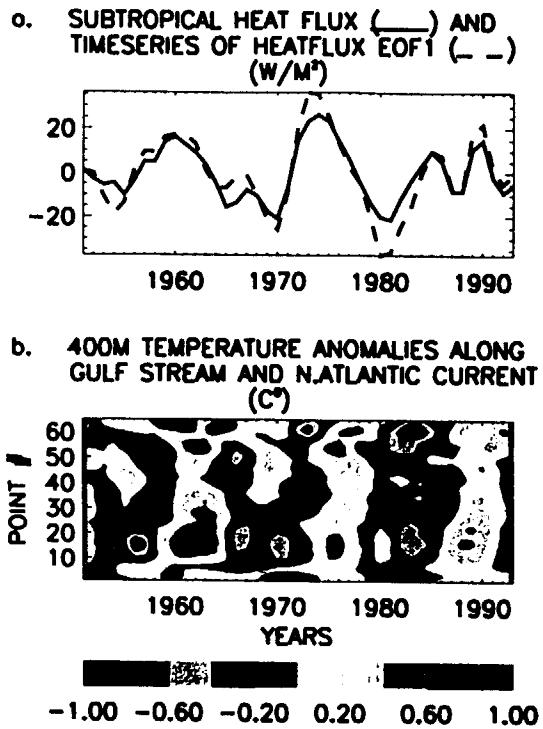


FIGURE 1



a. SUBTROPICAL HEAT FLUX (____) AND
HEAT FLUX EOF1 TIMESERIES (_ _)
(−0.2 × W/M²)
6
4
2
0
−2
−4
−6
1960
1970
1980
1990
OBSERVED ANOMALIES (MOLINARI AT AL.1997)
b. 400M TEMPERATURE ANOMALIES AT 26N
(C°)
LONGITUDE
70°W
60°W
50°W
40°W
30°W
20°W
1960
1970
1980
1990
YEARS
−0.30
−0.18
−0.06
0.06
0.18
0.30

FIGURE 2



a. SUBTROPICAL HEAT FLUX (___) AND TIMESERIES OF HEATFLUX EOF1 (_ _) (W/M²)
20
0
-20
1960
1970
1980
1990
b. 400M TEMPERATURE ANOMALIES ALONG GULF STREAM AND N.ATLANTIC CURRENT (C°)
POINT #
60
50
40
30
20
10
1960
1970
1980
1990
YEARS
-1.00
-0.60
-0.20
0.20
0.60
1.00

FIGURE 3

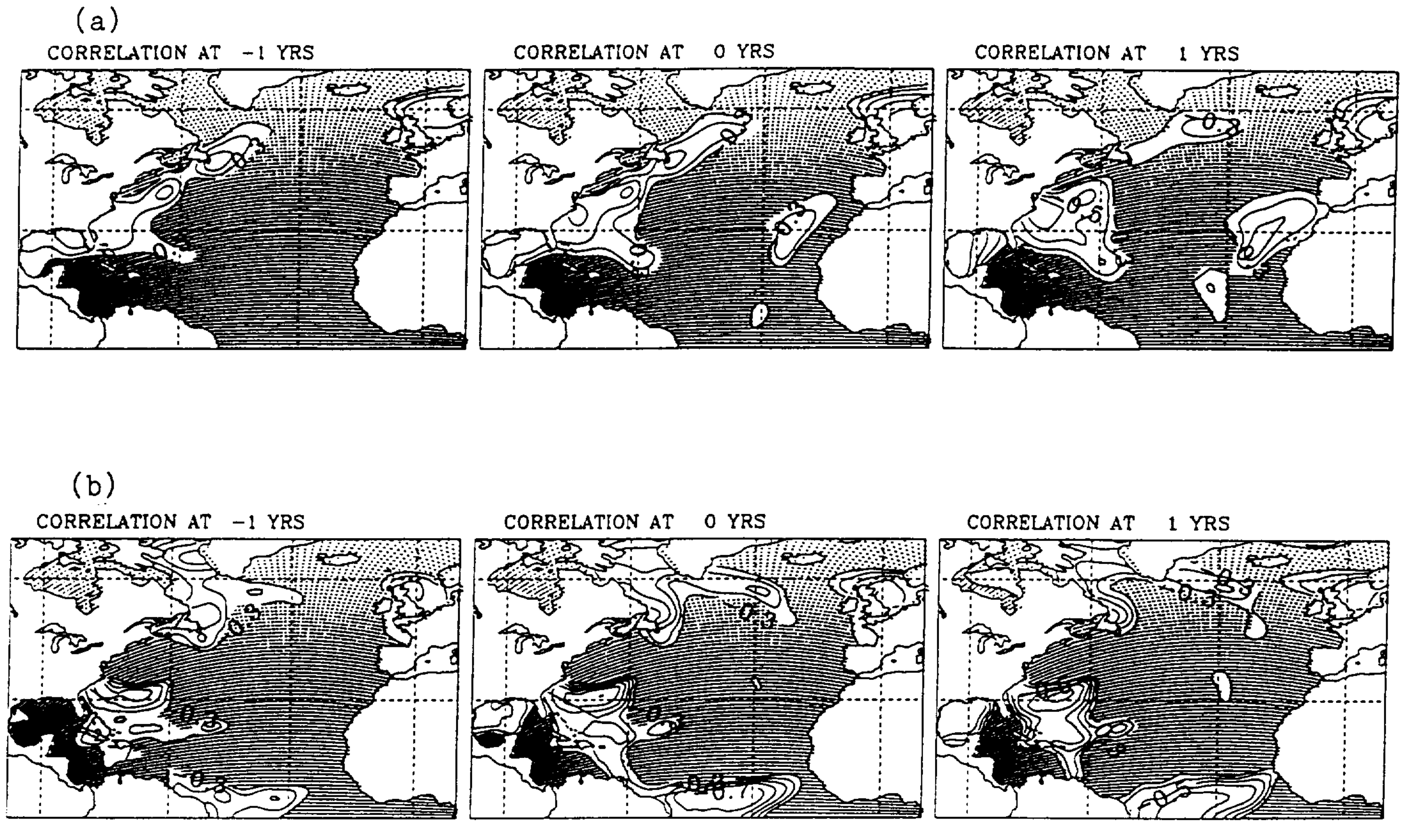

(a)
CORRELATION AT -1 YRS
CORRELATION AT 0 YRS
CORRELATION AT 1 YRS
(b)
CORRELATION AT -1 YRS
CORRELATION AT 0 YRS
CORRELATION AT 1 YRS

FIGURE 4