Seasonal Heat Budget in the Equatorial Atlantic Ocean

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ABSTRACT

The local seasonal variations of heat content in the equatorial Atlantic Ocean are found to be about ten times larger than the seasonal variations of the heat gain from the atmosphere through the surface, and are not confined to the upper mixed layer. This annual cycle of heat content appears to be mainly due to vertical movements of the thermocline associated with the dynamical response of the ocean to the seasonally varying winds. The heat storage variance is large in the western equatorial Atlantic where the sea surface temperature variance is small because the thermocline is deep. In the eastern equatorial Atlantic, where the thermocline is shallow, the sea surface temperature has a large variance and the heat storage a small variance.

1. Introduction

Heat balance studies appear as one of the most promising ways for looking at the influence of the ocean on climate. Recent investigations have drawn attention to the importance of the meridional oceanic heat transport occurring at low latitudes and its influences on the global heat balance (Oort and Vonder Haar, 1976). These investigators pointed out the large seasonal variations of the rate of heat storage by the oceans in the tropics. Phase differences between different parts of the tropical oceans suggest a redistribution of heat by seasonal changes of the equatorial current system. Direct estimates of the various components of the heat fluxes through the air-water interface permit computation of the net heat gain by the oceans in the Atlantic (Hastenrath, 1977; Hastenrath and Lamb 1977, 1978; Bunker and Worthington, 1976). Large seasonal variations in net heat flux have also been observed in the tropics but an almost permanent area of maximum heat gain is observed in the equatorial strip (Fig. 1).

The equatorial Atlantic is one of the best documented regions as far as hydrographic observations are concerned so that we can obtain a reasonable estimate of the seasonal variability of its heat content. The basic conservation law of heat for a water column is

$$F_{AO} = \mathrm{DIV}(\mathbf{T}_H) + \Delta\mathrm{HS}$$

where F_{AO} is the net heat flux through the air-ocean surface, $\mathbf{T}_H$ the oceanic heat transport and ΔHS the time rate of change of heat content. We can compute $\mathrm{DIV}(\mathbf{T}_H)$ as a residual term knowing F_{AO} and ΔHS.

The purpose of this preliminary study is to investigate the seasonal variations of heat content in the equatorial Atlantic Ocean, and by using the results of Hastenrath and Lamb (1978) for F_{AO}, to estimate some aspects of the divergence of the heat transport at the low latitudes in the Atlantic Ocean.

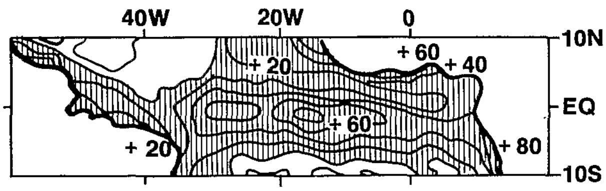

FIG. 1. Mean annual net oceanic heat gain (W m^{-2}). After Hastenrath and Lamb (1978, chart 83).

2. Data

We use the Nansen data file archived by the U.S. *NODC*. The space and time distribution of the data can be found in Merle (1978). Monthly mean temperatures in boxes of 4° of longitude and 2° latitude are considered. Heat content is computed with reference to standard levels. For missing data in some boxes, linear interpolation from month to month and from adjacent boxes is applied.

As shown in Fig. 2 the 6°N–6°S equatorial area is divided into a western region (from the Brazilian coast to 32°W) and an eastern region (from the African coast to 20°W). In addition, we consider the entire zonal region from Brazil to Africa, divided into the bands 0–6°N, 0–6°S and 6°N–6°S. In each of the 2° latitude strips (defined in Fig. 2) and for each month about ten to several hundred data are available. Data-sparse are found in the southwest

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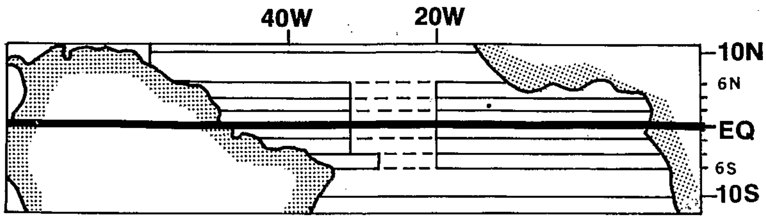

FIG. 2. Location of the areas considered in the study.

regions. The monthly mean of heat content is centered at the beginning of the month (mean from the 15th of the preceding month to the 15th of the considered month) in order to obtain a monthly mean of time rate of change of heat content centered at the middle of the month.

3. Results

Seasonal variations of heat content appear in layers deeper than the mixed layer. Fig. 3 shows annual variations of heat content by layers from 0 to 300 m for the latitude band 0–2°N. From 100 to 200 m an important seasonal variation is observed; also phase differences appear, especially between the upper layer (0–50 m) and the deeper layers. Thus, in order to take into account the major part of the seasonal variations, computation of the heat content has been performed to 300 m depth.

Seasonal variations of heat content from 0 to 300 m

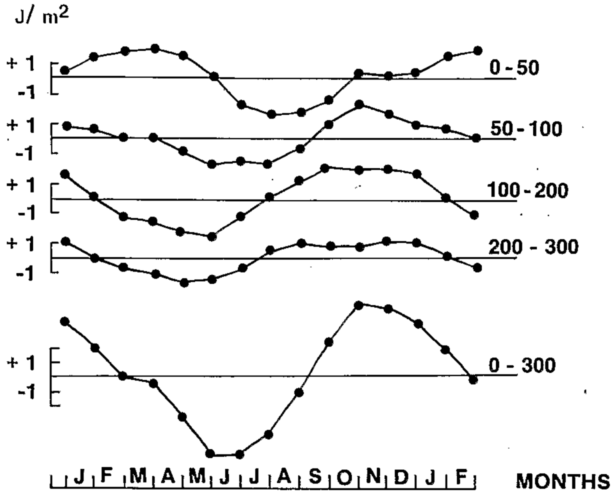

FIG. 3. Seasonal variation of heat content in different layers (0–50; 50–100; 100–200; 200–300; 0–300 m) of the 0–2°N zonal equatorial band. Each curve is related to its annual mean.

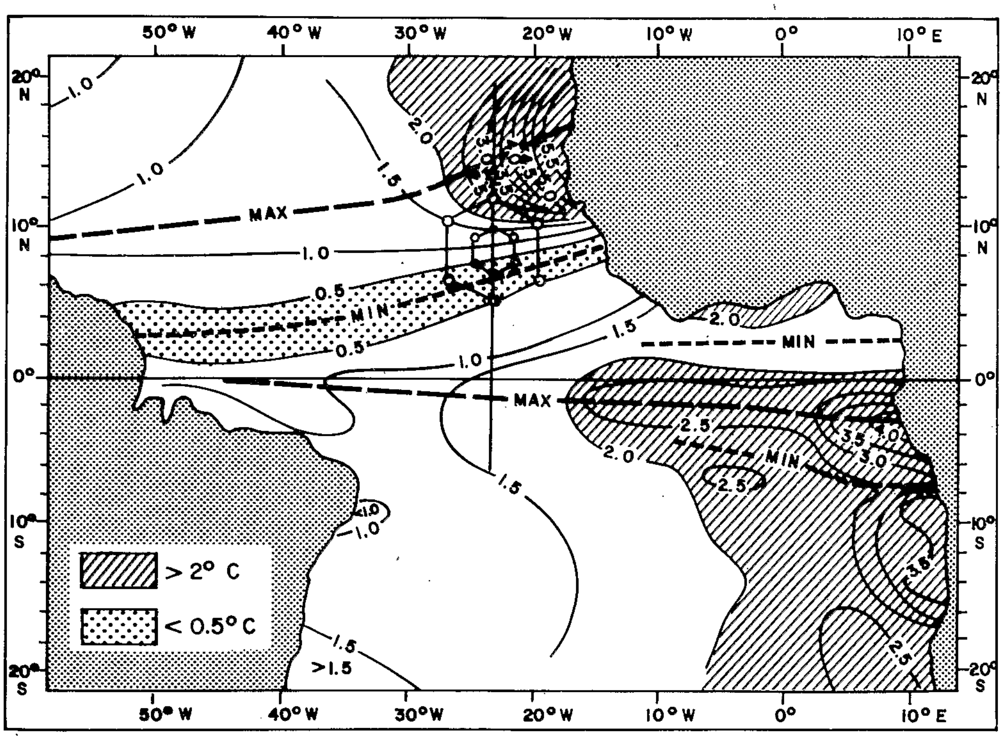

FIG. 4. Amplitude (°C) of the first harmonic of the annual signal of SST in the intertropical Atlantic Ocean (from Merle *et al.*, 1979).

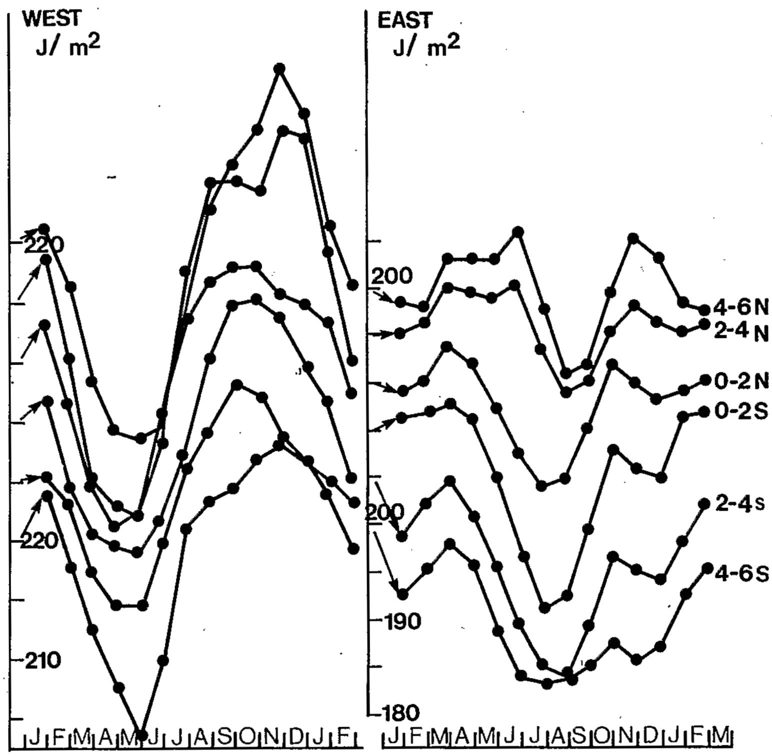

FIG. 5a. Seasonal variation of heat content (J m^{-2}) from 0 to 300 m in boxes of 2° latitude from 6°N to 6°S and in the western region of the equatorial Atlantic (see Fig. 2). Curves are shifted equal distances. FIG. 5b. As in Fig. 5a except for the eastern region (Gulf of Guinea).

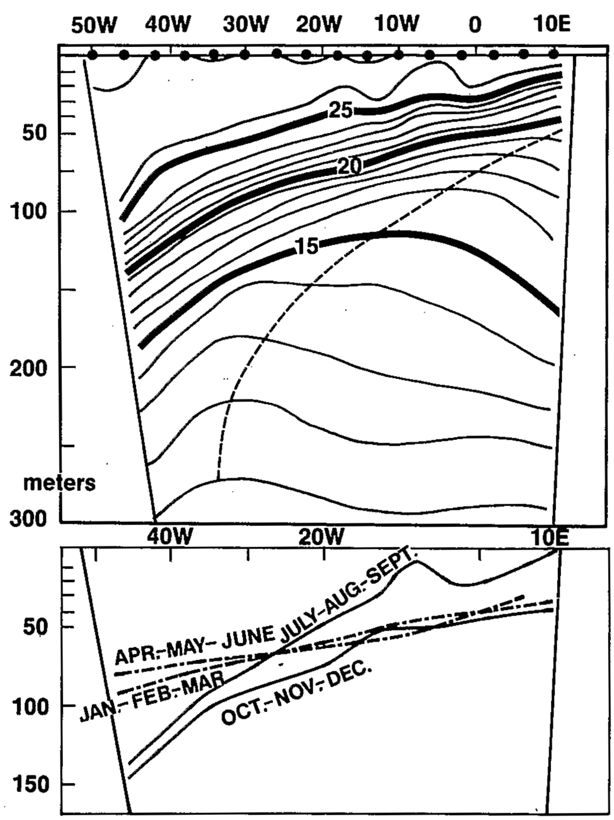

FIG. 6a. Mean annual temperature in the 0–2°S band from the Brazilian coast (50°W) to African coast (12°E). Nansen data averaged by 4° longitude. A dashed line indicates the minimum depth of isotherms FIG. 6b. Depth variation of the 23°C isotherm for the four seasons of the year along the section shown in Fig. 6a.

depth are not similar to seasonal variations of sea surface temperature (SST); previous analysis of SST variability (Merle *et al.*, 1979) in the intertropical Atlantic showed that the annual signal of SST has a large amplitude (3–4°C) in the eastern equatorial Atlantic and a smaller amplitude (<1°C) in its western part (Fig. 4). In contrast, the amplitude of the seasonal variations of the heat content in the west is about twice as much as the one in the east (Figs. 5a and 5b). The high variability of SST in the eastern equatorial Atlantic is related to the shallowness of the thermocline; it is clear from Figs. 6a and 6b that the large amplitude of the seasonal variability of heat content in the western Atlantic is due to the seasonal uplifting of the thermocline with a range of ~75 to 150 m. Phase differences in the annual cycle of heat content of about 3–4 months from the eastern to the western equatorial Atlantic are observed; the minimum of heat content is found in May in the west and in August–September further east (0–10°W). Continuous and progressive

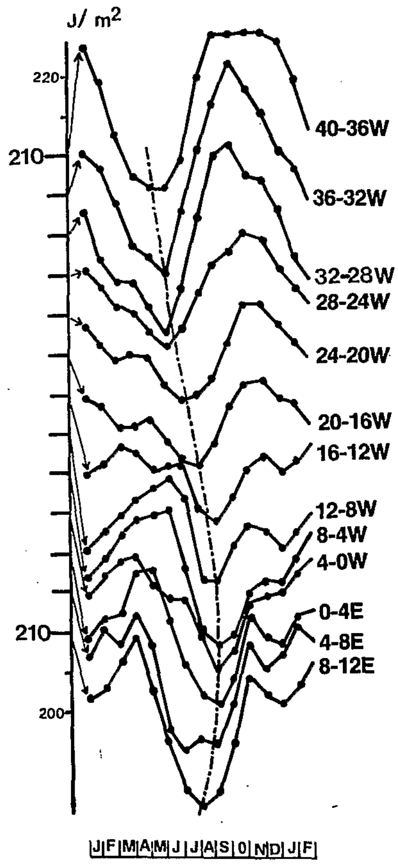

FIG. 7. Annual variation of the heat content from 0 to 30 m along the equatorial region (from 4°N to 4°S) averaged by 4° longitude. Minimum is indicated by an interrupted line. Note the continuous eastward phase displacement from the western region to the 0–8°W region.

displacement in the period of this minimum along the equator suggests an eastward propagation (Fig. 7). The phase speed is of the order of 30 cm s^{-1}, nearly an order of magnitude less than first baroclinic mode Kelvin wave speed. Considering the 0–6°N, 0–6°S and 6°N–6°S total zonal bands, it appears that the heat content in the equatorial area as a whole is minimum in May–July and maximum in October–December (Fig. 8). In February–April a secondary maximum appears in the southern region (0–6°S).

The seasonal variation of the time rate of heat content is about 10 times larger than the seasonal variation of the net heat flux through the surface given by Hastenrath and Lamb (1978) (Figs. 9a–9c). In the western region a divergence (or export) of heat is observed from October to May with a maximum in March; a heat convergence (or import) occurs during the summer from June to September in the 6°N–6°S region as a whole and from June to November in its northern part (0–6°N). In the eastern region (Gulf of Guinea) heat divergence occurs in two periods: the main period is April–August and the secondary period is November–December; slight differences are observed between the northern (0–6°N) and the southern (0–6°S) regions. Considering the 6°N–6°S strip as a whole for the entire equatorial Atlantic, divergence of heat is observed from November to June (Fig. 9c); convergence is observed in summer (from July to November). Thus in an annual mean the equatorial Atlantic region is exporting heat but not throughout the year.

4. Conclusions

To summarize, the observations show that substantial redistribution of heat occurs on a seasonal time scale in the equatorial Atlantic Ocean. The seasonal variation of the local rate of heat storage in the ocean is about 10 times larger than the seasonal variation of the net input of heat through the air-sea surface and is not confined in the first hundred upper meters of the ocean. Hence, the thermocline layer has to be taken into account for the seasonal budget of heat. The global equatorial region (6°N–6°S) as a whole is exporting heat during the major part of the year, except during the summer from July to October. Important differences appear between the eastern and western regions. In the west, divergence of heat is observed in a single period of the year (October–May) with a maximum in late winter (February–March). In the east, divergence of heat is observed in two periods: the main period is spring–summer with a maximum in June–July; a secondary period of divergence appears in November–December. In addition the amplitudes are smaller in the east than they are in the west. The phase difference of the period of maximum divergence of heat is re-

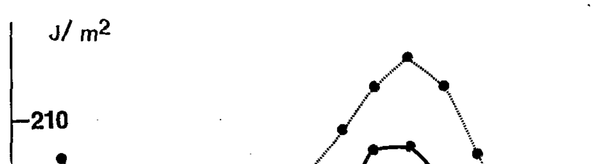

FIG. 8. Annual variation of heat content from 0 to 300 m for the entire zonal Atlantic bands: 0–6°N, 0–6°S and 6°N–6°S.

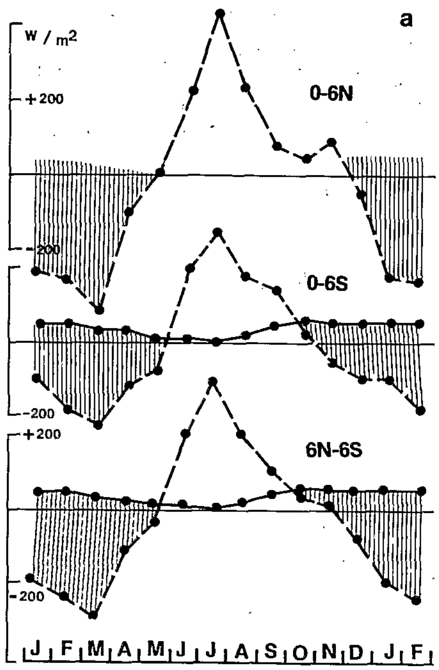

FIG. 9a. Comparison of annual variation of time rate of change of heat content (interrupted line) and annual variation of net heat oceanic gain (full line) in the western equatorial Atlantic region. 0–6°N, 0–6°S and 6°N–6°S regions are considered. Units are W m^{-2}. Dashed areas represent divergence of heat. The values of net heat gain are provided by Hastenrath and Lamb (1978) for the region of 0–5°S only. We assume that these values are representative of the 0–6°S and 0–6°N regions considered here.

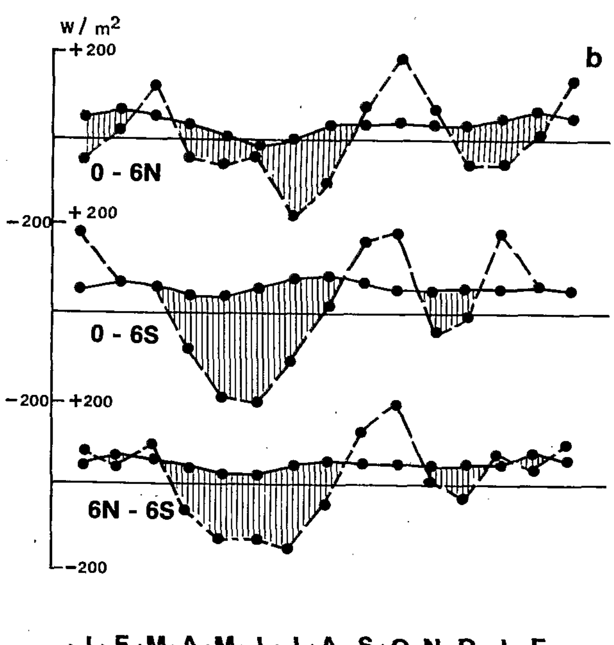

FIG. 9b. As in Fig. 9a except for the eastern region. Hastenrath and Lamb (1978) provide values of the net oceanic heat gain for the 0–5°N and 0–5°S region.

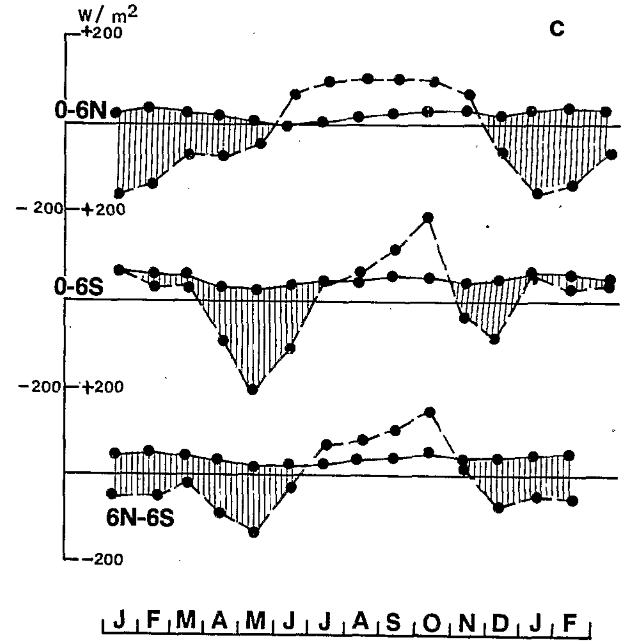

FIG. 9c. As in Fig. 9a except for the entire zonal Atlantic bands. The value of net heat gain are those provided by Hastenrath and Lamb (1978) for the 0–5°N, 0–5°S and 5°N–5°S bands.

lated to an uplifting of the thermocline and is found to be moving progressively from the west (40°W) in February–March to the east (5°W) in July–August. (The phase speed is ~30 cm s^{-1}.) Further east this zonal displacement of the maximum heat divergence moves westward. (The annual signal of sea surface temperature also has westward phase propagation in this region).

The results of Katz *et al.* (1977) indicate that the redistribution of heat described here is associated with the dynamical response of the ocean to the seasonal changes in surface winds: the thermocline in the western equatorial Atlantic is deepest when the westward winds are most intense in the autumn, and is shallow when the winds are weak in the spring. This dynamical response is in marked contrast to the regions poleward of ~15° latitude where changes in local heat storage are principally due to fluxes across the air-sea interface. The heat budget for the entire tropical Atlantic will be described in a future paper.

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