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# Seasonal variation of heat-storage in the tropical Atlantic Ocean

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## ABSTRACT

The monthly mean heat-content in the superficial (0-300 m) layers of the tropical Atlantic Ocean (20°N-20°S) is obtained through the processing of all available Nansen historical data.

Large, non-symmetrical in relation to the equator, spatial variations are observed. It is the depths' repartition of the thermocline which fits in best with the spatial repartition of heat-content. Seasonal variations of heat-content are large, especially in the equatorial band. These variations are due to a seasonal uplifting of the thermocline. An Eastward movement of the annual heat-content signal's phase, along the equator, suggests a baroclinic event affecting the whole thermocline on a seasonal time-scale.

The local seasonal variations of heat-content in the equatorial region are found to be about 10 times larger than the seasonal variations of the oceanic heat-gain from the atmosphere through the surface. Thus, the ocean dynamics, more than the local thermal forcing by the atmosphere, is responsible for the seasonal variations of heat-content in the upper layers (0-300 m) of the tropical Atlantic Ocean. This huge redistribution of heat by the ocean circulation on a seasonal time-scale, could explain the singularities noticed by Oort and Vonder Haar (1976) in the low latitudes concerning the out of phase of the heat-storage seasonal variation and the large cross-equatorial meridional heat-fluxes found for the whole North hemisphere.

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## RÉSUMÉ

### Variation saisonnière du contenu thermique dans l'océan Atlantique tropical

Le contenu thermique des couches superficielles (0-300 m) de l'océan Atlantique intertropical (20°N-20°S) est calculé par moyenne mensuelle en utilisant l'ensemble des données historiques disponibles de type Nansen.

Des variations spatiales importantes, non symétriques par rapport à l'équateur, sont observées. Il apparaît que c'est la profondeur de la thermocline qui caractérise le mieux les variations spatiales du contenu thermique. Les variations saisonnières du contenu thermique sont très importantes, particulièrement dans la bande équatoriale. Ces variations sont dues à des mouvements verticaux de la thermocline, et un déplacement progressif d'Ouest en Est de la phase du signal annuel du contenu thermique au voisinage de l'équateur suggère qu'un mouvement baroclinique affecte cette thermocline à une échelle saisonnière.

La comparaison du taux de variation mensuelle du contenu thermique avec les valeurs mensuelles du gain thermique océanique à travers sa surface, montre que les variations saisonnières du contenu thermique sont d'un ordre de grandeur 10 fois supérieur au gain net de chaleur par l'océan. C'est donc la dynamique océanique, plus que l'action

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thermodynamique locale de l'atmosphère, qui conditionne les variations saisonnières du contenu thermique des couches superficielles (0-300 m) de l'océan Atlantique tropical. Ce sont ces redistributions thermiques considérables opérées par la circulation océanique qui peuvent expliquer les singularités observées pour l'ensemble de l'hémisphère Nord par Oort et Vonder Haar (1976) concernant le déphasage de la variation saisonnière du taux de stockage thermique aux basses latitudes et les flux méridiens transéquatoriaux.

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## INTRODUCTION

Heat-storage and heat-transport are the most important functions of the ocean in the climate. Recent investigations have focused attention on the large meridional oceanic heat-transport occurring at low latitudes in the entire North hemisphere (Oort, Vonder Haar, 1976). Strong seasonal variations and out of phase

## DATA AND PROCESSING

The data used in this study belong to the Nansen data file archived by the NODC. About 18 000 hydrographic casts are considered in the 30°N-30°S band. Most of them (10 000) are concentrated in the 10°N-10°S band. Due to this unequal spatial partition of data, we consider two scales of processing: a global scale zonally integrating

study  $Z_N = 300$  m. The rate of heat-storage  $\Delta HS$  for a given month, is obtained through the difference of heat-content between two adjacent months. For example,  $\Delta HS_{July} = (HS_{August} - HS_{June})/2$ ;  $\Delta HS$  is converted to watt per square meter.

Standard deviations of heat-content from the surface down to 300 m, are generally large, of the order of  $2 J/m^2$ , and in some areas the small number of data gives a relatively low significance in terms of the confidence interval. But the consistency of the results presented in the following sections, represents a good test of the global significance of these results.

## RESULTS

### Mean annual heat-storage pattern

Large spatial variations of the mean annual heat-content from the surface down to 300 m, are observed in the tropical Atlantic Ocean; the range of values appears from  $160 J/m^2$  off the African coast at  $20^\circ S$ , to  $270 J/m^2$  at  $20^\circ N$  and  $60^\circ W$  (Fig. 3). Lower values are found in the Eastern regions ( $< 200 J/m^2$ ). Strong zonal gradients appear in the vicinity of  $20^\circ N$  and  $20^\circ S$ . Near equatorial areas on the contrary, are affected by a weaker zonal gradient. North of the equator ( $3-5^\circ N$ ), a ridge of relative maximum values appears at the Southern border of the

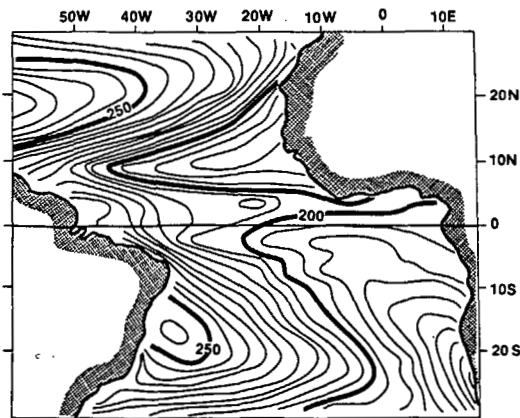


Figure 3  
Distribution of heat-content from 0 to 300 m-depth in the tropical Atlantic Ocean. Units are Joules per square meter.  
Moyenne annuelle du contenu thermique entre 0 et 300 m dans l'Océan tropical Atlantique. L'unité est le Joule par mètre carré.

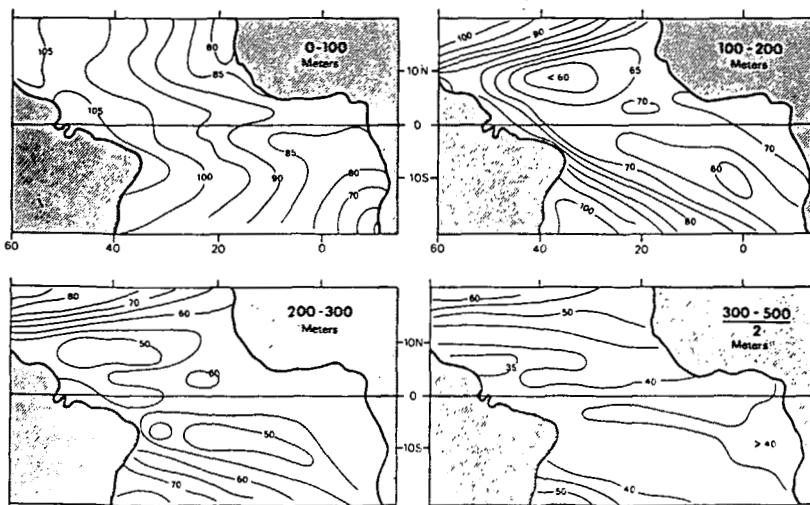


Figure 4  
Repartition of heat content ( $J/m^2$ ) from 0 to 500 m-depth by layers of 100 m. Note that from 100 to 300 m-depth (thermocline), the largest spatial variations are observed.

Moyenne annuelle du contenu thermique entre 0 et 500 m par tranches de 100 m. Remarquez que c'est entre 100 et 300 m (profondeur de la thermocline) que les variations spatiales du contenu thermique sont les plus importantes.

North Equatorial Counter-Current. The subsurface layers, from 100 to 300 m, which roughly belong to the main thermocline, appear to be responsible for this global pattern of the mean annual heat-content (Fig. 4); the largest spatial variations are observed in the 100 to 200 m layer. Hence, the spatial variation of the 0 to 300 m heat-content layer, is mainly related to the spatial variation of the depth of the thermocline, and appears to be very different from the mean sea-surface temperature-pattern. Thus, the zonal gradient of heat-content appears to be mainly due to the zonal slope of the thermocline (Merle, 1980).

### Seasonal variations of heat-storage

Seasonal variations of heat-content are not confined to the mixed layer; the thermocline-layer has to be accounted for. As an example, Merle (1980) showed that in the equatorial band, subsurface layers down to 300 m are affected by seasonal variations. This fact justifies the integration of heat-content down to 300 m, in order to fully describe its seasonal variations. Phase-differences between the surface layer (0-50 m) and subsurface layers, are also observed. These phase-differences seem to affect only the Western regions (from the Brazilian coast to  $32^\circ W$ ), where the mixed layer is very thick (Fig. 5 a and 5 b). This phase-change in the near equatorial band ( $2^\circ N-2^\circ S$ ), will be discussed in detail. Unfortunately, on the outside of the equatorial band, data are so scarce that it is not possible to investigate any zonal change in the annual signal of heat-storage. We will consider only these regions zonally in averaging heat-content in large zonal bands of several degrees of latitude, corresponding approximately to the major components of the equatorial current system.

If we consider the  $20^\circ N-20^\circ S$  intertropical region as a whole, the annual signal of heat-storage from 0 to 300 m appears to be minimal during the Southern Summer (June to August), and maximal during the Southern Spring (November-December): Figure 6 a. The amplitude of the annual variation is about  $3 J/m^2$ . Separating each hemispheric part of this region, it appears that the Southern tropical region ( $0-20^\circ S$ ) is also characterised by a minimum of the heat-storage annual signal in the Winter season (June to September). The maximum appears in Summer (December to March). The amplitude

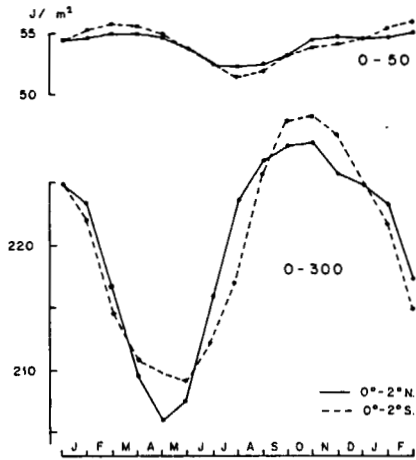


Figure 5a  
Seasonal variation of heat-content in the 0-50 and 0-300 m layers, and for the 0-2°N and 0-2°S Western equatorial bands. See Figure 2.

Variation saisonnière du contenu thermique entre 0 et 50 m et entre 0 et 300 m pour les bandes 0-2°N et 0-2°S de la région Ouest (voir fig. 2).

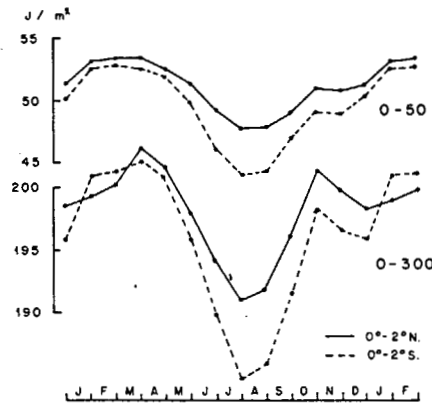


Figure 5b  
Same as 5a, for the Eastern (0-2°N and 0-2°S) equatorial bands (Gulf of Guinea). See Figure 2.

Semblable à 5a, mais pour la région Est (voir fig. 2).

is about  $5 \text{ J/m}^2$ . The Northern tropical region ( $0-20^\circ\text{N}$ ) does not show any typical Northern aspect. If a marked minimum is observed in the Northern Winter (January to April), a Summer maximum does not clearly appear; it seems that the two periods of maxima, in Spring (June-July) and fall (October-December), can be distinguished; a secondary minimum in August could be due to the influence of the Southern minimum in this season. Thus the annual signal of the global region ( $20^\circ\text{N}-20^\circ\text{S}$ ) seems almost in phase with its Southern component, suggesting a predominant influence of the Southern hemisphere.

Considering the  $10^\circ\text{N}-10^\circ\text{S}$  region as a whole (Fig. 6b), its annual cycle of 0-300m heat-content shows also a minimum from June to September and a maximum in November-January, similar to that observed in the  $20^\circ\text{N}-20^\circ\text{S}$  region. Nevertheless, the  $10^\circ\text{N}-10^\circ\text{S}$  region shows a

larger amplitude ( $5 \text{ J/m}^2$ ), suggesting an amplification of the annual signal in the near equatorial regions. This point will be discussed further on. Considering each hemisphere, the Northern region ( $0-10^\circ\text{N}$ ) has a pattern similar to that of the  $0-20^\circ\text{S}$  region with a maximum in the fall and early Winter (October-December) and a minimum in the late Winter (February-April). The Southern region ( $0-10^\circ\text{S}$ ) is also similar to the  $0-20^\circ\text{S}$  region with a marked minimum in the Northern Summer (July-September), and a maximum extending during all the Winter, from November to April. It is clear that the annual cycle of heat-content of the  $10^\circ\text{N}-10^\circ\text{S}$  region is mainly in phase with its Southern region ( $0-10^\circ\text{S}$ ), and therefore that the equatorial Atlantic area is essentially thermally governed by the Southern hemisphere. Figure 3 suggests that from  $20^\circ\text{N}$  to  $20^\circ\text{S}$ , we can distinguish different zonal bands in relation with the main major currents of the equatorial system. Outside of the equatorial band ( $6^\circ\text{N}-6^\circ\text{S}$ ), investigated in the next paragraph, we will consider a  $6^\circ\text{N}-10^\circ\text{N}$  region, or North Equatorial Counter-Current (NECC) region; a  $10^\circ\text{N}-20^\circ\text{N}$  region, or North Equatorial Current (NEC) region; a  $6^\circ\text{S}-10^\circ\text{S}$  region (Fig. 7).

Figure 7  
Seasonal variation of heat-content for various zonally averaged bands from  $20^\circ\text{N}$  to  $10^\circ\text{S}$ .  
Variation saisonnière du contenu thermique pour différentes bandes zonales entre  $20^\circ\text{N}$  et  $10^\circ\text{S}$ .

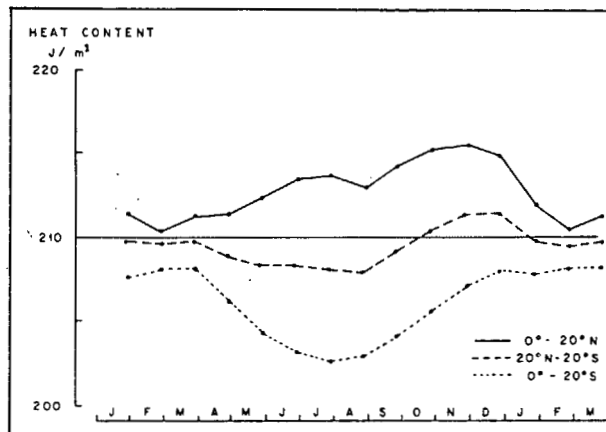
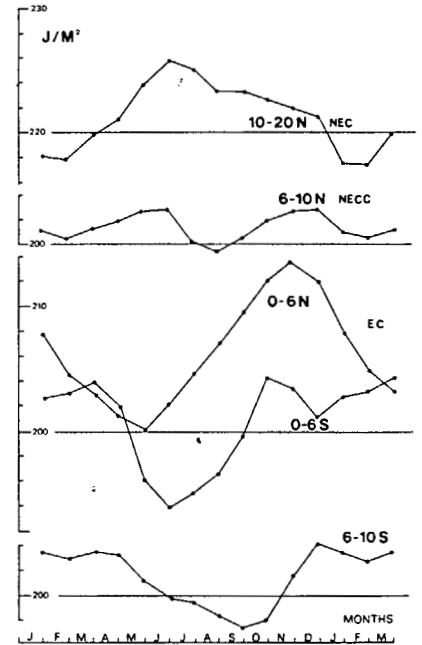


Figure 6a  
Seasonal variation of heat-content from  $20^\circ\text{N}$  to  $20^\circ\text{S}$ .  
Variation saisonnière du contenu thermique entre  $20^\circ\text{N}$  et  $20^\circ\text{S}$ .

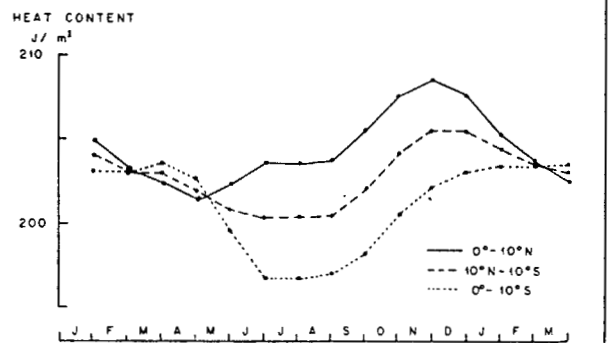


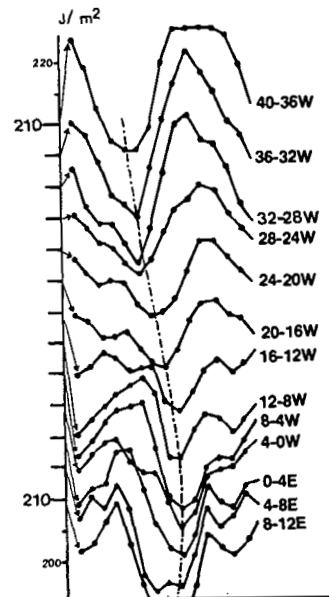
Figure 6b  
Same as 6a, for  $10^\circ\text{N}-10^\circ\text{S}$ .  
Semblable à 6a, mais entre  $10^\circ\text{N}$  et  $10^\circ\text{S}$ .

The NEC region (10°N-20°N) shows a typical North tropical pattern with a marked maximum in Summer (June-September) and a minimum in Winter (December-March), but few data are available in this region, and standard deviation for each monthly mean is about  $2 \text{ J/m}^2$ ; therefore, a weak confidence can be given to the details of this annual variation. The 6°N-10°N region (NECC) is characterized by a bimodal annual cycle with two marked maxima in Northern Spring (May-June) and fall (November-December), suggesting an alternative influence of the Northern and Southern hemisphere. A similar annual cycle of the Sea Surface Temperature (SST) has been observed in this region (Merle, Fieux, Hisard, 1979). Compared to this large semi-annual component of the signal, the annual amplitude appears minimal. The symmetrical Southern region (6°S-10°S) shows a larger amplitude than the Northern region, with a marked minimum in the Northern Summer (July-September), and a long period of maxima with possibly,

Figure 9

Annual variation of the heat-content (0-300 m) ( $\text{J/m}^2$ ) along the equatorial region (from 4°N to 4°S) averaged by 4° longitude. The minimum is indicated by a dotted line. Note the continuous Eastward phase displacement from the Western region to the 0-8°W region. From Merle (1980).

Variation saisonnière du contenu thermique entre 0 et 300 m le long de l'équateur (de 4°N à 4°S) et par 4° de longitude. Le minimum est marqué par un trait pointillé. Remarquer le changement de phase continu depuis l'Ouest jusqu'à environ 8°W. D'après Merle (1980).



equatorial Atlantic (Gulf of Guinea), is also due to this near surfacing of the thermocline, whose depth variation affects both heat-content and SST. In the Western and Central region, the Westward propagation of the annual signal of heat-content cannot be related to a propagation of the annual signal of SST, because this signal becomes very small and no clear propagation can be depicted.

Seasonal variations of rates of heat storage and heat

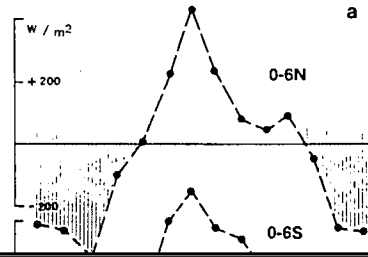


Figure 11 a  
Seasonal variation of rate of heat storage (dotted line) and net heat oceanic gain (full line) in the Western equatorial Atlantic region: 0-6°N, 0-6°S and 6°N-6°S regions are considered. The values of net heat gain are provided by

exporting heat during the major part of the year, except in the fall from September to December. Distinguishing each hemisphere, the Southern region (0-10°S) is exporting heat with a maximum in Spring (from April to June), and importing heat in the fall (from September to November). The Northern region (0-10°N) is exporting heat mainly in Winter (from December to April), but it seems that there are two periods of import of heat: a fall main period (September to November), and a secondary period in Spring (April to June).

In the near equatorial band (6°N-6°S), the seasonal variation of the rate of heat-storage appears even larger; its amplitude is found some eight times larger than the amplitude of seasonal variations of the net heat flux through the surface (Fig. 11 a, b, c). Heat-export is observed year round, but from July to October. Northern (0-6°N) and Southern (0-6°S) regions are slightly different in phase, showing a maximum of heat-export in January in the Northern region, and in May in the Southern region. We can also note in the Southern region a secondary maximum of heat-export in December. In this 6°N-6°S band, changes in amplitude and in phase by 2° latitude from 6°N to 6°S, appear to be continuous and consistent (Fig. 12). Nevertheless, important differences

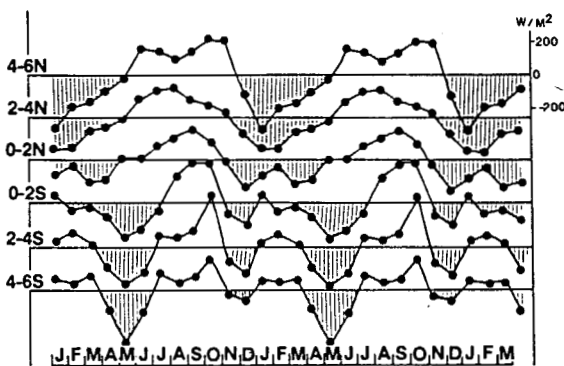


Figure 12  
Seasonal variation of rate of heat storage by 2° latitude band from 6°N to 6°S. Units are watts per square meter. Note the continuous evolution of curves from North to South.

Variation saisonnière du taux de stockage thermique par 2° de latitude de 6°N à 6°S. L'unité est le watt par mètre carré. Remarquez l'évolution continue des courbes du Nord au Sud.

between Eastern and Western regions can be noted. In the Western region (from the Brazilian coast to 32°W, Fig. 11 a), the annual cycle of the rate of heat-storage is unimodal with a marked maximum in July and a minimum in March. No significant difference could be noted between the North (0-6°N) and the South (0-6°S). In the Eastern region (Gulf of Guinea, Fig. 11 b), the annual cycle of the rate of heat-storage appears bimodal, giving two periods of heat-export. The main period takes place from April to August. The secondary period appears in November-December. Differences between the North (0-6°N) and the South (0-6°S) are noticeable. It seems that the heat-export of the total region (6°N-6°S) is mainly due to its Southern part (0-6°S), and the secondary period of heat-export is more marked and appears earlier in the Northern region (0-6°N).

## DISCUSSION AND CONCLUSIONS

The intertropical oceanic regions are providing the heat necessary to equilibrate the heat-losses of the middle and high latitudes. On a long-term mean (annual), we can assume that the oceanic heat-content does not vary, and equation (1) becomes:

$$F_H = \text{DIV}(\vec{T}_H)$$

The divergence of the oceanic heat-transport is equal to the net heat-gain by the ocean. Several papers in the past gave an estimate of this divergence of the mean oceanic heat-transport zonally integrated by latitude for the World Ocean (Sverdrup, 1957; Budyko, 1956; Bryan, 1962; Vonder Haar, Oort, 1973). All these authors found a large maximum near the equator and positive values covering the intertropical regions. In the Atlantic Ocean, Emig (1967), using the Budyko data, and Hastenrath (1977), using a different and more complete data set, found a similar result (Fig. 13).

But this region of the maximum mean heat-divergence is affected by seasonal variations. Oort and Vonder Haar (1976) found that these are very large and even maximal in the tropics. Negative values of heat-divergence can even be observed in some seasons near the equator.

The seasonal variation of heat-divergence is caused by two factors:

1° seasonal variation of heat-storage (HS); 2° seasonal variations of net heat-gain ( $F_H$ ). The main result of our study is that the seasonal variation of heat-storage ( $\Delta HS$ : rate of heat-storage) is the most important factor affecting the seasonal variation of heat-divergence in the intertropical Atlantic Ocean. In the whole intertropical region (20°N-20°S), the amplitude of the seasonal variation of  $\Delta HS$  is about twice the amplitude of the seasonal variation of  $F_H$  (Fig. 10 a). But if we consider smaller regions, this ratio is increasing, due to the fact that the larger the area, the most effective the compensation between the different values (negative or

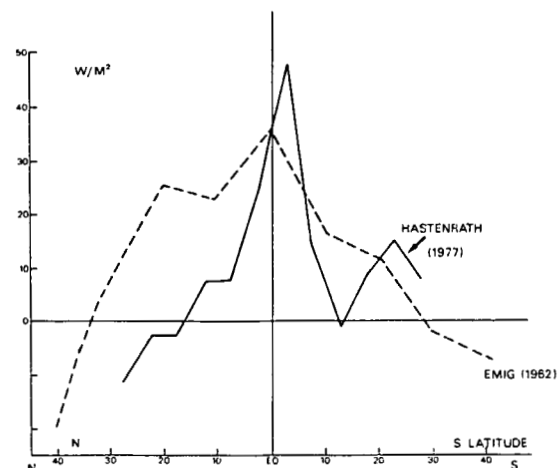


Figure 13  
Latitudinal variation of mean annual oceanic heat divergence ( $\text{DIV}(\vec{T}_H)$ ) in the tropical Atlantic Ocean. From Hastenrath (1977) and Emig (1962). Variation en fonction de la latitude de la moyenne annuelle de la divergence océanique ( $\text{DIV}(\vec{T}_H)$ ) dans l'Océan Atlantique tropical, d'après Hastenrath (1977) et Emig (1962).

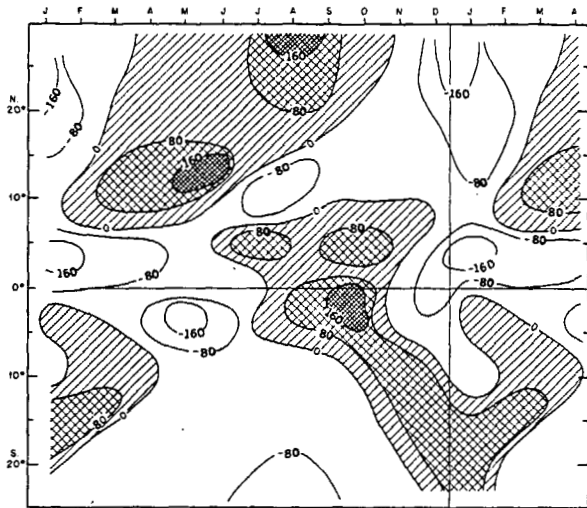


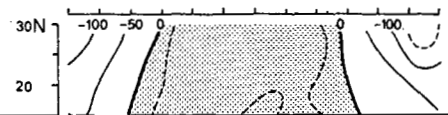
Figure 14  
 Seasonal and latitudinal variation of rate of heat storage ( $\Delta HS$ ) in the tropical Atlantic Ocean. Units are watts per square meter. Dashed areas represent positive values or increasing values of the heat-content. Note the similarities with the Oort-Vonder Haar diagram (Fig. 1), particularly the phase-difference of the period of heat-storage's positive rate around  $10^\circ N$  (in Spring).

Diagramme temps-latitude des variations du taux de stockage thermique ( $\Delta HS$ ) dans l'Océan Atlantique tropical. L'unité est le watt par mètre carré. Les zones hachurées représentent un accroissement du stockage thermique. Remarquez la similitude avec la figure 1 de Oort et Vonder Haar, particulièrement en ce qui concerne le déphasage de la période d'accroissement maximal du stockage thermique autour de  $10^\circ N$  (printemps).

positive) of smaller included areas. Thus, in the  $10^\circ N$ - $10^\circ S$  region, the amplitude of the seasonal variation of  $\Delta HS$  is about three to four times higher than the amplitude of the seasonal variation of  $F_H$  (Fig. 10 b). The monthly variation of the zonal integration by  $5^\circ$  latitude-

year when the  $20^\circ N$ - $20^\circ S$  region is exporting heat (positive divergence), mainly in Winter and Spring (December to July-August); and consequently, that during the period of heat-import, the heat-flow is Southward, and coming from the North.

This Northward mean heat-flow is certainly related to the thermal intertropical mean structure observed (Fig. 3). We already noticed that the  $0$ - $10^\circ N$  and even the  $0$ - $20^\circ N$  regions as a whole, are influenced by the Southern hemisphere, as appears in the curves of the seasonal variations of heat-content (Fig. 6 a and 6 b). We should also remark that the equator is not an axis of symmetry: a maximum of heat-content appears at about  $3^\circ N$  and a minimum at about  $10^\circ N$  and  $3^\circ S$ , suggesting that the entire equatorial system is shifted of about  $3^\circ$  toward the North, with a real thermal equator at about  $3^\circ N$ . This thermal equator is lying under the mean position of the atmospheric Inter-Tropical Convergence Zone (ITCZ), and is characterized by a maximum of the sea-surface temperature (Hastenrath, Lamb, 1978; Lamb, 1978), and a minimum of the amplitude of the SST seasonal variations (Merle, Le Floch', 1978). This region is also the Southern boundary of the NECC, which is probably, as in the Pacific Ocean, advecting a large quantity of heat toward the East. The rôle of this warm advection has been invoked to explain a "El Niño"-like phenomenon in the Eastern equatorial Atlantic (Merle, Fieux, Hisard, 1979; Hisard, Merle, 1979). Zonal advection certainly plays a very important rôle in the near equatorial regions.





Adamec and O'Brien (1978) offered a Kelvin-wave model out of phase in the annual signal of heat-storage (Fig. 1).