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OCEANOGRAPHIC EFFECTS OF THE BERMUDA-AZORES ANTICYCLONE

WILLIAM STEVENS

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OCEANOGRAPHIC EFFECTS OF THE BERMUDA-AZORES ANTICYCLONE

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William Stevens

OCEANOGRAPHIC EFFECTS OF

THE BERMUDA-AZORES ANTICYCLONE

by

William Stevens

Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
METEOROLOGY

United States Naval Postgraduate School
Monterey, California

1961

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This work is accepted as fulfilling

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IN

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from the

United States Naval Postgraduate School

ABSTRACT

The monthly values of a function which measures the Ekman drift across a portion of the Gulf Stream near the Florida-South Carolina coast are computed. The function depends upon geostrophic winds which are obtained from monthly mean surface weather maps.

The values are compared with the secular variation of the areal ice extent in the Barents Sea, the annual variation of sea level along the Florida-South Carolina coast, and the annual variation of Gulf-Stream surface velocity in the same area.

Results indicate that the variation of these winds off the south-east coast of the United States is an important factor in the determination of ice extent in the Barents Sea, that these winds have a minor influence on the annual variation of local sea level, and that they are highly correlated with the annual variation of local Gulf-Stream velocities.

The investigation was carried out at the U. S. Naval Postgraduate School, Monterey, California, during the period March 1961 to May 1961 in partial fulfillment of the requirements for the degree of Master of Science in Meteorology.

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TABLE OF CONTENTS

Section	Title	Page
1.	Introduction	1
2.	Theory	2
3.	Method	4
4.	Results, Conclusions, and Illustrations	8
5.	Bibliography	17
6.	Appendix I, Data	18

LIST OF ILLUSTRATIONS

Plate		Page
1.	Curve of integration	10
2.	Vector wind diagram	11
3.	Secular variation of F compared with the secular variation of the areal extent of ice in the Barents Sea	12
4.	Annual variation of sea-level anomalies due to non-advective heat transfer and mean annual variation of sea level (1945-1955). Florida-South Carolina area	13
5.	Mean annual sea level variation corrected for non-advective heat transfer (1945-1955). Florida-South Carolina area	14
6.	Mean annual variation of sea level anomalies due to advection compared with the mean annual variation of F (1945-1955). Florida-South Carolina area	15
7.	Mean annual variation of F (smoothed) compared with the mean annual variation of Gulf-Stream velocities. Florida-South Carolina area	16

TABLE OF SYMBOLS

$\mathbb{M}$ = mass transport

f = coriolis parameter

$\mathbb{n}$ = unit vector normal to curve

$\mathbb{T}$ = vector wind stress

F = integrated Ekman drift

C_d = drag coefficient

ρ_a = air density

U_0 = surface wind speed

$\mathbb{U}_0$ = surface wind velocity

U = surface wind speed uncorrected for friction

U_g = geostrophic wind speed

Θ = angle between surface and geostrophic winds

α = angle between geostrophic wind and curve of integration

n = subscript used to indicate component normal to curve of integration

s = subscript used to indicate component parallel to curve of integration

a = geostrophic wind ratio

1. Introduction.

Iselin [1] has suggested that during periods of increasing Gulf-Stream flow less heat may be available downstream in the Gulf-Stream system. This is based on the hypothesis that increased flow of the Stream occurs simultaneously with a contraction of the warm surface waters into the Sargasso Sea area.

Elliott [2] attempts to relate changes in the areal extent of ice in the Barents Sea to fluctuations in the Florida Current deduced from variations in sea level along the Florida-South Carolina coast. His hypothesis is that low sea level along the coast indicates an increase in the speed of the adjacent current system, which, in turn, is indicative of the decrease in heat flow. Eventually the Barents Sea, downstream in the Gulf-Stream system, is deprived of heat.

This paper originally was planned to investigate a hypothesis similar to Elliott's from a slightly different point of view. A function representing the normal component of Ekman drift currents is computed from the field of atmospheric pressure across a line roughly paralleling the mean Gulf-Stream position from Florida to about 40 N latitude. Data are presented comparing the value of the computed drift function with a measure of the heat budget of the Barents Sea.

During this investigation, results were compared with the annual sea level variation in the area, suggested by Patullo et al [3], and with Fuglister's work [4] on Gulf-Stream velocity variations in the area.

2. Theory.

Stommel [5] has shown that the intensity of the Gulf Stream is related to the curl of the wind integrated over the entire North Atlantic Ocean; this implies that convergence of warm water (Ekman drift) increases into the Bermuda-Azores area as the intensity of the Stream increases. If there is a secular variation in the curl of the wind, then one can expect a comparable secular variation in the heat available to be transported downstream by the Gulf Stream; roughly, the downstream heat transport would be inversely proportional to the Gulf-Stream intensity. To partially test such a model, the secular variation in Ekman drift across a portion of the Gulf Stream is compared with the secular variation in the areal extent of ice in the Barents Sea, which reflects the downstream heat transport of the Gulf Stream with a time lag.

Patullo [3] observes that, in subtropical latitudes, sea level variations are principally steric; the steric departures are mostly thermal, and they usually agree with recorded departures of sea level. Therefore, a curve much like the recorded annual sea-level oscillation should be obtained by calculation of monthly values of the heat budget in a given locality and the corresponding changes in density and sea-level. These thermally induced density changes (and sea-level oscillations) represent the net effect of radiation, evaporation, sensible heat transfer, and advection. If it is assumed that advective changes are primarily caused by the Ekman drift of warm surface waters, then the influence of this drift can be shown by removing the non-advective thermal effects from

actual sea-level oscillation curves.

Since the Ekman transport is a function of surface winds [see equations (1) and (4)], purely local fluctuations of surface velocities of the Stream can be compared with local variations in the Ekman transport across the selected curve of integration to verify the relation of Iselin [1].

The primary tool in the proposed investigations results from Ekman's classic study of wind-drift currents [6]. According to this theory, the net mass transport is given by

$$\mathbb{M} = -\frac{1}{f}\,\mathbb{k} \times \mathbb{T}. \tag{1}$$

Integrating the normal component of this mass transport along a curve yields

$$F = \int_s \mathbb{M} \cdot \mathbb{n}\, ds. \tag{2}$$

Substituting (1) into (2) results in

$$F = -\int_s \frac{1}{f}(\mathbb{k} \times \mathbb{T}) \cdot \mathbb{n}\, ds, \tag{3}$$

which is the rate at which the integrated Ekman flow crosses the curve of integration outward from the Bermuda-Azores gyre ($F > 0$).

3. Method.

In order to evaluate (3) in terms of some measurable quantity for which data exist, i.e., the surface pressure field, certain simplifying assumptions had to be made.

Standard texts define the wind stress by the formula

$$\mathbb{T} = C_d \rho_a \mathbb{U}_o |\mathbb{U}_o| . \tag{4}$$

Changes in C_d and ρ_a in (4) were assumed to have little effect on gross variations of the integrated stress function, and C_d and ρ_a were assigned constant values.

The following identities are illustrated in plate 2:

$$U = U_g ; \tag{5}$$

$$U_o = a U = a U_g ; \tag{6}$$

$$U_{on} = a U_n = a U_g \sin(\theta + \alpha) ; \tag{7}$$

$$U_{os} = a U_s = a U_g \cos(\theta + \alpha) ; \tag{8}$$

$$U_{gs} = U_g \cos\alpha ; \tag{9}$$

$$U_{gn} = U_g \sin\alpha . \tag{10}$$

In (6) through (8), the geostrophic wind ratio, a was taken to be a constant value less than one. The angle between the geostrophic wind and the surface wind, θ, was taken to be a constant, eleven degrees [7]. By expanding (7) and (8) and inserting (9) and (10) into these expansions, it is possible to eliminate α, the widely-varying angle between the isobars and the curve of integration.

Plate 2 shows that

$$U_o = [U_{on}^2 + U_{os}^2]^{1/2} . \tag{11}$$

The finite difference approximations for the normal and parallel components of geostrophic wind, relative to the line of integration,

$$u_{gs} = -\frac{1}{\rho_a f}\frac{\Delta P}{\Delta N} \tag{12}$$

and

$$u_{gn} = \frac{1}{\rho_a f}\frac{\Delta P}{\Delta S} \tag{13}$$

are used, as well as (4) through (10), in the manner described; thus, (3) becomes

$$F = K \int_S \frac{1}{f^3}\left[\left(\frac{\Delta P}{\Delta N}\right)^2 + \left(\frac{\Delta P}{\Delta S}\right)^2\right]^{1/2}\left[\frac{\Delta P}{\Delta N}\cos\theta - \frac{\Delta P}{\Delta S}\sin\theta\right]\Delta S, \tag{14}$$

where $K = \frac{C_d a^2}{\rho_a}$.

Originally, it was planned to determine the Ekman drift across a line paralleling the mean Gulf-Stream position around the west and north sides of the Bermuda-Azores anticyclonic area. Preliminary computations of the drift across the line proposed above indicated that the most significant fluctuation took place in the western segment of the Gulf Stream from Florida to about 40 N latitude; as a result, the determination of Ekman drift was restricted to this segment (plate 1). A grid was constructed along the line of integration (plate 1). Only the terms inside the integral sign of (14) were computed. Hence the F values, to which later reference is made, are in reality the evaluation of a function $\frac{F}{K}$, which is proportional to Ekman drift. The computed values of F for each month

were recorded, deduced from monthly-mean surface weather maps of 1945 through September 1955. The net F across that part of the grid labeled S2 (plate 1) was almost always smaller than that across the part S1 by at least two orders of magnitude. As a result, only the values of F across S1 were graphed in arbitrary units.

Data are not available to determine the variation in ice coverage in precise quantitative terms. However, a subjective description of this variation is possible, based on information in [8]. A heavy ice year may be defined as one where the limit of the ice exceeds the limits of the average of years 1919-1943, and a light ice year where the ice lies within these limits; then certain gross comparisons to the secular variation in F can be made (plate 3).

The average heat transfer due to evaporation, radiation, and sensible heat exchange in the area west of S1 was computed for each month (see Appendix I). These values were used to estimate local density and resulting sea-level changes (plate 4). To estimate advective thermal effects on sea level the values estimated above were subtracted from the observed annual sea-level variation (plates 4 and 5). Since the annual variation of sea level remaining after the removal of these changes (see Theory) represents the cumulative effect of heat advection in the area, the first derivative of this cumulative curve was obtained to determine the monthly advective anomalies. This curve was compared to the mean annual fluctuation of F (plate 6).

The mean annual variation of F determined in this paper represents a

small sample (1945-1955). In order to compare this variation to local velocity oscillations computed on the basis of observations taken over many years [4], it was necessary to minimize effects of random variation in the shorter record. This was done by smoothing the annual variation of F in the manner

$$\overline{F}_1 = \frac{1}{4} F_0 + \frac{1}{2} F_1 + \frac{1}{4} F_2 .$$

These smoothed monthly values were then compared with the local velocity oscillations of the Gulf Stream (plate 7).

4. Results, Conclusions, and Illustrations.

Plate 3 shows that 1949 through 1952 were "heavy" ice years, while 1953 through 1956 were "light", as defined earlier. There is large negative correlation between the net annual values of the function F and the ice year intensity, with a four-year lag. Going further, it would be concluded that 1957 was a "heavy" year and 1958 a "light" year. Unfortunately, information was not available to determine if, in fact, this were so. The results do suggest a significant influence of the wind field off the south-east coast of the United States on the Barents Sea climate. Since the sample is small, a continuation of the study is recommended to further test this indicated relation.

Plate 6 compares the annual variation of sea level anomalies due to advection with the annual variation of F in the investigated area. During the summer and winter stable periods the curves appear to be generally in phase. Near the time of the equinoxes the curves are definitely out of phase. It would appear that during the stable periods Ekman drift is a factor of some importance to sea level oscillation. During the equinox periods, which are times of great change in the sea-air relationships, Ekman drift appears to have little significance. Some other advective factor(s), perhaps due to the Gulf Stream itself, apparently become dominant during these unstable periods.

Finally, plate 7 compares mean annual fluctuations in the velocity of the Gulf Stream with the smoothed variation of F in the same geographical area. The variations are in accordance with Iselin's suggestion [1]

(see Introduction), since negative values of F do indicate movement of warm surface waters into the Sargasso-Sea area with the corresponding increase in Gulf-Stream velocity. Specifically, plate 7 indicates that the annual variation of local winds is a significant factor influencing the annual variation of Gulf-Stream surface velocity in the same area.

Wertheim [9] compared consecutive monthly values of mass transport of the Florida Current with wind curl over the North Atlantic for a period of 16 months with little correlation. It may be that if Wertheim had available longer samples of these quantities, allowing determination of mean annual variations, a significant relationship would be shown as in the present study. There is evidence that <u>short term</u> Florida-Current transport between Key West and Havana is influenced by factors other than wind stress [5, pp. 142-143]. Thus, only for long-term averages does one expect to find the close correspondence shown in plate 7.

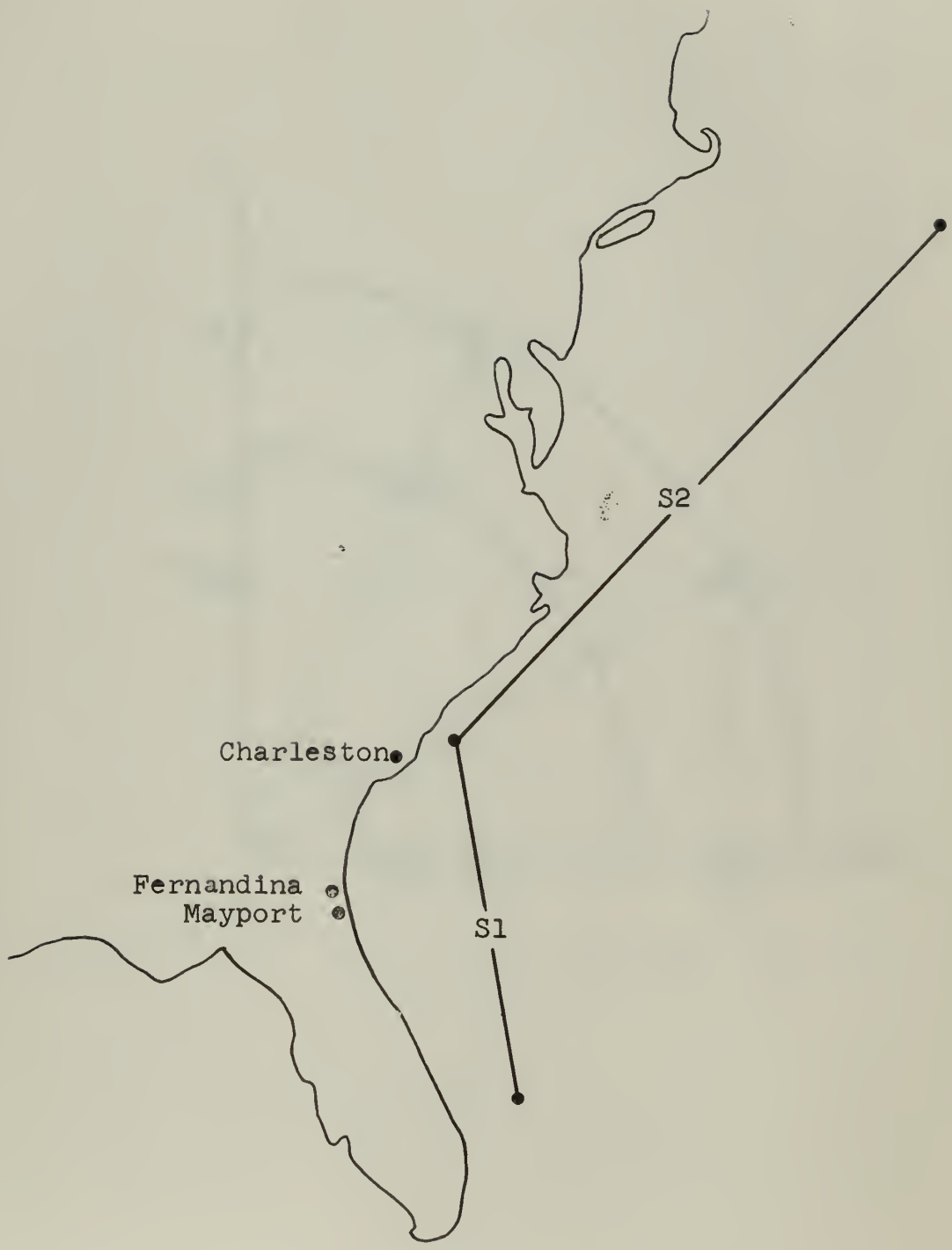


PLATE 1. Curve of integration

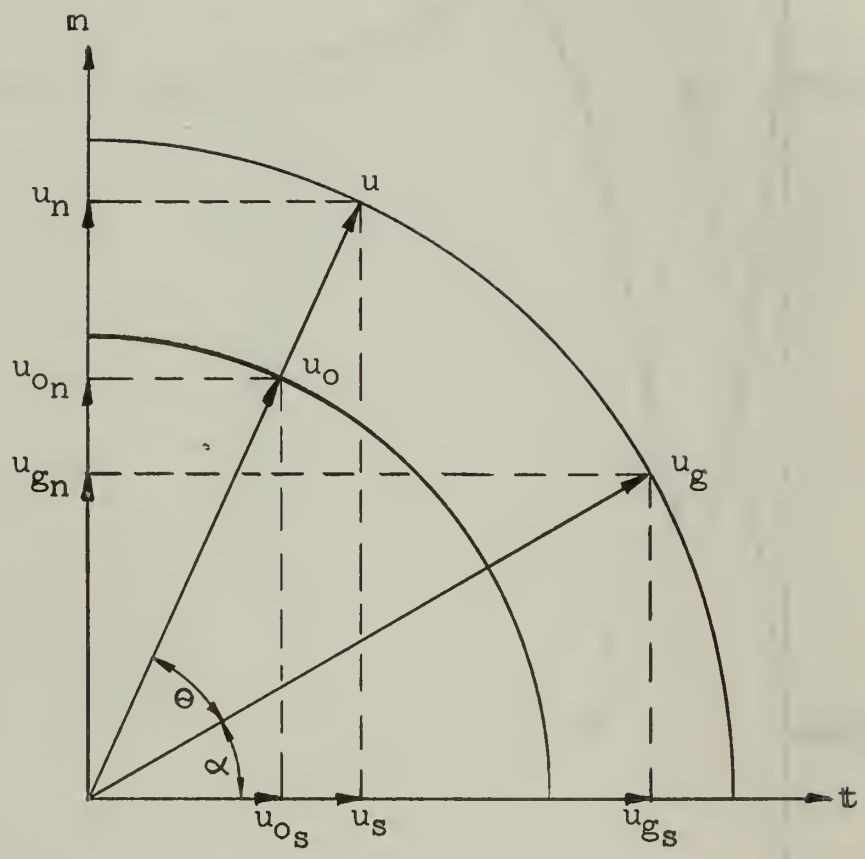


PLATE 2. Vector wind diagram

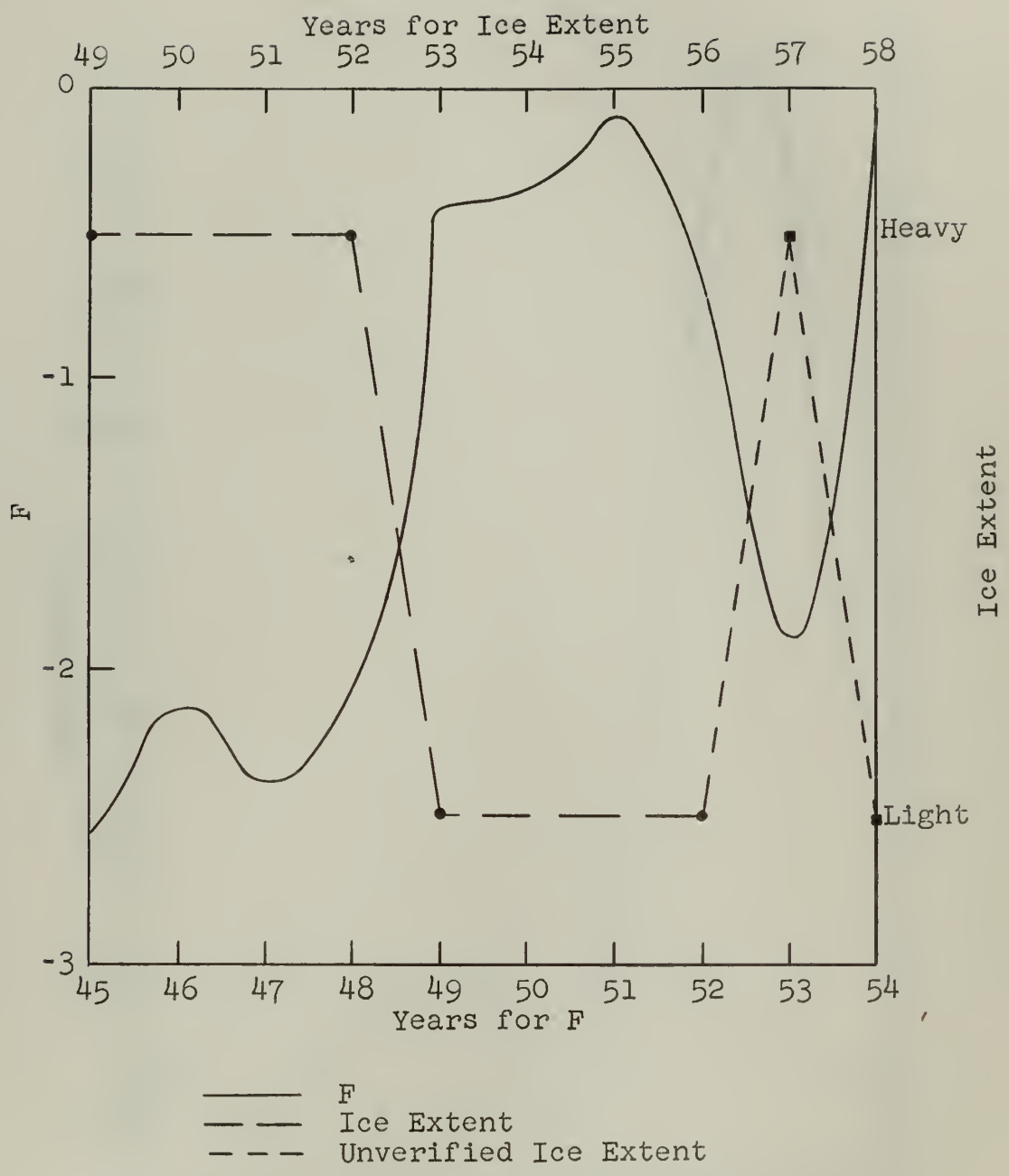
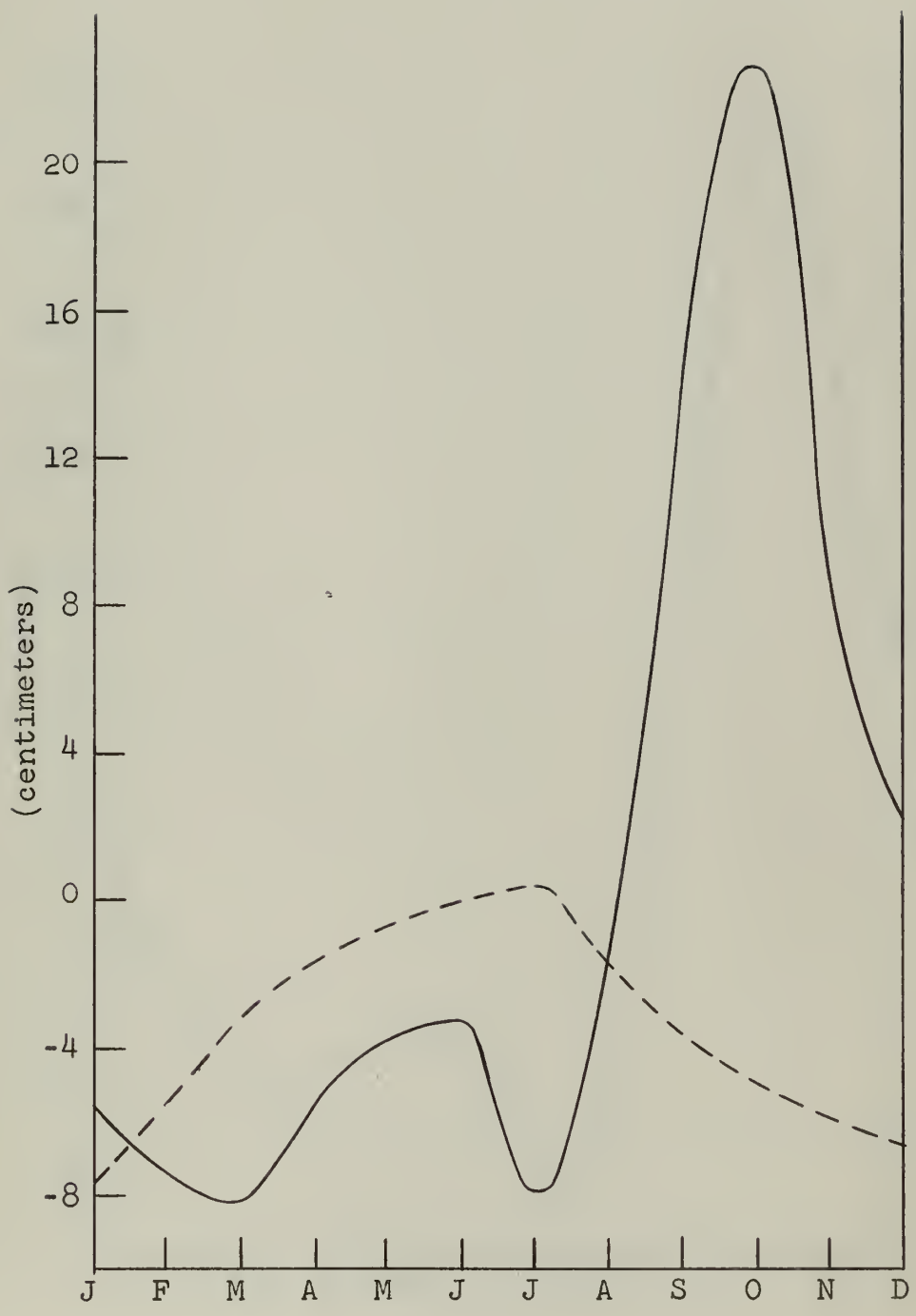


PLATE 3. Secular variation of F compared with the secular variation of the areal extent of ice in the Barents Sea



——— Sea Level
– – – Density Changes

PLATE 4. Annual variation of sea-level anomalies due to non-advective heat transfer and mean annual variation of sea level (1945-1955). Florida-South Carolina area

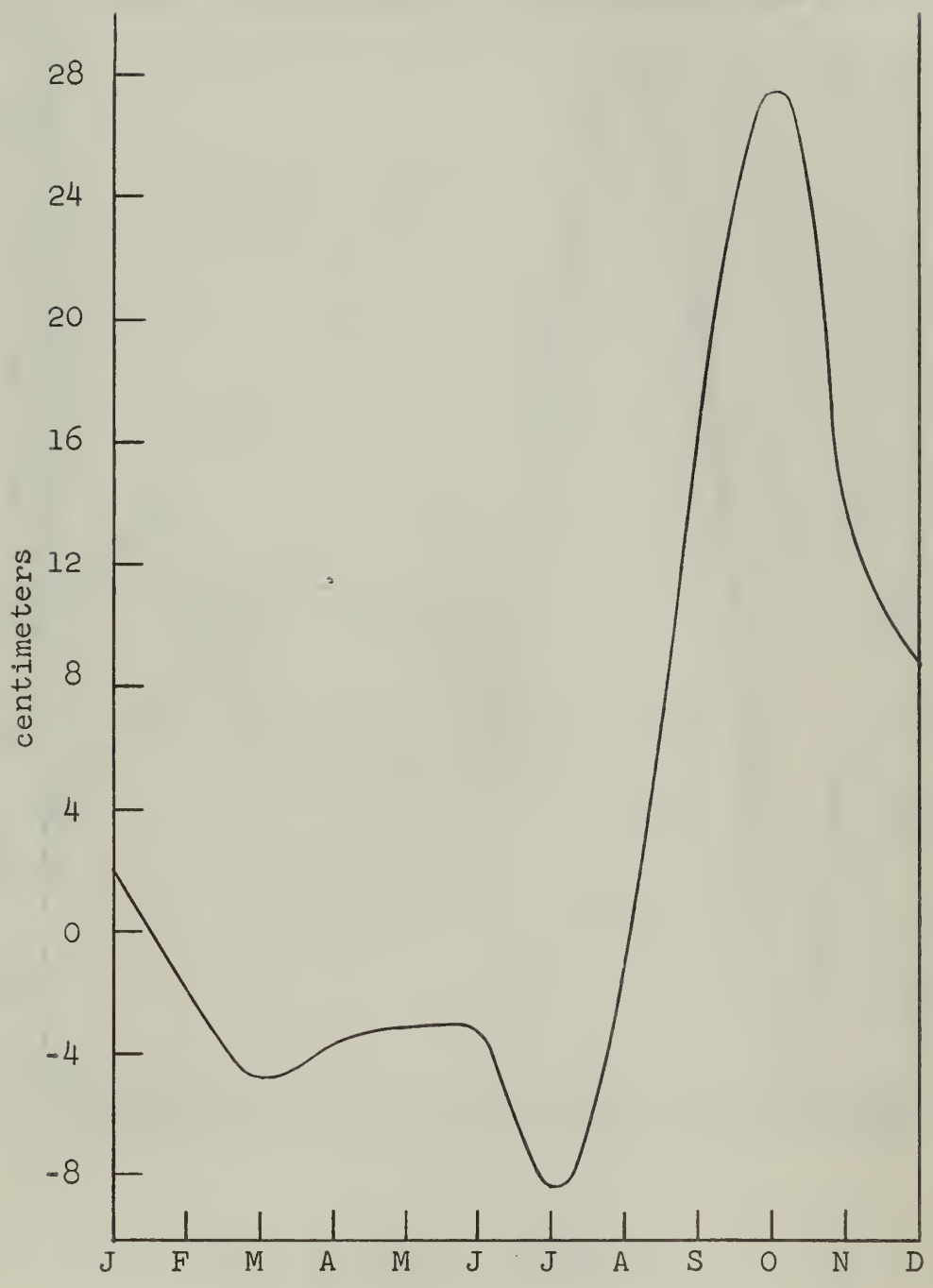


PLATE 5. Mean annual sea level variation corrected for non-advective heat transfer (1945-1955) Florida-South Carolina area.

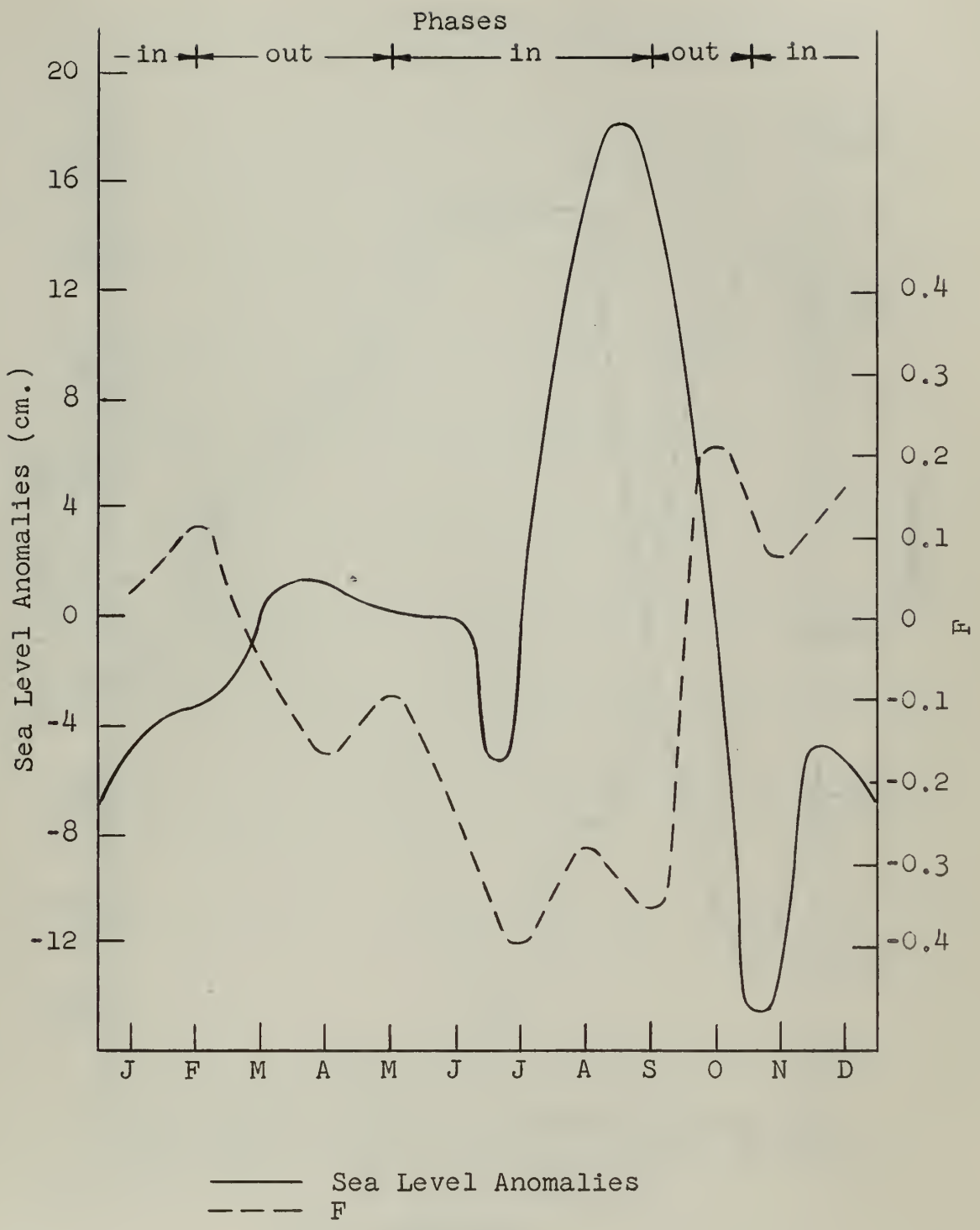


PLATE 6. Mean annual variation of sea level anomalies due to advection compared with the mean annual variation of F (1945-1955) Florida-South Carolina area

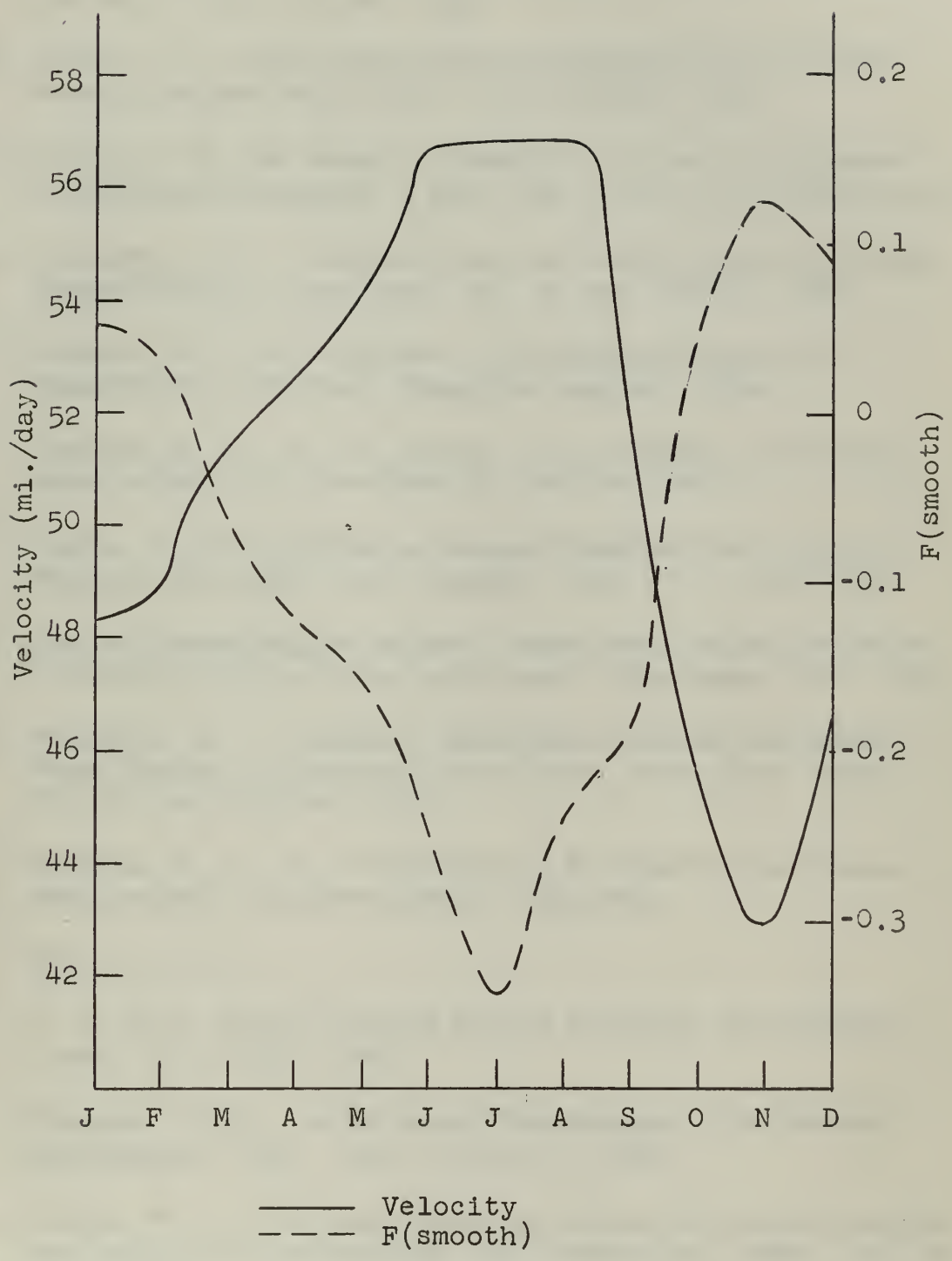


PLATE 7. Mean annual variation of F(smooth) compared with the mean annual variation of Gulf-Stream velocities Florida-South Carolina area

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APPENDIX I

DATA

Sea-level records for the period 1945 through September 1955 were obtained from United States Commerce Department data, consisting of mean monthly sea level records for: Charleston, South Caroline; Mayport, Florida; and Fernandina, Florida. These records were corrected for atmospheric pressure, after Patullo [3] ; i.e., one centimeter was added to the recorded sea level for each millibar of pressure by which the local pressure exceeded the average over all the oceans.

Mean monthly surface pressure maps for the period 1945 through September 1955 were obtained from the United States Weather Bureau. Since these charts were analyzed in five millibar increments, which gave too gross an indication of the wind flow, the author interpolated the pressure field in one millibar increments, for the investigated area.

The values for the annual surface velocity fluctuations of the Gulf Stream used in this paper were those computed by Fuglister [4] . They represent the annual mean variation of surface velocities in the area.

The annual variation of non-advective heat transfer for the area, in terms of sea level changes shown in plate 4, was determined by the following procedure. The monthly values of incoming sun and sky radiation received at the surface in the area [10] were computed. From these were subtracted the monthly values of back radiation assuming a relative humidity of 85 per cent [11] , the local mean sky-cover conditions, and

local sea surface temperature [12] . Also subtracted was the reflected radiation assumed constant at 7 per cent of the incoming radiation [13] . To these monthly radiation values were added the mean monthly latent and sensible heat losses [14] . These totals were then converted to sea level changes by assuming that the effects of heating were manifested uniformly throughout the upper 100 meters of the ocean. Average values for the coefficient of thermal expansion and the specific heat at constant pressure of sea water were used.

The values for the annual variation of advective anomalies shown in plate 6 were derived simply by computing the differences between the monthly values of sea level due to advection shown in plate 5. These differences are proportional to the slope of the curve shown in plate 5.

The ice information was derived from the 1949 through 1956 editions of [8] . The 1956 edition was the latest giving summarized data available from the Danish Meteorology Institute.

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