FISHERIES RESEARCH BOARD
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MANUSCRIPT REPORT SERIES
(OCEANOGRAPHIC and LIMNOLOGICAL)
No. 156

Transport Computations for the North Atlantic Ocean

Annual Means and Standard Deviations 1950-1961

by
N. P. Fofonoff and F. W. Dobson

Pacific Oceanographic Group
Nanaimo, B.C.

April 11, 1963

Programmed
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Introduction

Sverdrup (1947), Stommel (1948), and Munk (1950) have shown that the total steady-state transport of the mass in the ocean depends primarily on the curl of the wind stress components acting on the surface of the ocean. The theory has been applied to compute the transports in the North Atlantic Ocean from 1950 to 1961 (Fofonoff and Ross, MSS 1962), and in the North Pacific Ocean from 1950 to 1961 (Fofonoff, MSS 1960, 1961; Fofonoff and Dobson, MSS 1963). The transport components for many years are required to determine the averaging period necessary for steady-state conditions and the variability of transport with time and latitude.

Monthly means (averaging twice daily observations) of sea-level atmospheric pressure at a regular set of grid points are issued by the Extended Forecast Section of the U.S. Weather Bureau. The pressures from the region 15° N to 65° N and 105° W to 10° E were read from the charts and the resulting geostrophic winds computed. The surface stresses were estimated from the geostrophic winds by a method similar to that used by Montgomery (1935).

The computations at a grid point are made in terms of the mean pressure at that point and the six surrounding grid points. The geostrophic velocity vector is computed first. It is rotated 15° to the left of the downwind direction and reduced to 70% of its original magnitude to represent surface wind. The stress vector is assumed to be in the direction of the surface wind and to be proportional to the square of the wind speed. The stress law used is $|\vec{\tau}_s| = \rho_a \gamma^2 v^2$ where ρ_a is the air density taken as 1.22×10^{-3} gm/cm^3, γ^2 is a nondimensional drag coefficient chosen to be 2.6×10^{-3} and v is wind speed in centimetres per second.

From the geostrophic velocity, using the transformation for surface velocity and the stress law, the components of Ekman and total transport are computed. Details of the calculations and a description of the computer program are contained in the program manual M-1 (Fofonoff and Froese, MS, 1960).

Errors in the absolute values of the transports arise due to uncertainty in surface stresses calculated from the geostrophic winds. The surface stress is dependent on variation of wind with altitude as well as velocity. Further error is encountered by using the square of the mean velocity rather than the mean of the velocity squared in the stress law. The error will be proportional to the variance of the atmospheric pressure gradients.

Care must be exercised in interpreting the transport charts. As the calculations for each month are carried out independently of other months, the transports so obtained must refer to the limiting case of the transports resulting from a pressure distribution persisting without change for an

indefinitely long period of time. The computed transports may, therefore, be thought of as indices indicating the relative range and frequency of variations applied to the ocean by the atmosphere. Long-term averages of transport computed from the pressure distribution should converge to the mean transport observed in the ocean within the limits of accuracy of the method. It should be remembered that the transports are very sensitive to the proportionality factors used in relating geostrophic to surface wind and to surface stress. Numerical equivalence of computed and observed transports is not anticipated.

Description of Transport Charts

Section I - Atmospheric pressure

The mean monthly sea-level atmospheric pressure is calculated from twice-daily observations. The charts are obtained from the Extended Forecast Section of the U.S. Weather Bureau. The pressures plotted are the anomalies from 1000 millibars given in units of 1/10 millibar.

Section II - Meridional component of Ekman transport V_E

The Ekman transport is computed directly from the surface stress induced by the geostrophic wind and is directed at right angles to the stress. The meridional component of Ekman transport is given by

$$V_E = -\tau_\lambda / f$$

Where τ_λ is the zonal component of stress in dynes per square centimetre and f is the coriolis parameter in radians per second. The charts show the component in units of 10 metric tons per second per kilometre.

Section III - Zonal component of Ekman transport U_E

The zonal component of Ekman transport is given by

$$U_E = \tau_\phi / f$$

where τ_ϕ is the meridional component of stress. U_E is given in units of 10 metric tons per second per kilometre.

Section IV - Meridional component of total mass transport V

The total meridional component of mass across a unit length of a latitude circle is given by

$$V = (\mathrm{curl}_z \tau_s) / \beta$$

where $\beta = \partial f / R d\phi$. Allowing the total transport to satisfy the continuity equation, it is possible to define a transport function Ψ such that

$$U = \frac{1}{R}\frac{\partial \Psi}{\partial \phi}, \qquad V = -\frac{1}{R\cos\phi}\frac{\partial \Psi}{\partial \lambda} = (\mathrm{curl}_z \tau_s/\beta)$$

$\partial\Psi/R\cos\phi\,\partial\lambda$ or $-V$ is shown on the chart in units of 100 metric tons per second per kilometre.

Section V - Integrated total transport Ψ

The meridional component of total transport along the latitude under consideration is integrated westward from the eastern shoreline. For simplicity in programming the integration is continued across the islands of the Carribean into the Gulf of Mexico and also across Newfoundland into the Gulf of St. Lawrence. It is necessary to subtract the value of Ψ at the islands from the values in the gulfs to obtain the values of the actual transport function. No provision has been made for calculating the western boundary currents. It may be assumed that the net transport across any line of latitude is zero and thus the value at the western shores of the ocean represents the transport of the western boundary currents.

The charts of integrated transport are given in units of 100,000 metric tons per second.

Section VI - Integrated geostrophic transport Ψ_g

The net mass of water Ψ_g transported by the geostrophic current across latitude circles is obtained from the difference between the meridional component of total transport and the meridional component of Ekman transport. The geostrophic mass transport is proportional to the zonal component of the gradient of potential energy according to the equation

$$-\frac{1}{R\cos\phi}\frac{\partial \Psi_g}{\partial \lambda} = V - V_E = \frac{1}{fR\cos\phi}\frac{\partial \chi}{\partial \lambda}; \qquad \Psi_g = \frac{\chi_{\lambda_o} - \chi_\lambda}{f}$$

where λ_o is the longitude of the eastern boundary grid point.

The integration is carried out using zero as the boundary condition for Ψ_g at the grid point nearest the eastern coast. Thus, although the east-west changes of potential energy are given by the geostrophic transport function, the north-south components are not correctly represented. The difference between values of the total transport and the geostrophic transport functions at any grid point represents the contribution of the meridional Ekman transport to the integrated total transport eastward of the point.

The geostrophic transport is given in units of 100,000 metric tons per second.

Annual Means and Standard Deviations

Each section contains twelve charts - one for each of the years 1950 through 1961. The means for a given year are calculated as the arithmetic average of the values for the twelve months of that year. Units are the

same as those on the monthly charts, which are already published as Fisheries Research Board of Canada MS Reports (Fofonoff and Ross, MSS 1962). The standard deviations are computed from:

$$\sigma = \sqrt{\frac{N\Sigma x_i^2 - (\Sigma x_i)^2}{N(N-1)}}$$

where N = number of months of data being averaged = 12
x_i = values of data being averaged.

Acknowledgement

Charts of mean sea-level atmospheric pressure were made available through the courtesy of Mr. Jerome Namais, Chief of the Extended Forecast Section and Mr. Roy Fox, Director of the National Weather Records Centre of the U.S. Weather Bureau. The initial preparation of the data for computation was supervised by Mr. V.K. Jain. The computer program for obtaining transport components was constructed by Dr. Charlotte Froese of the Department of Mathematics, University of British Columbia. The computer tapes were prepared by Miss Mary Cairns. The assistance of these individuals and all others who helped in the preparation of the charts for publication is gratefully acknowledged.

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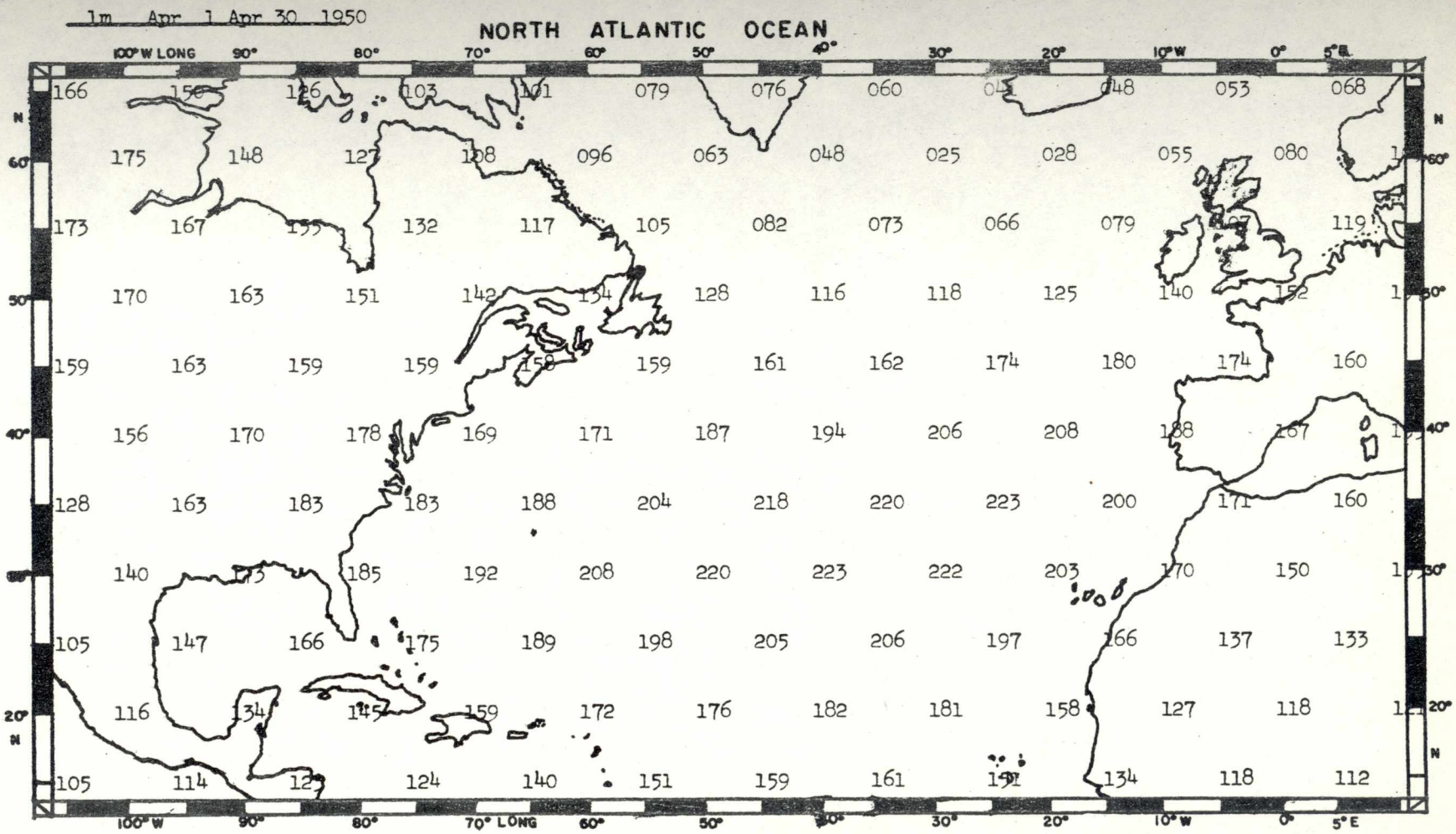
Section I

Atmospheric Pressure



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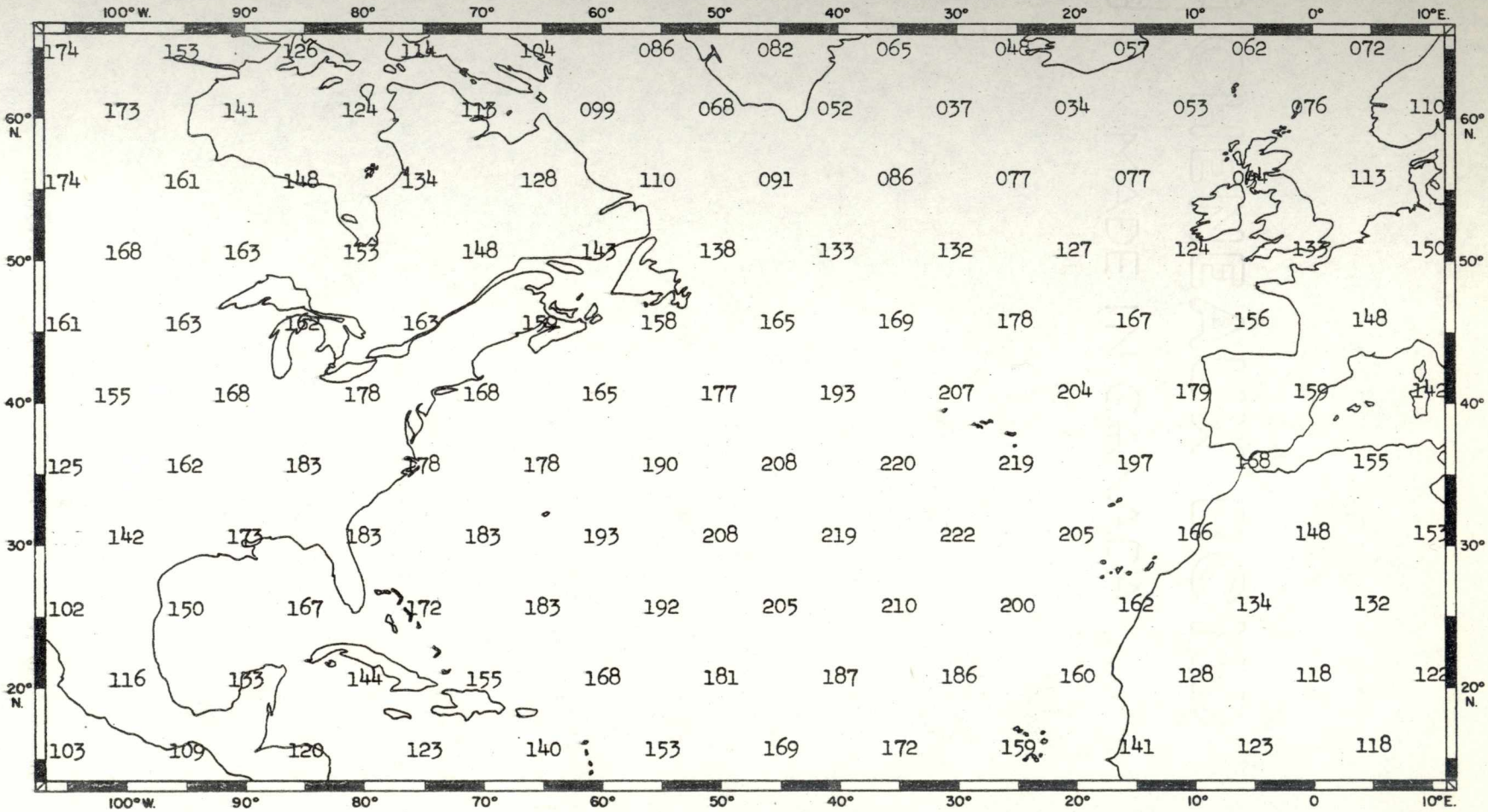

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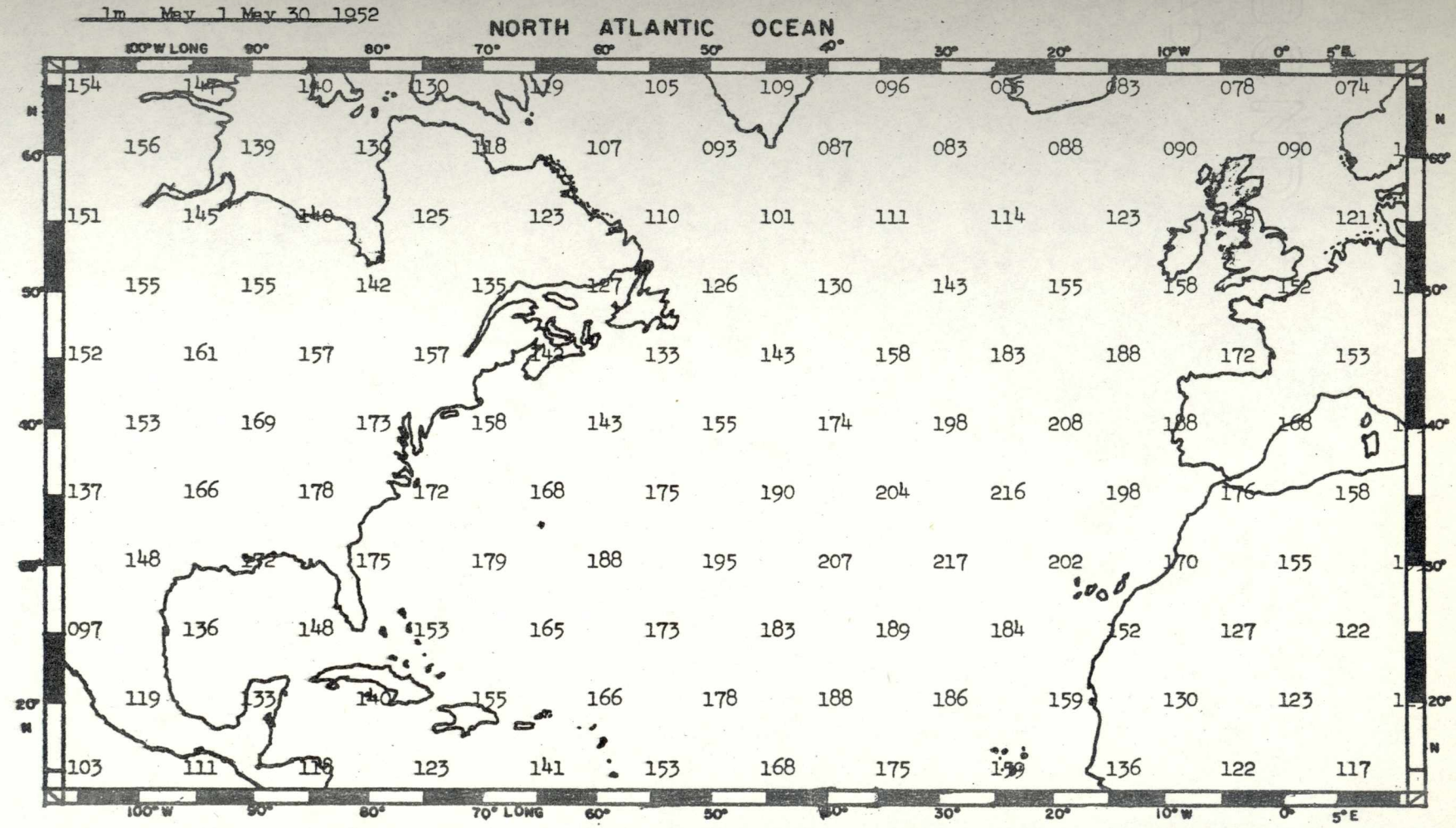

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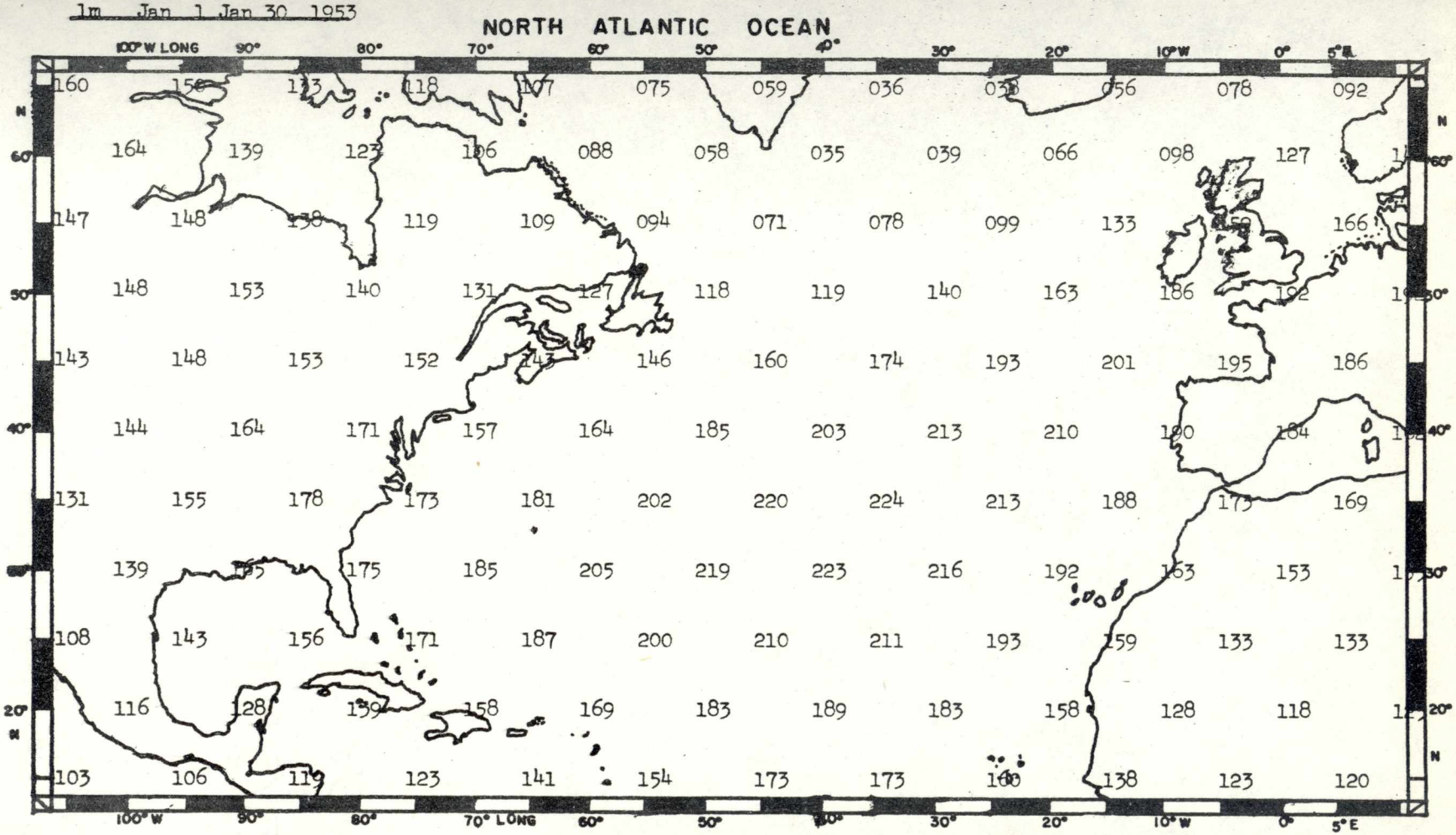

I. Atmospheric Pressure ANNUAL MEAN 1953

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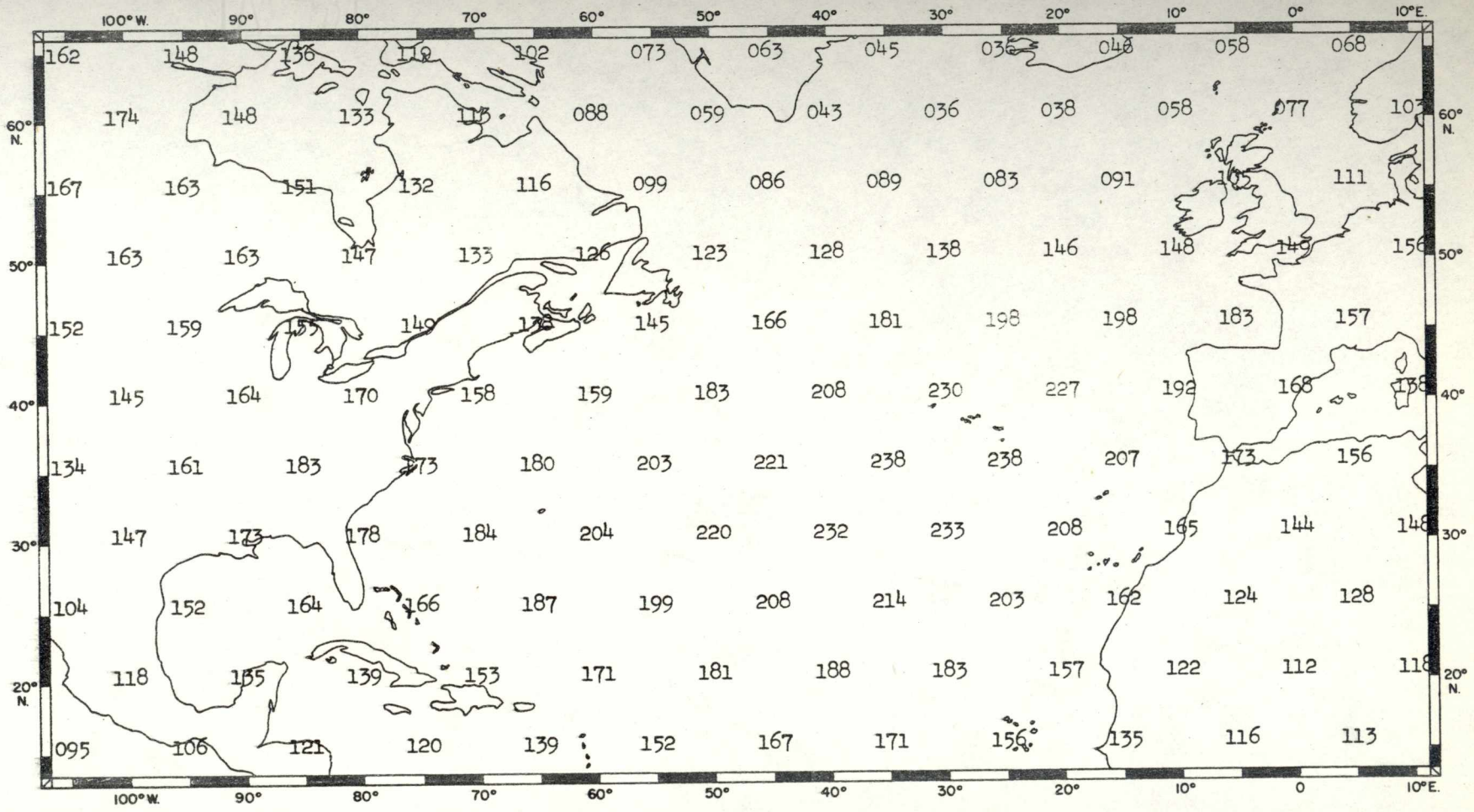
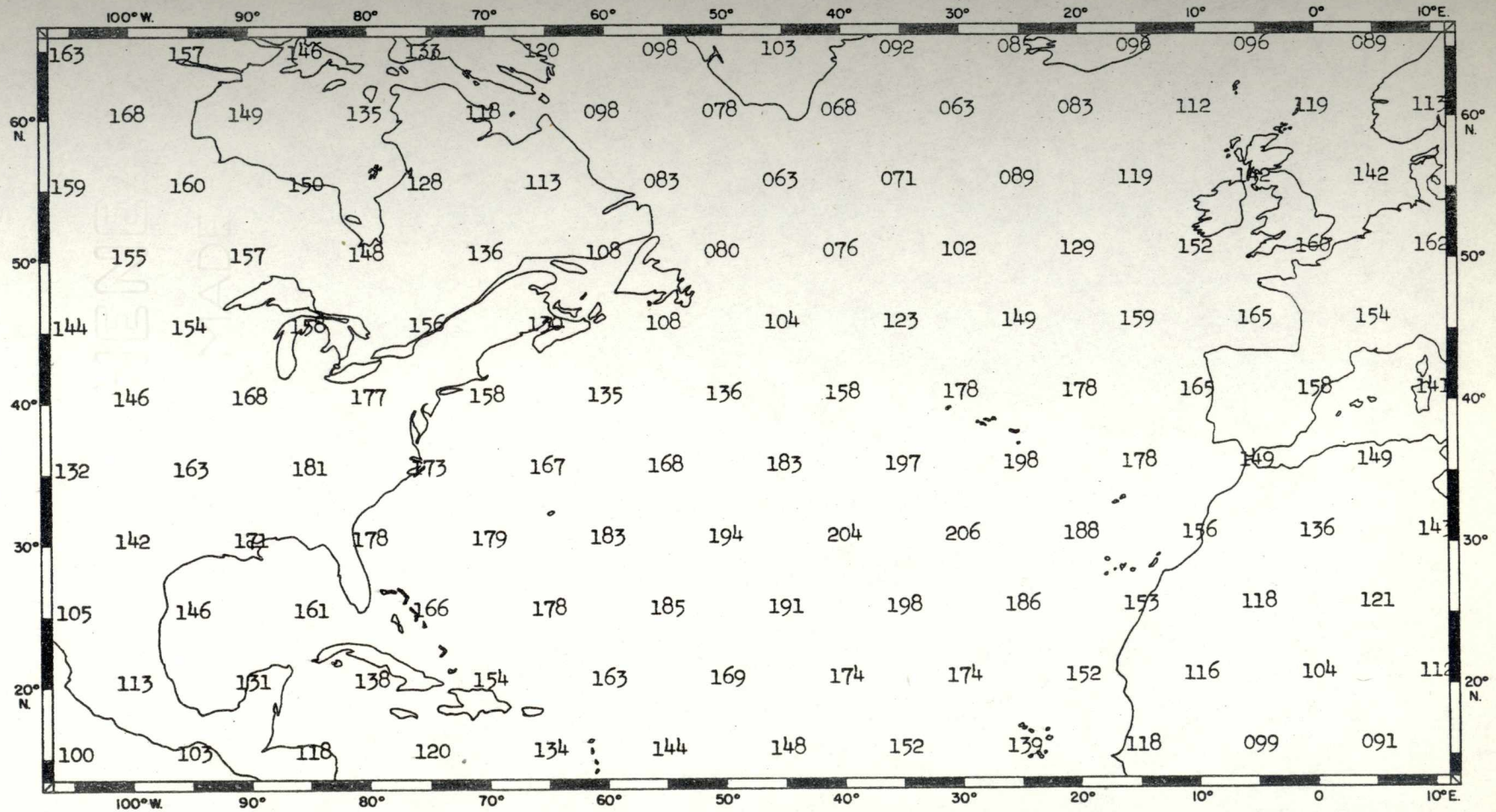


I. Atmospheric Pressure

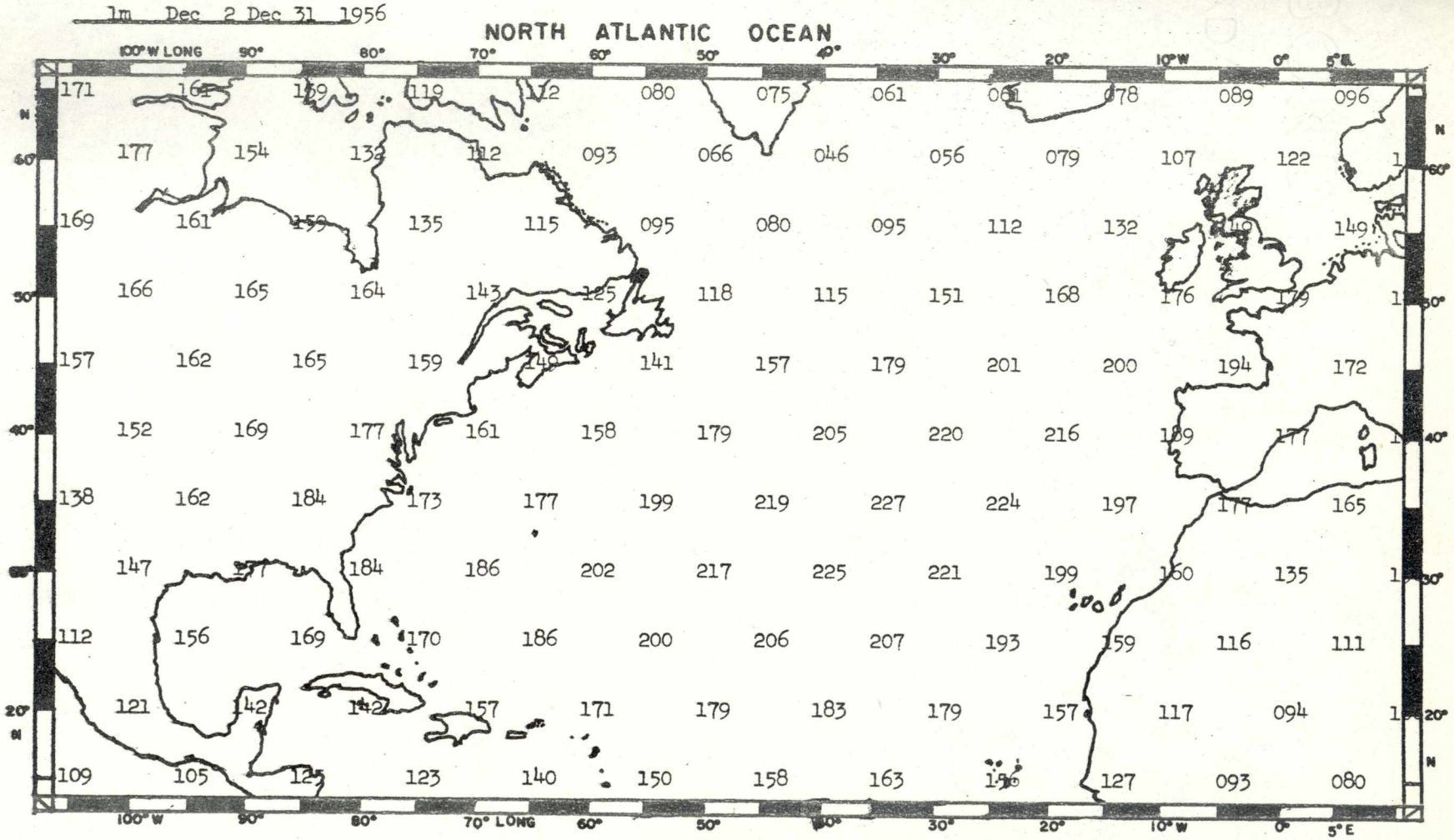
ANNUAL MEAN 1954

1m Mar 29 Apr 27 1955



I. Atmospheric Pressure

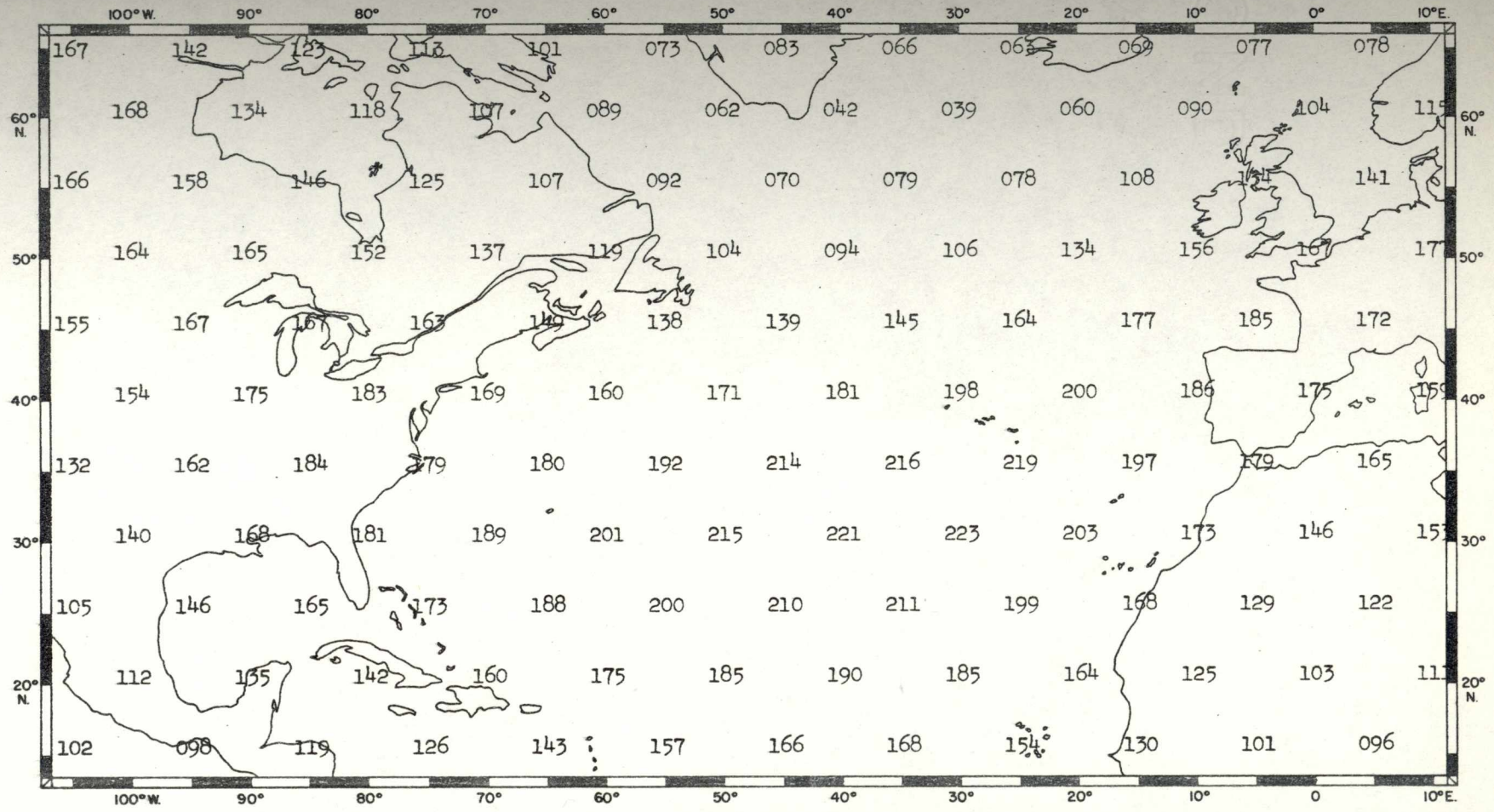
ANNUAL MEAN 1955



I. Atmospheric Pressure

ANNUAL MEAN 1956

lm Mar 29 Apr 27 1957



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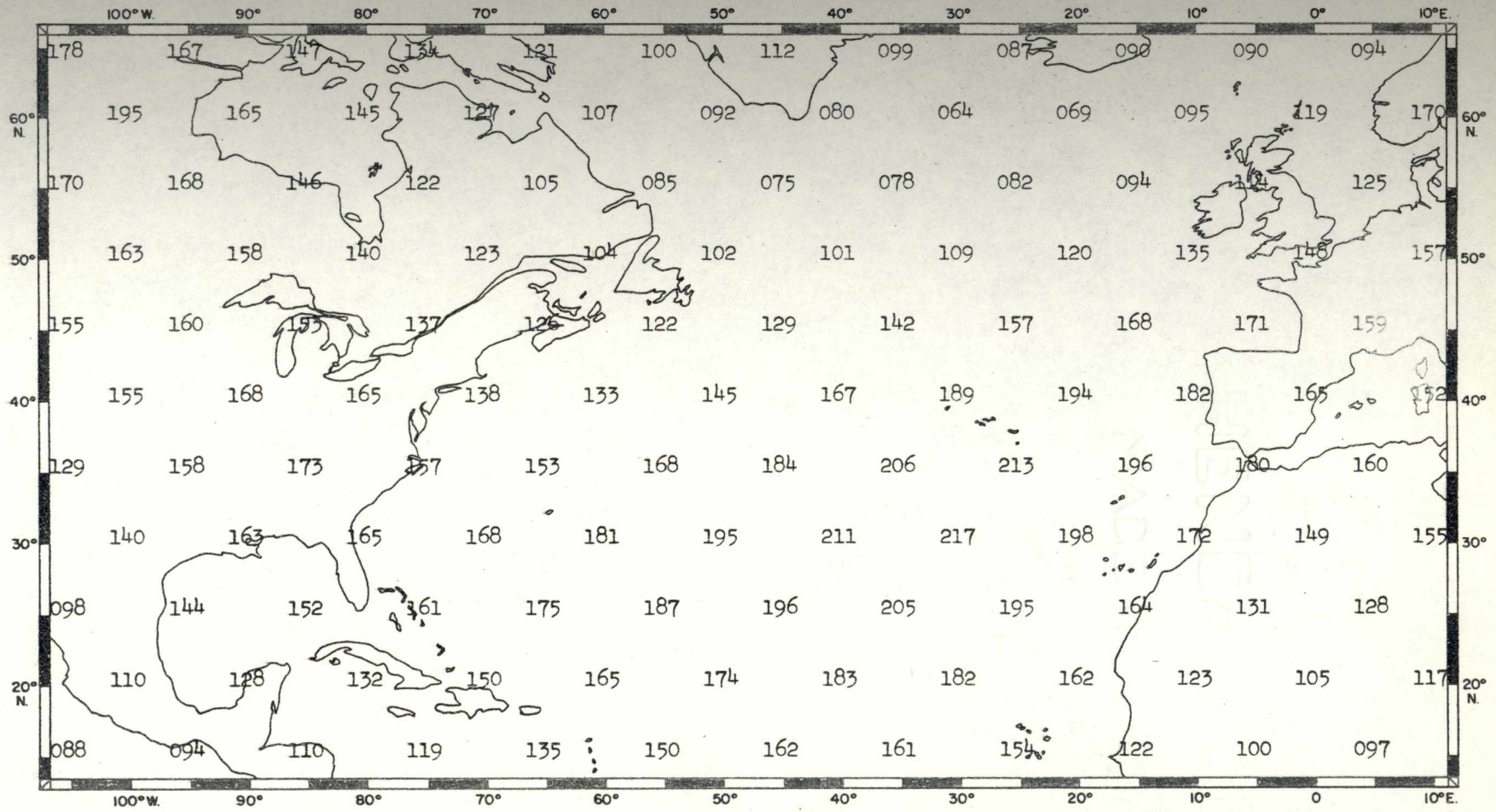

I. Atmospheric Pressure ANNUAL MEAN 1958

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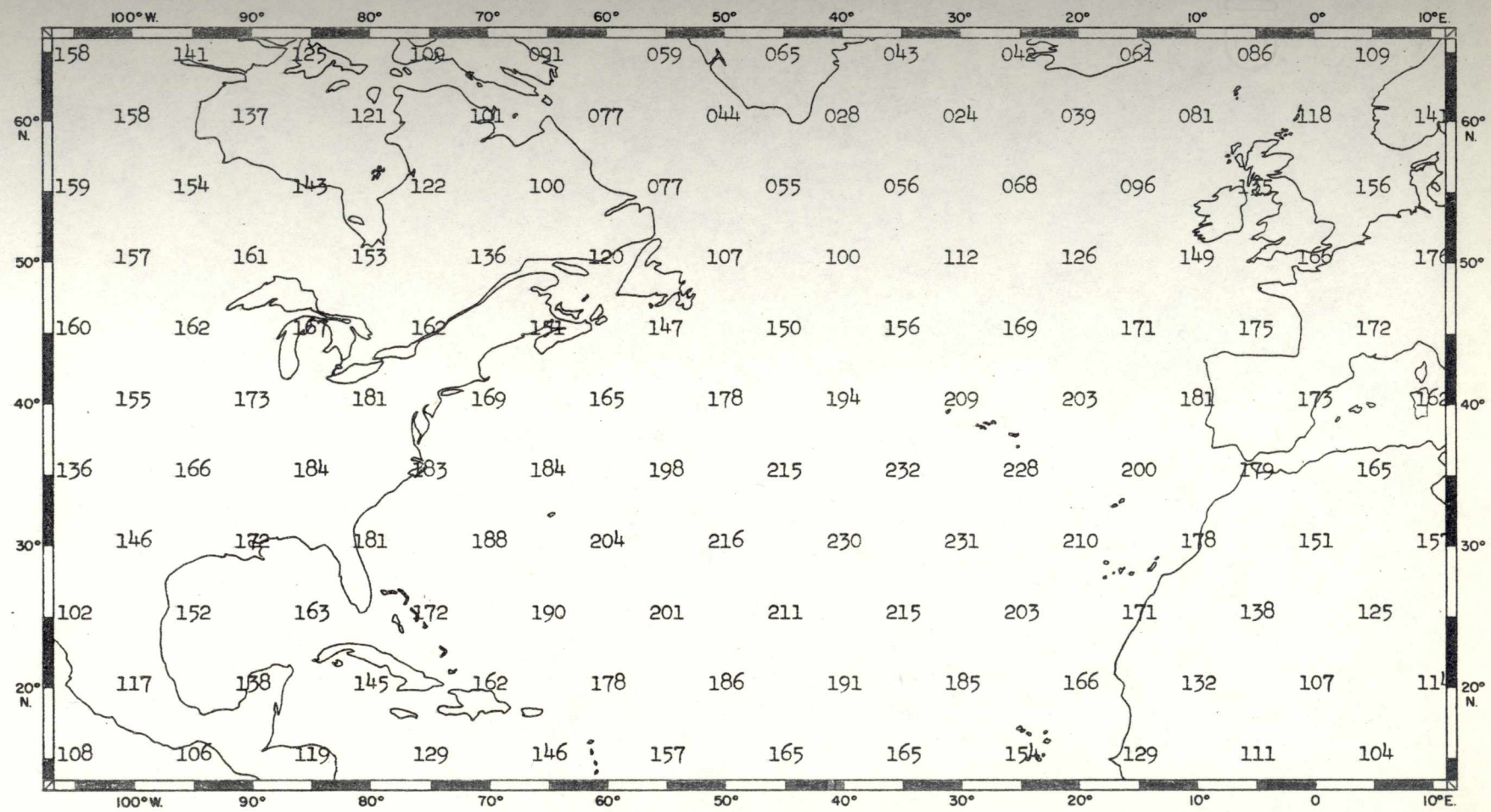

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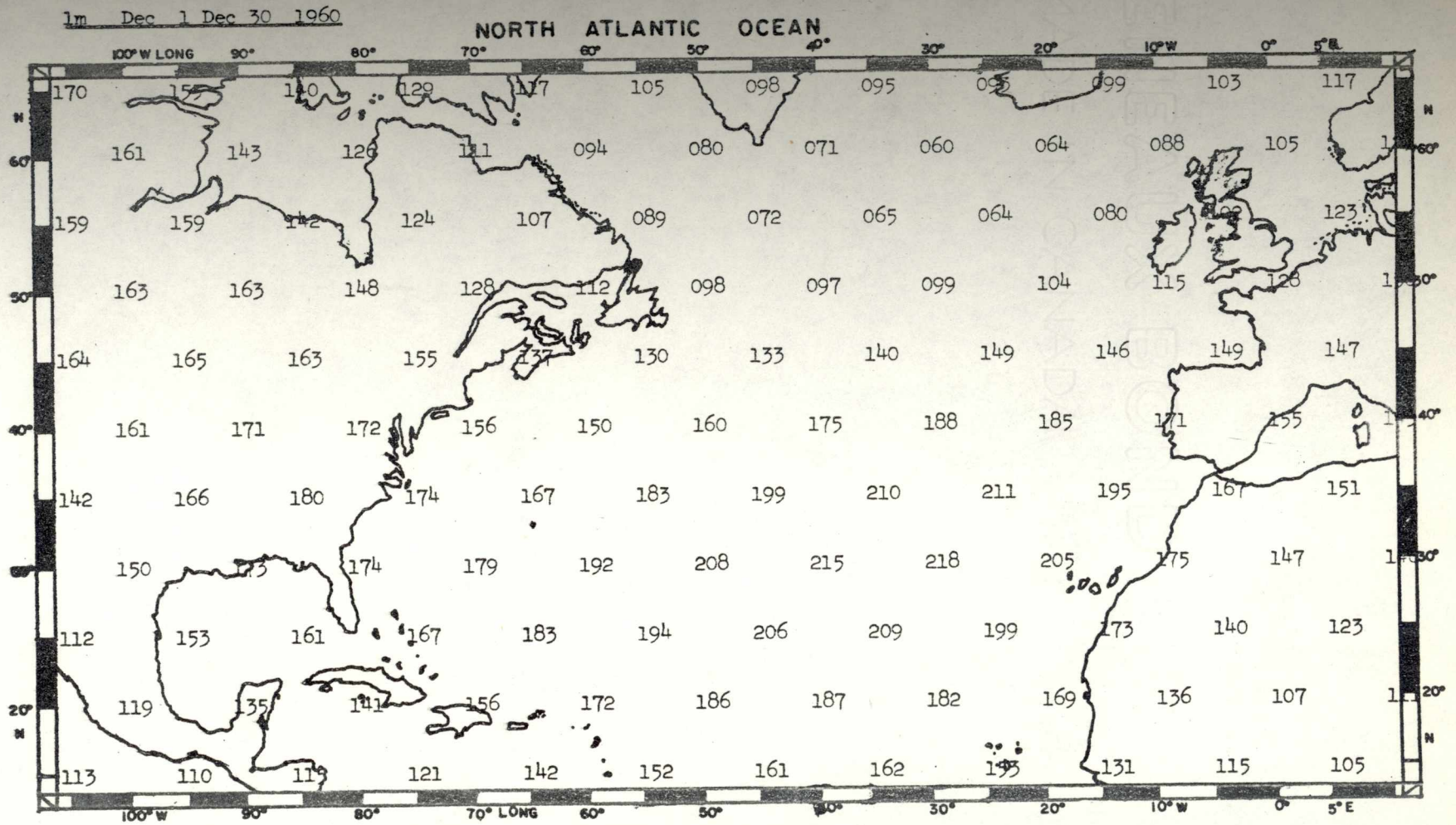
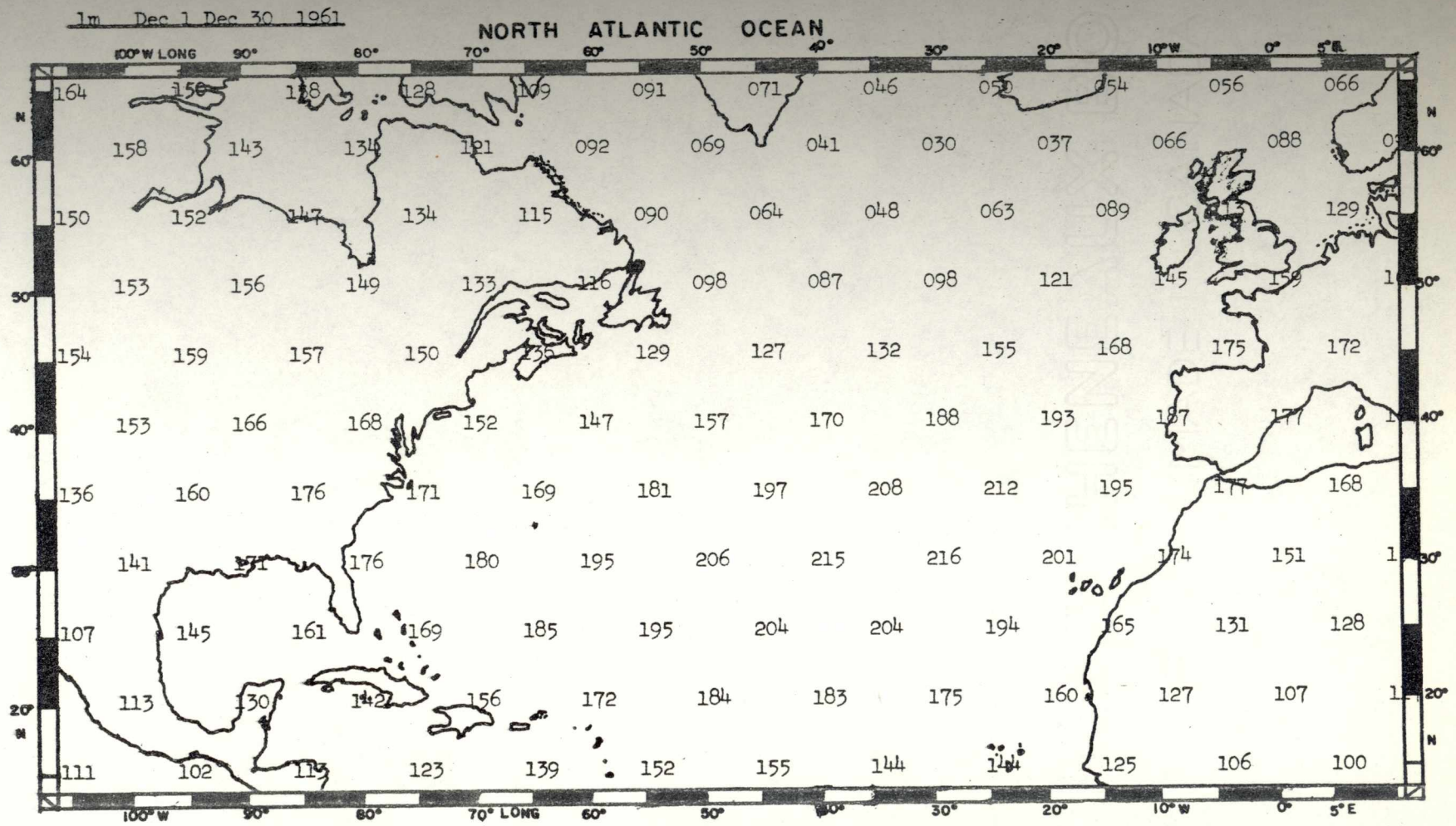


I. Atmospheric Pressure

ANNUAL MEAN 1960



I. Atmospheric Pressure

ANNUAL MEAN 1961

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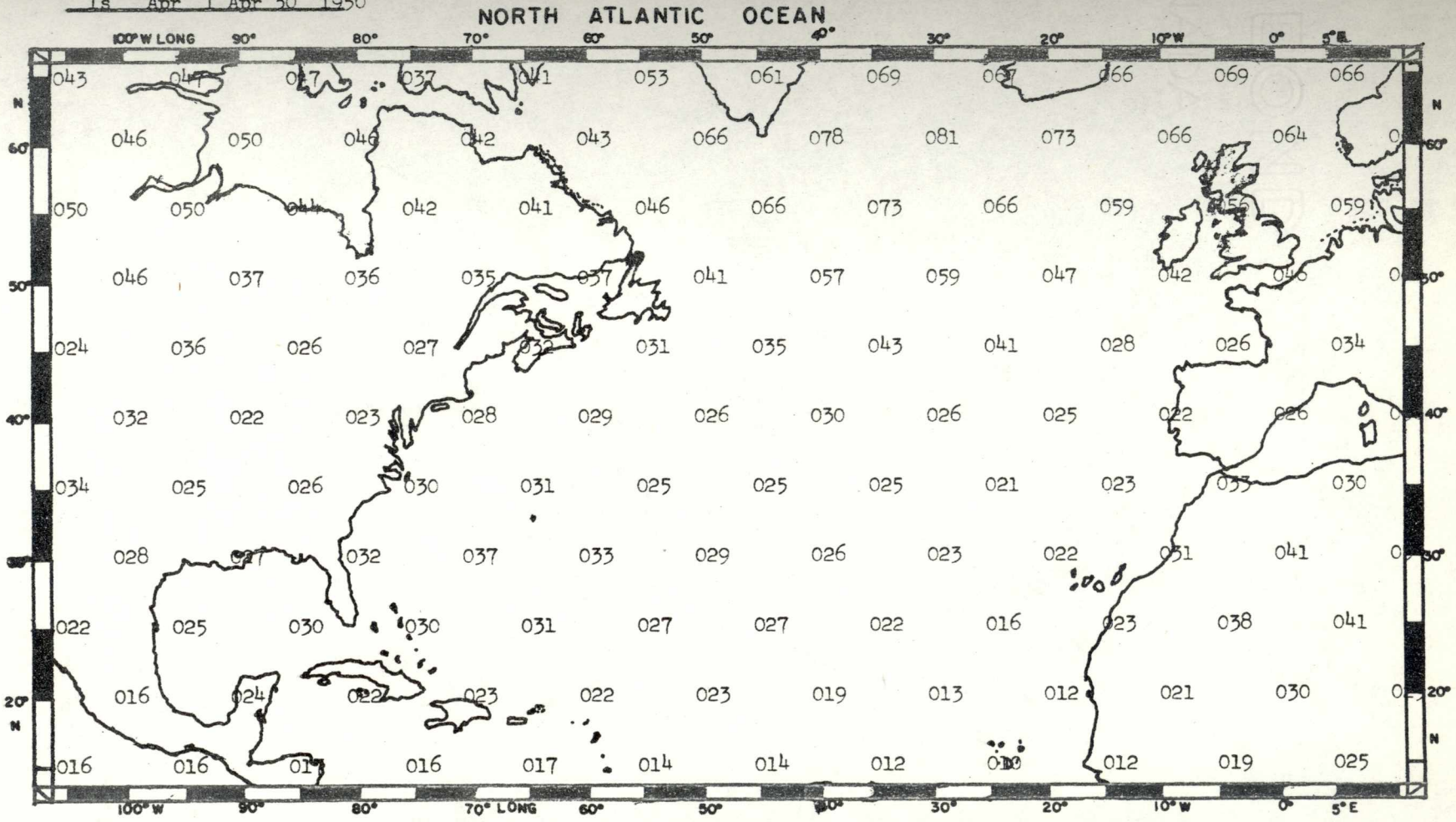

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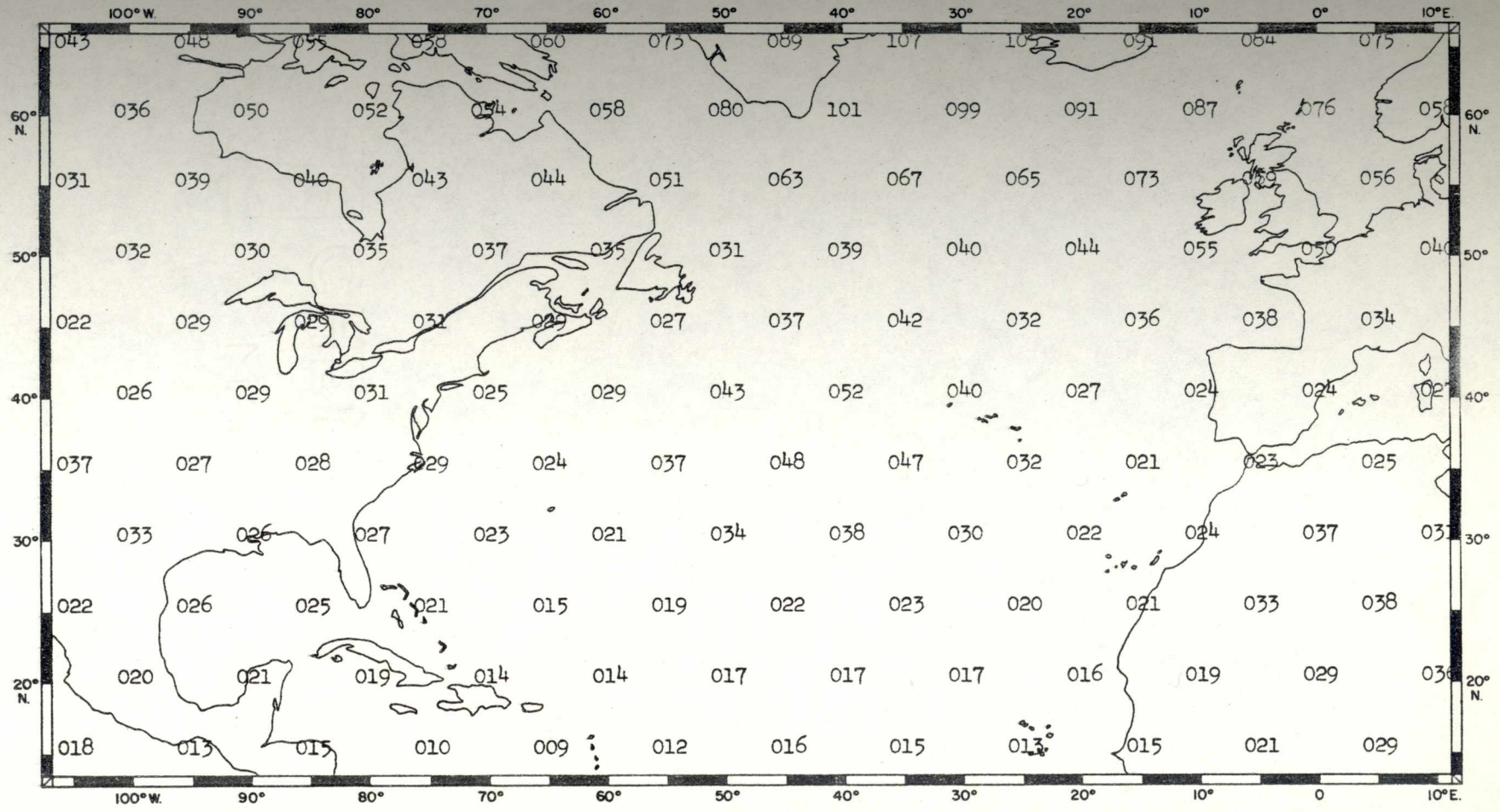

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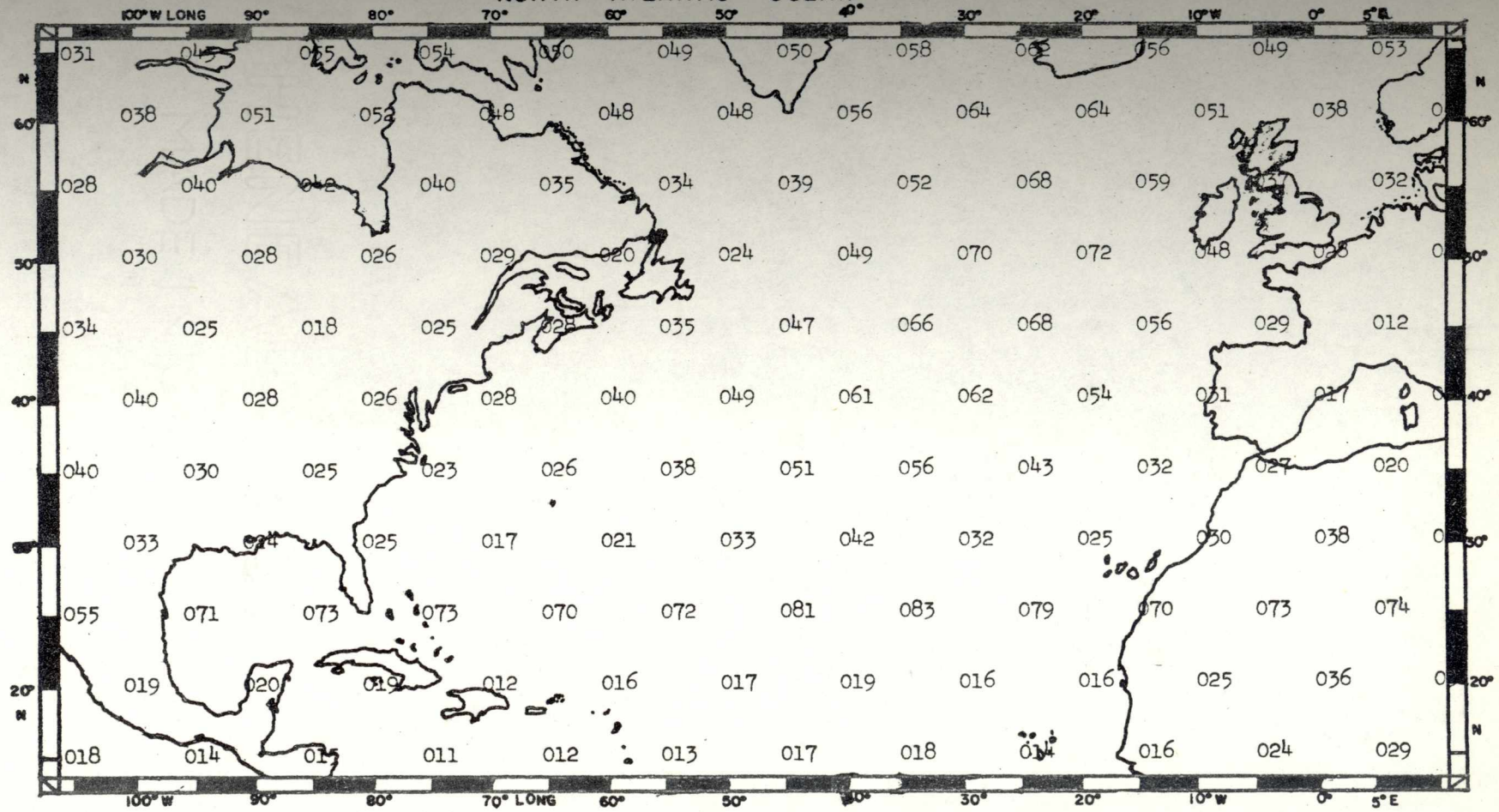
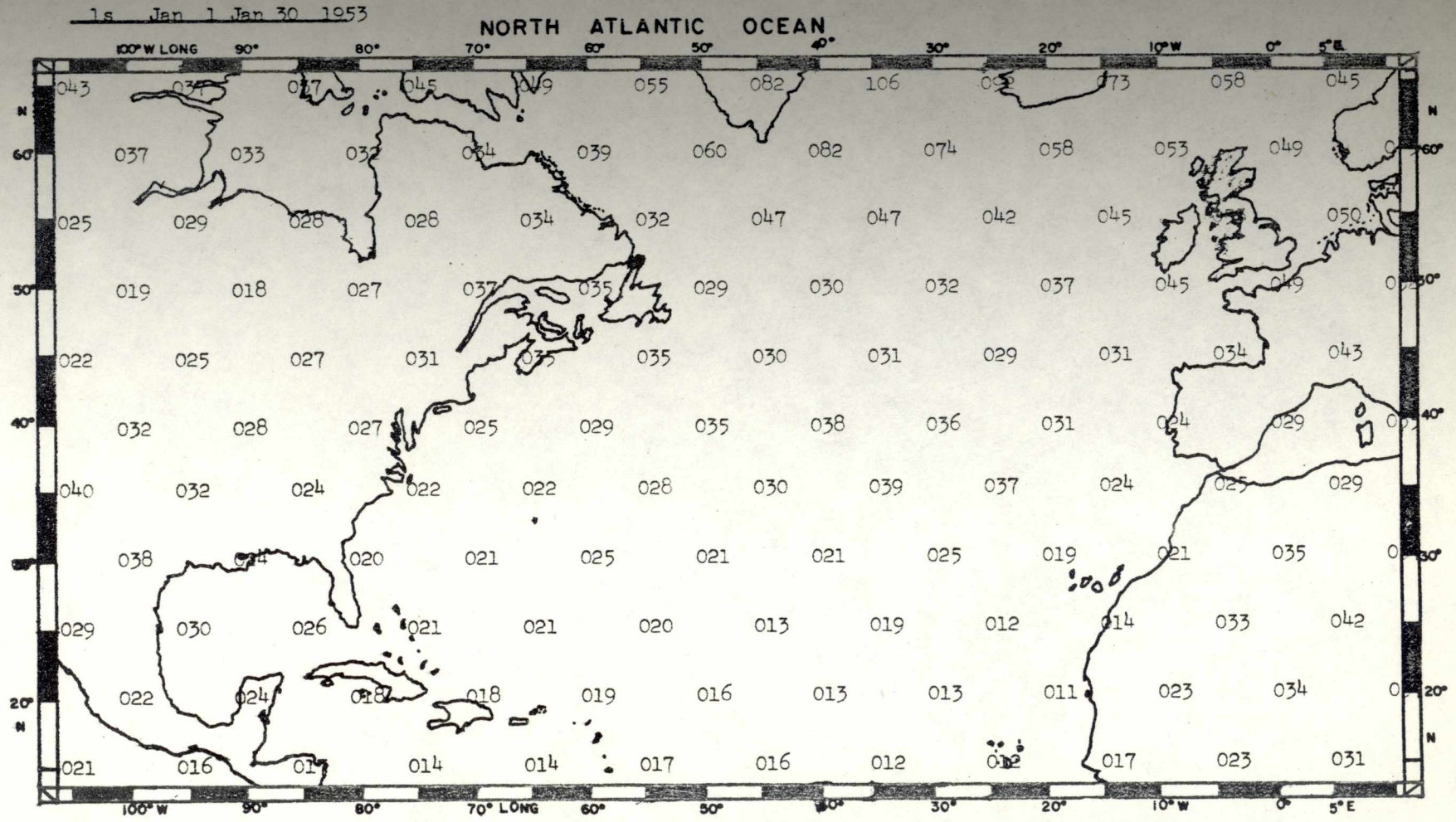
1s May 1 May 30 1952

NORTH ATLANTIC OCEAN



I. Atmospheric Pressure

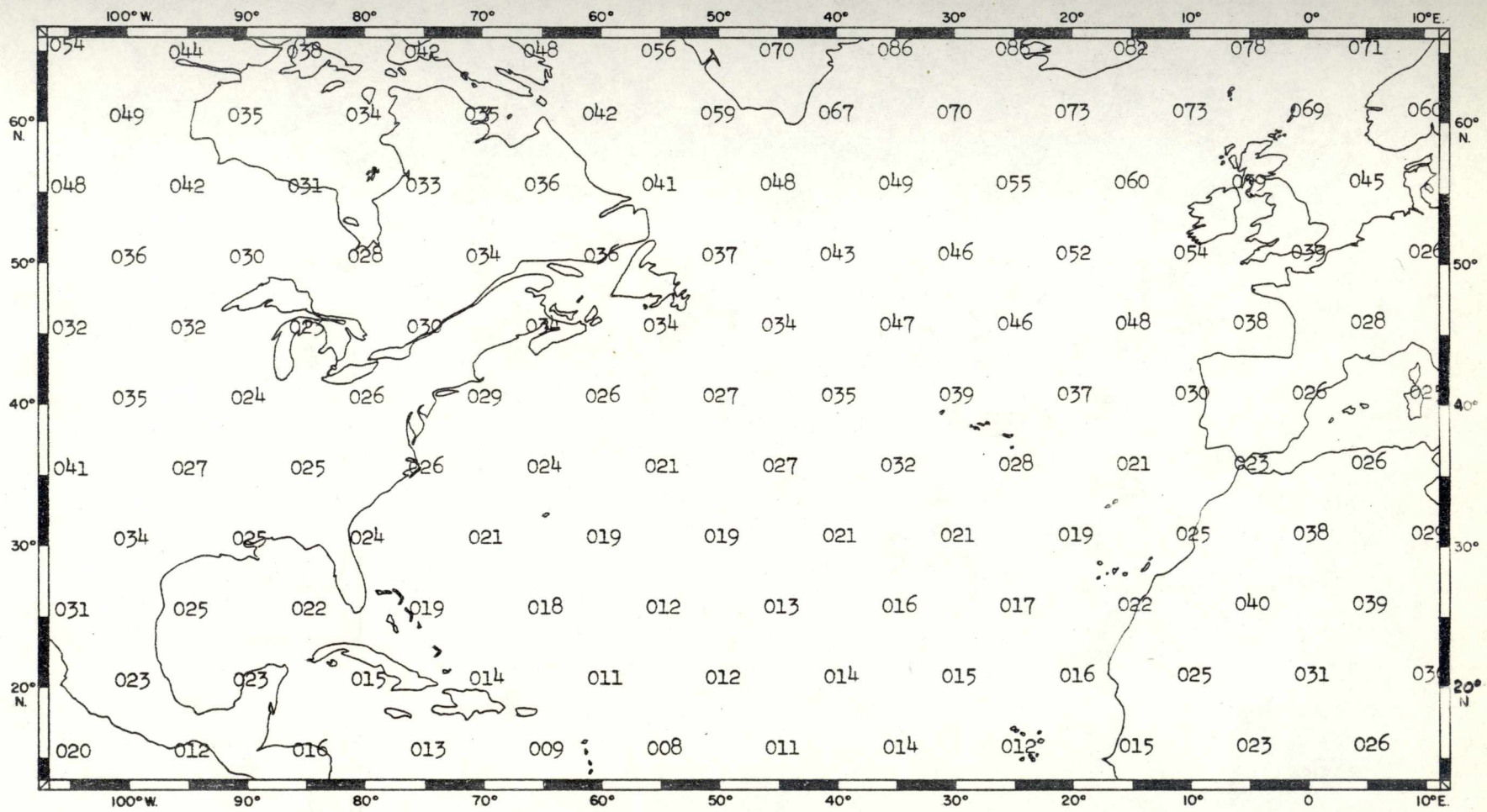
STANDARD DEVIATION 1952



I. Atmospheric Pressure

STANDARD DEVIATION 1953

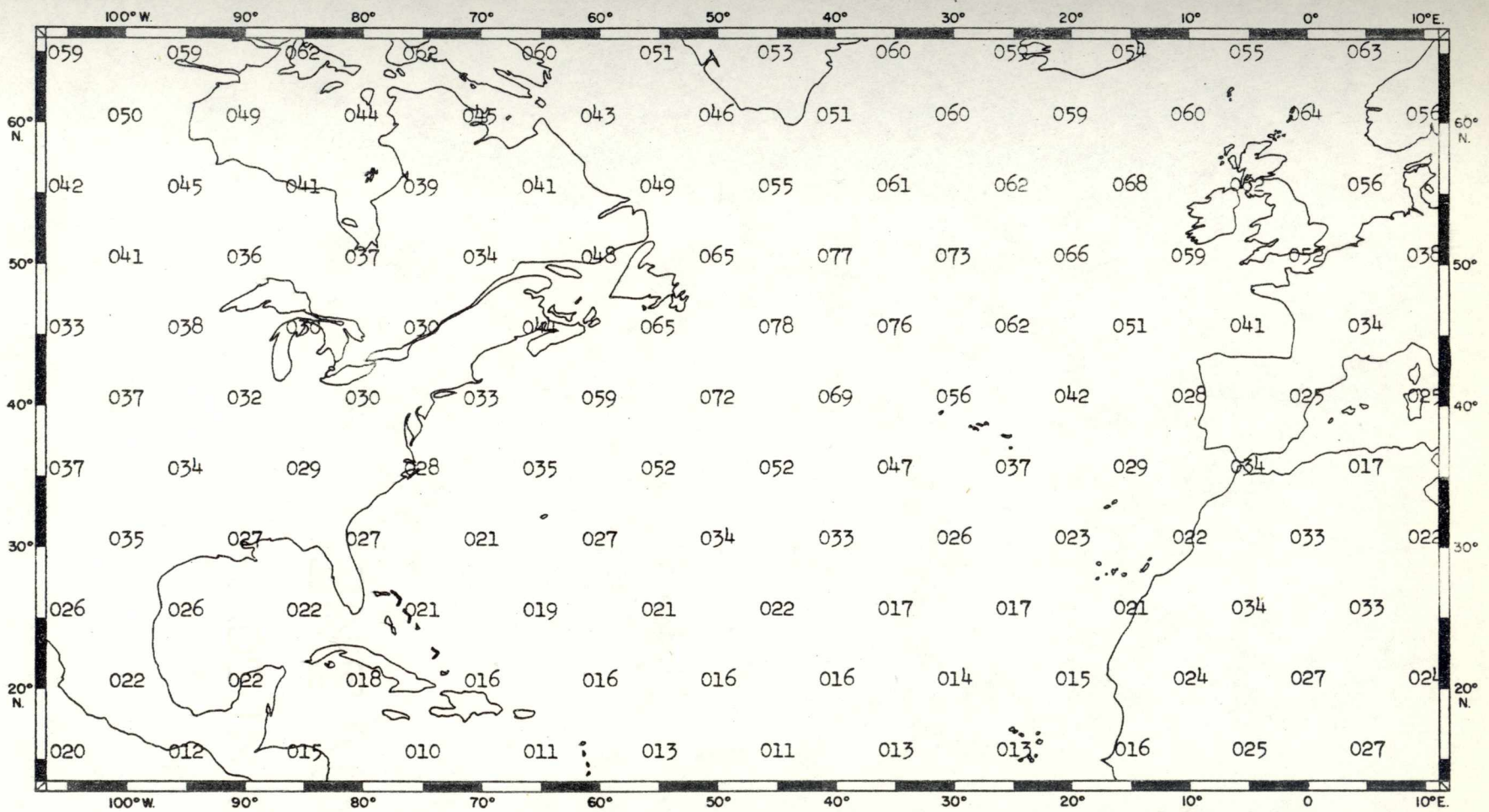
1s Sep 1 Sep 30 1954



I. Atmospheric Pressure

STANDARD DEVIATION 1954

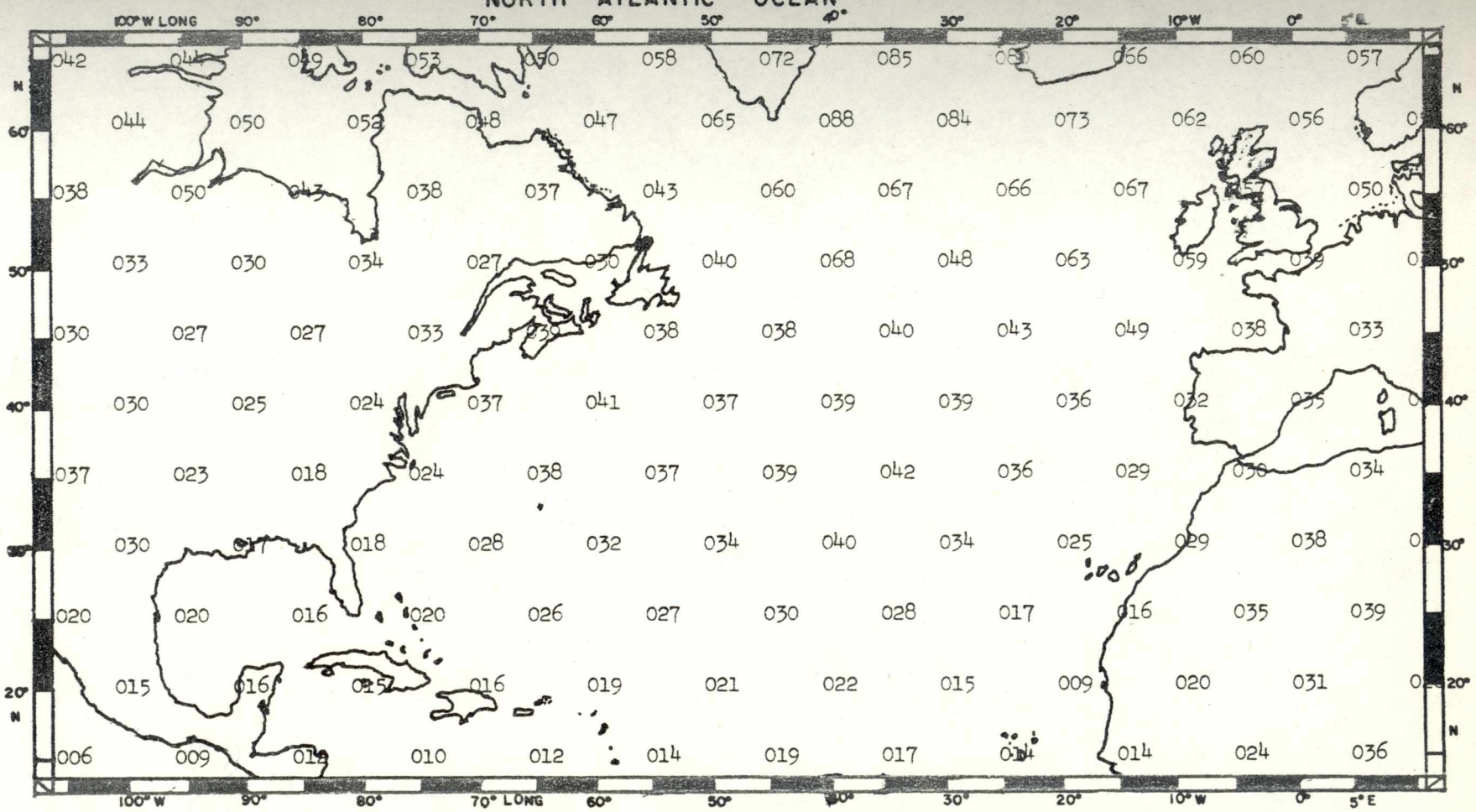
1s Mar 29 Apr 27 1955



I. Atmospheric Pressure STANDARD DEVIATION 1955

1s Dec 2 Dec 31 1956

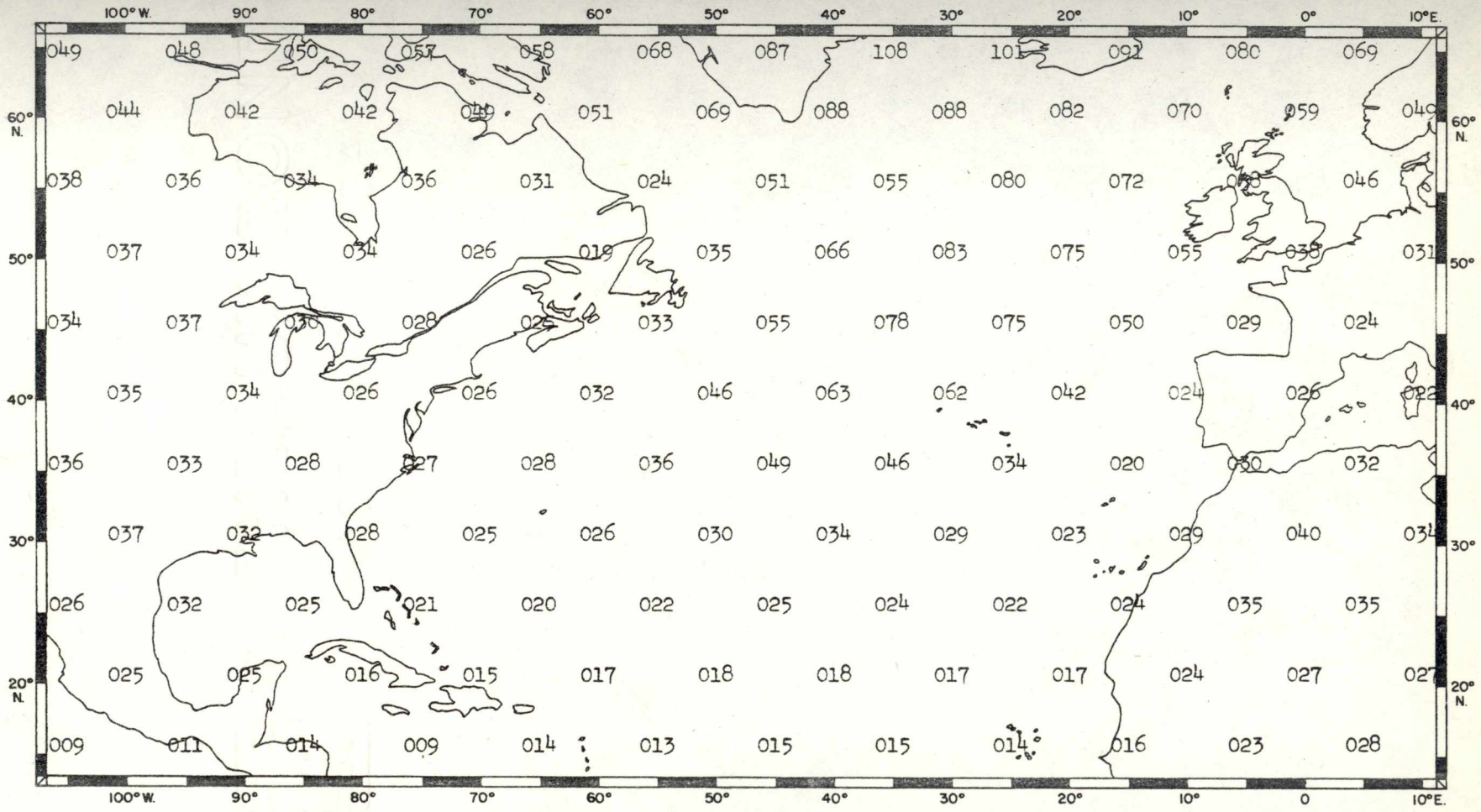
NORTH ATLANTIC OCEAN



I. Atmospheric Pressure

STANDARD DEVIATION 1956

1s Mar 29 Apr 27 1957



I. Atmospheric Pressure STANDARD DEVIATION 1957

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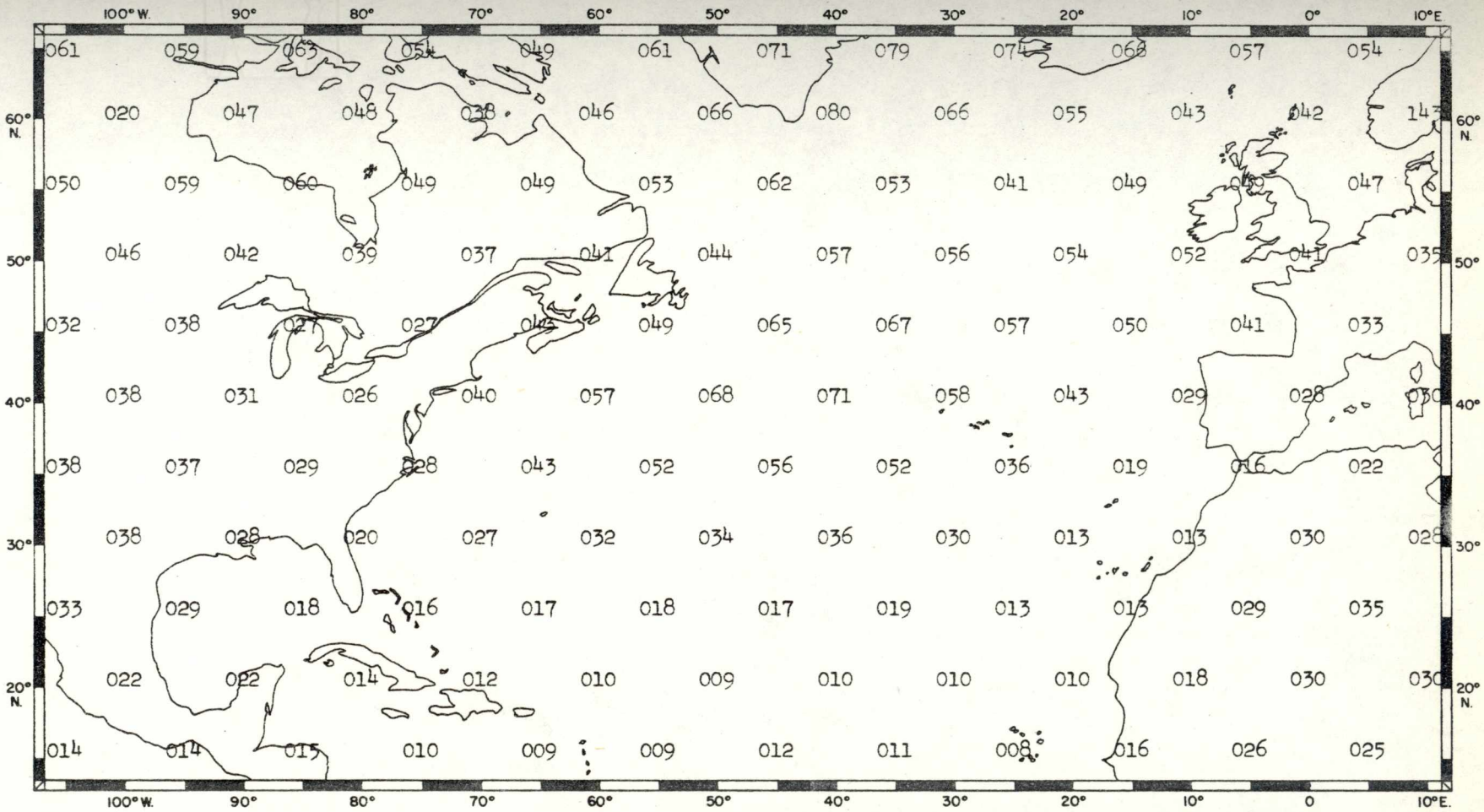

I. Atmospheric Pressure STANDARD DEVIATION 1958

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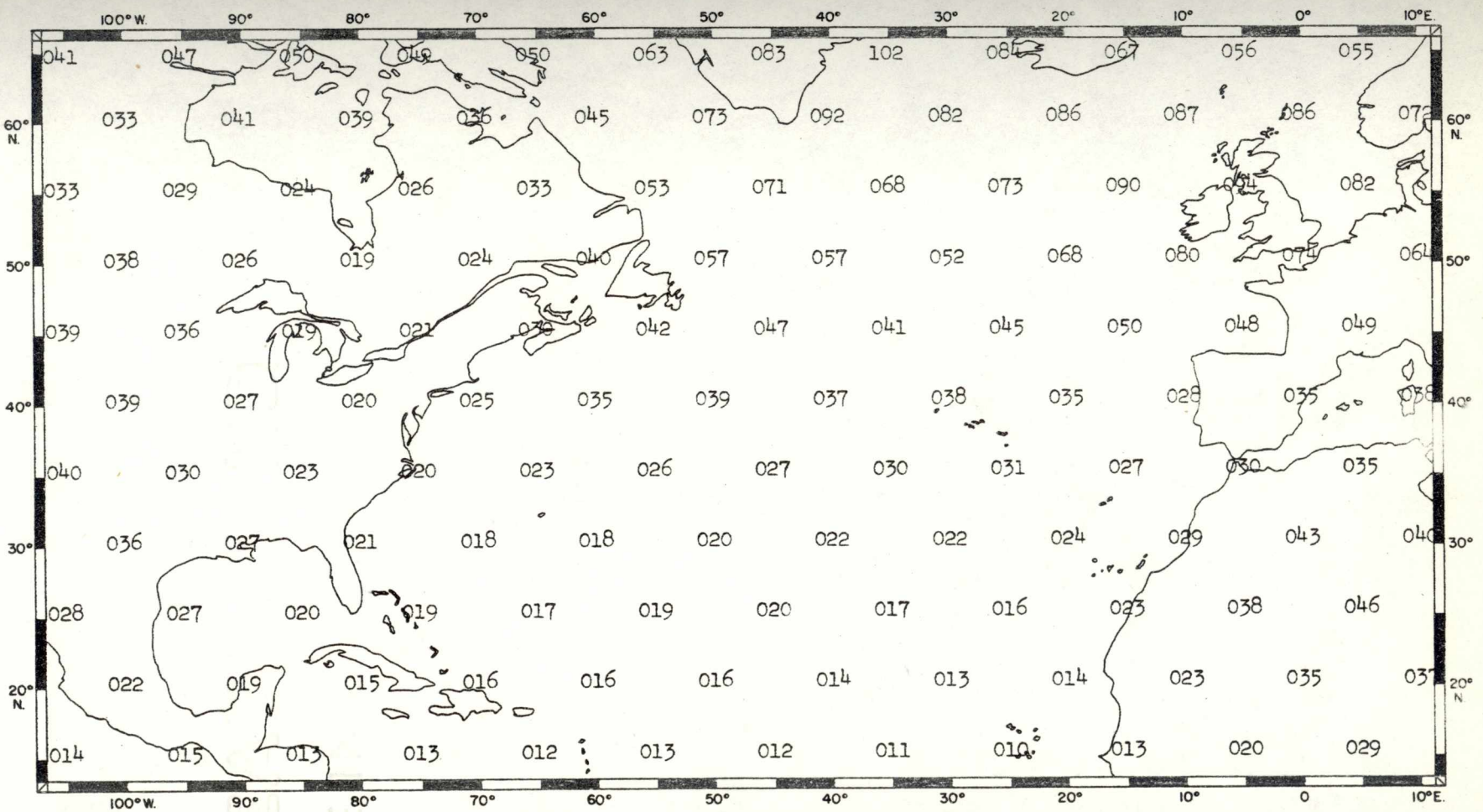
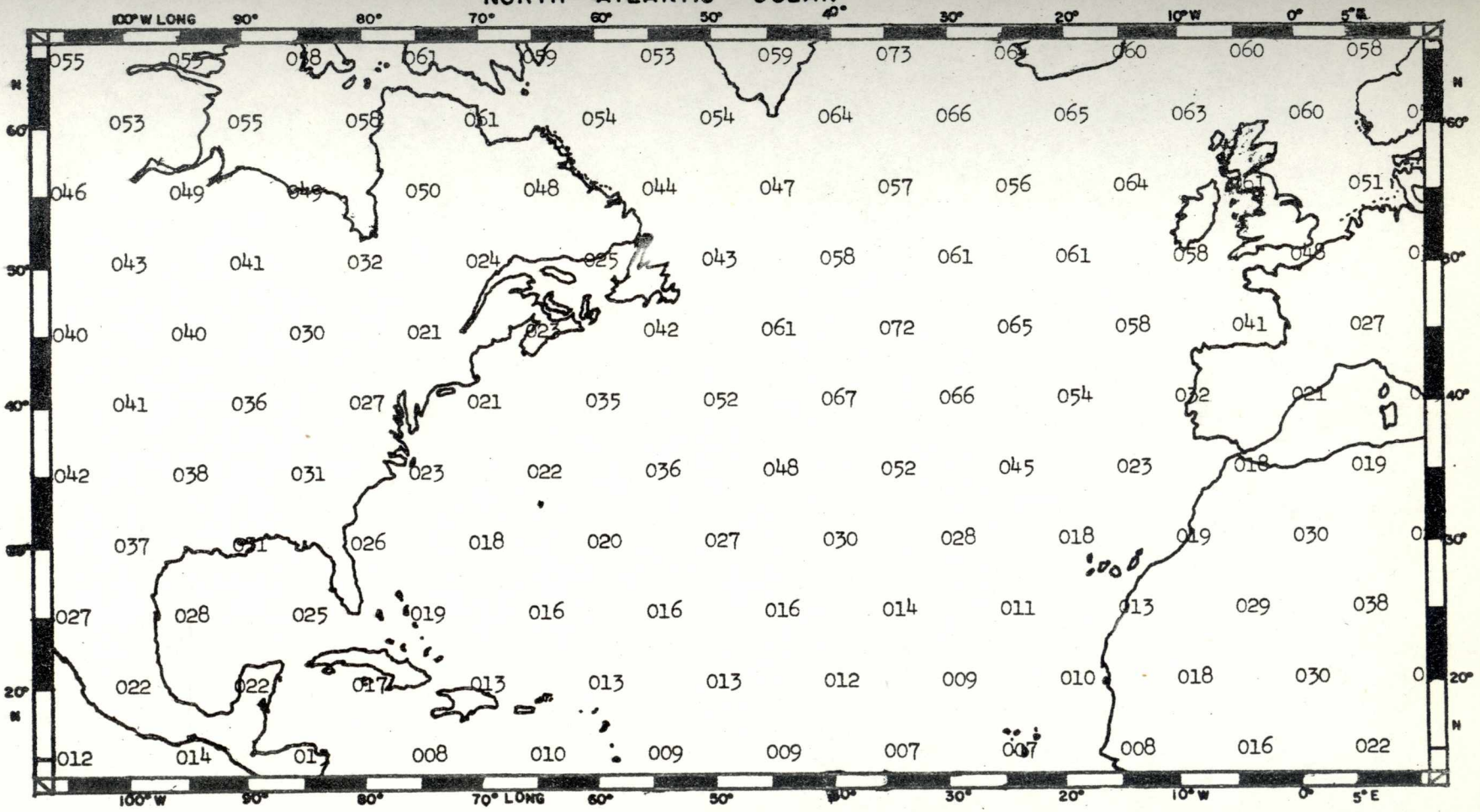


I. Atmospheric Pressure

STANDARD DEVIATION 1959

1s Dec 1 Dec 30 1960

NORTH ATLANTIC OCEAN



I. Atmospheric Pressure

STANDARD DEVIATION 1960

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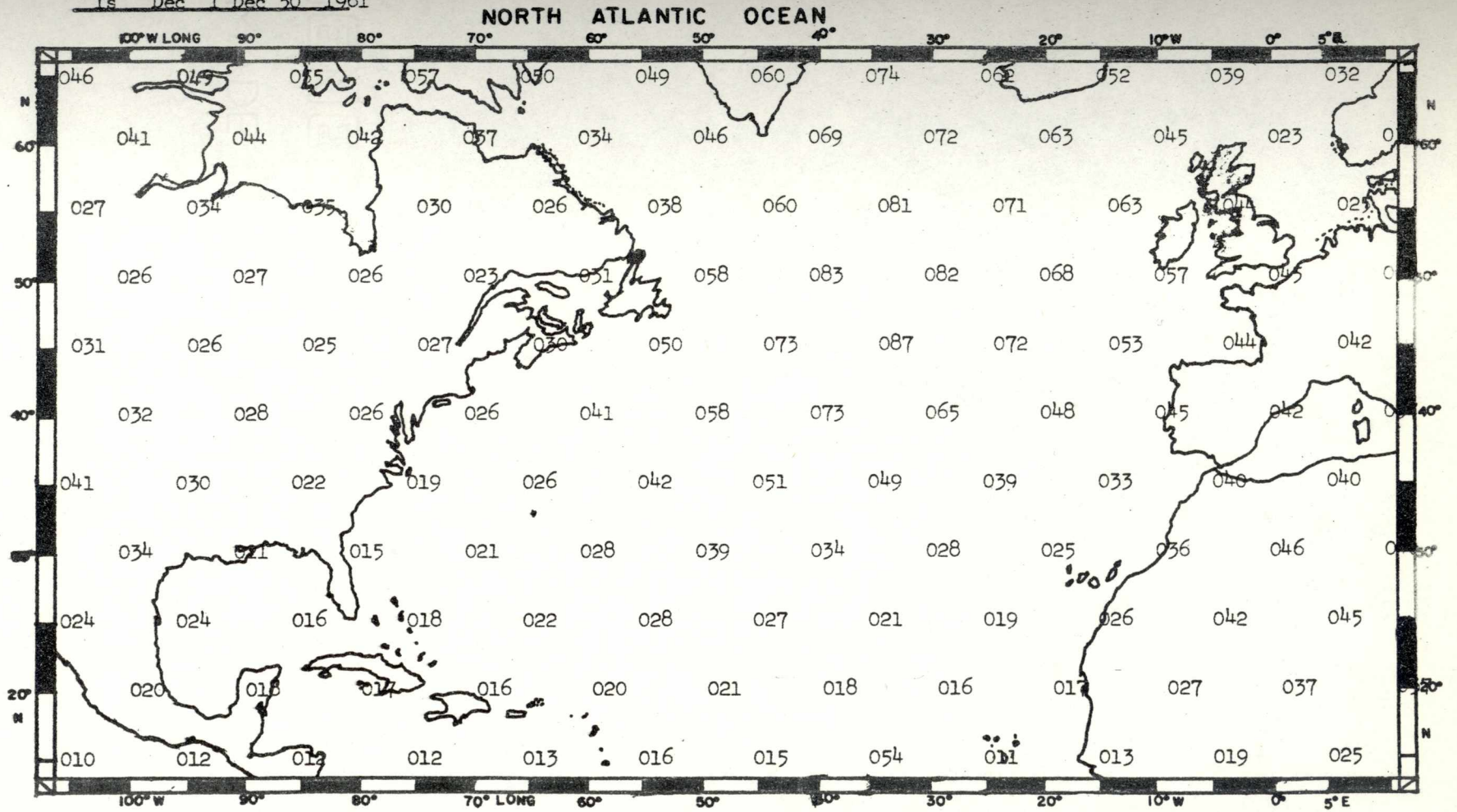

I. Atmospheric Pressure

STANDARD DEVIATION 1961

Section II

Meridional Component of Ekman Transport

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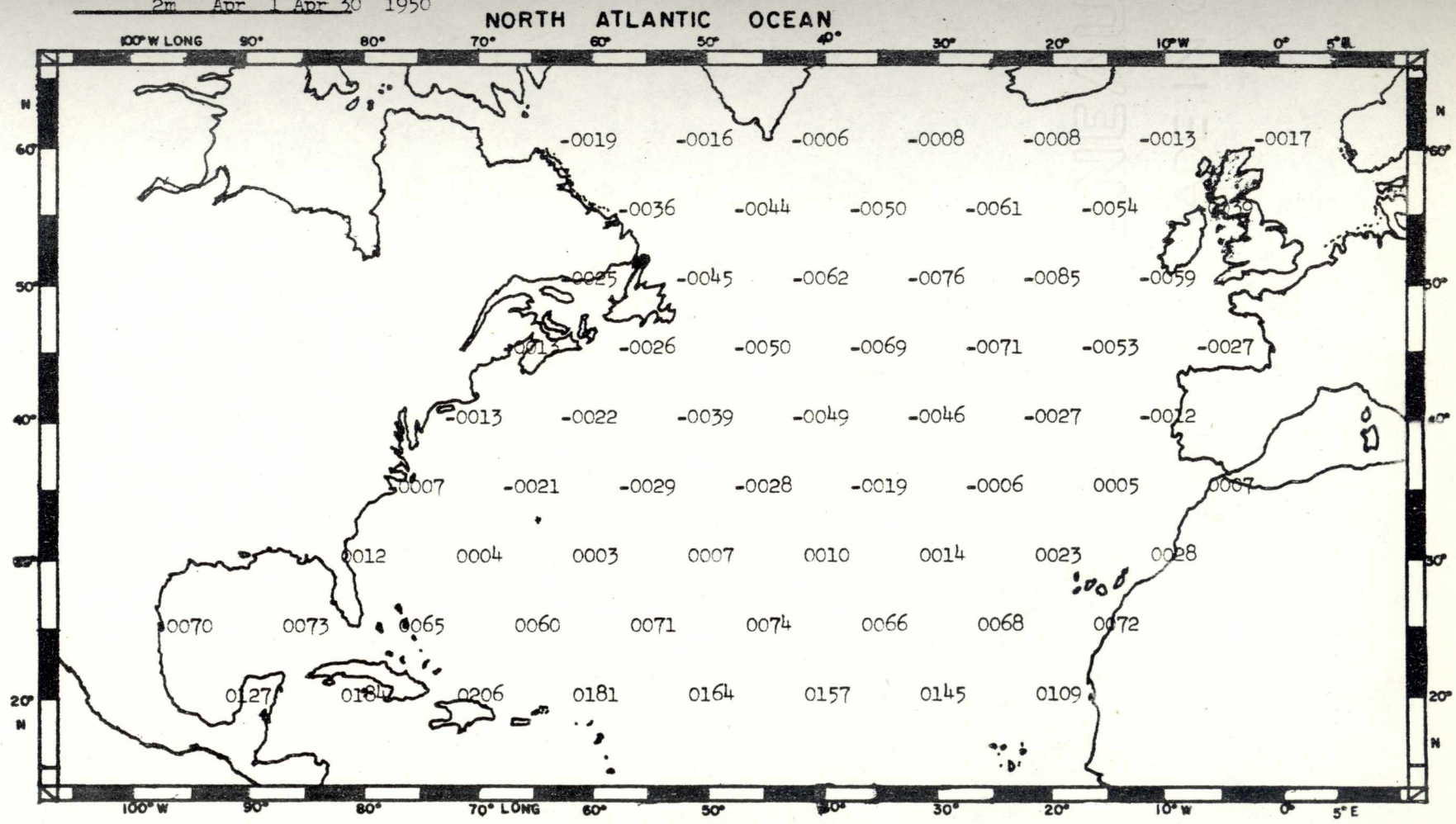
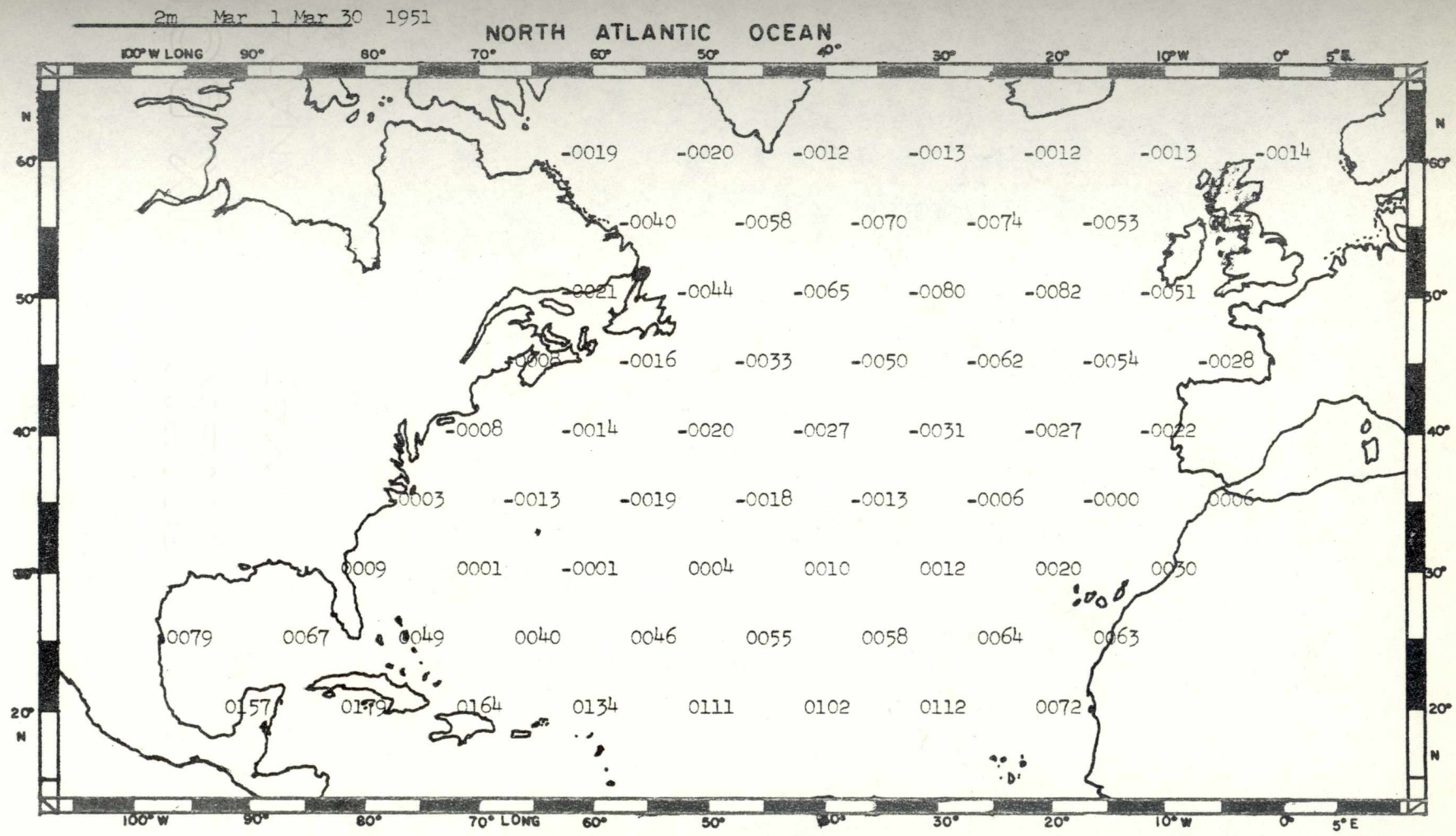


II. Meridional Component of Ekman Transport ANNUAL MEAN 1950



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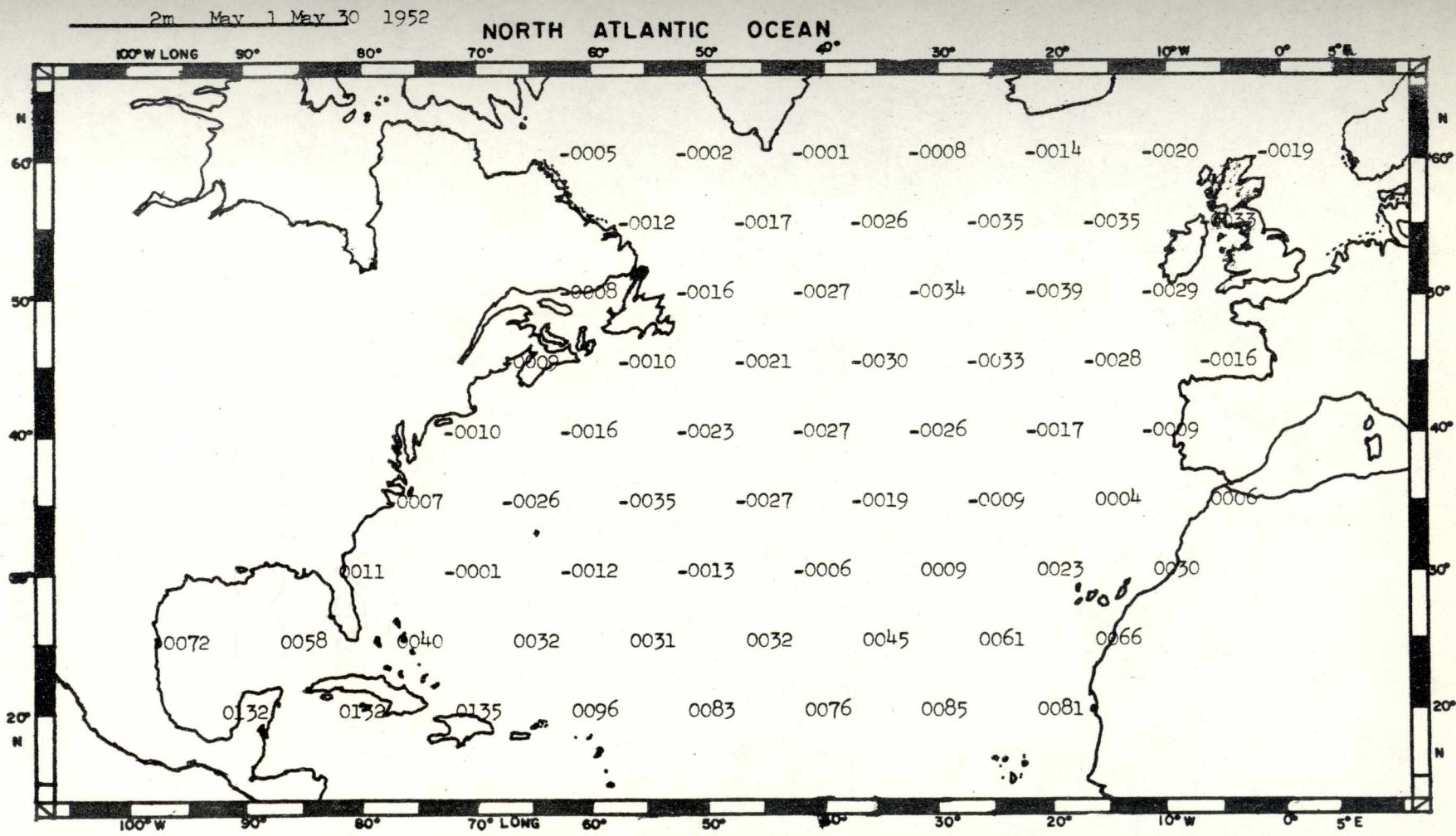
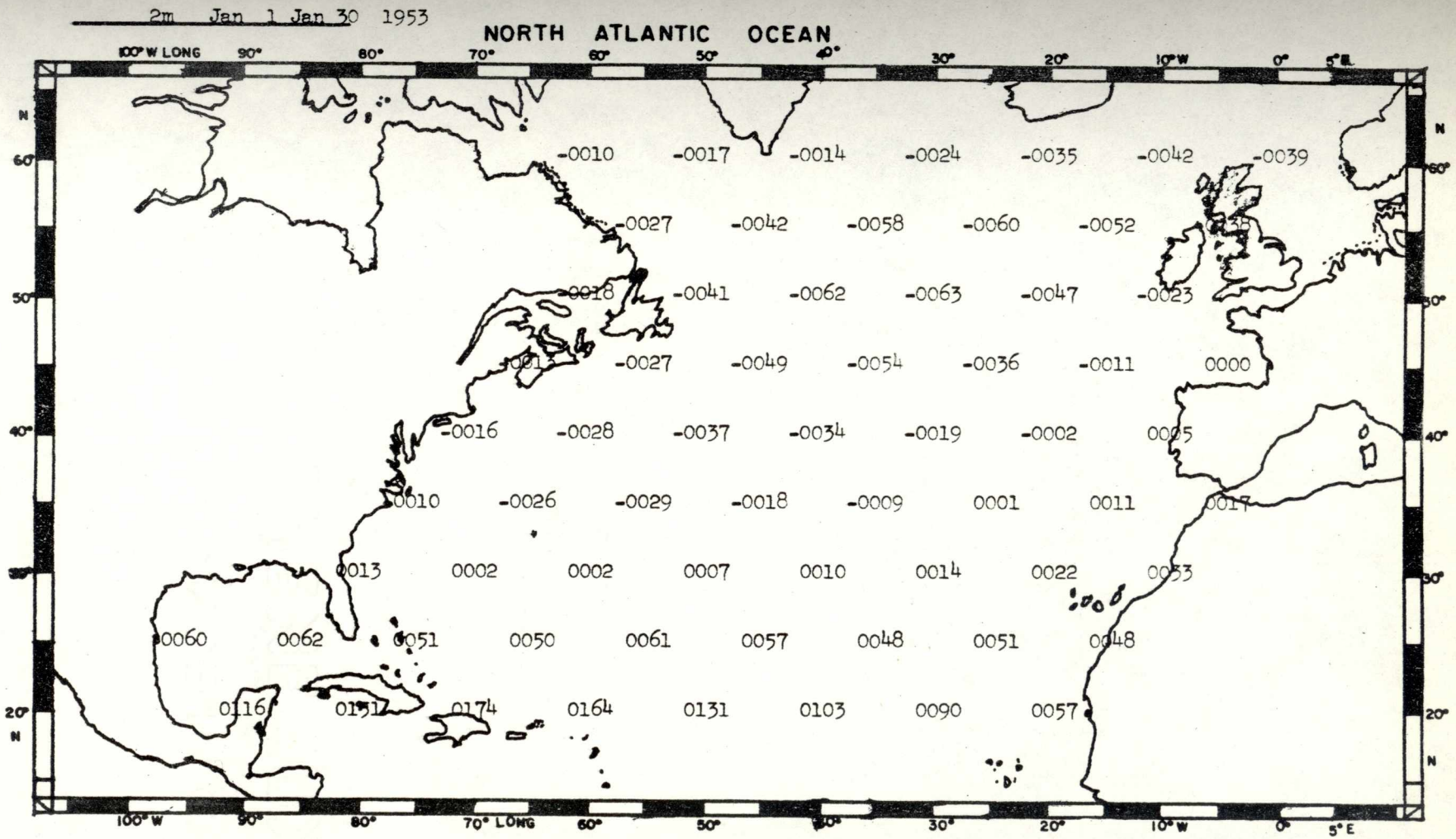
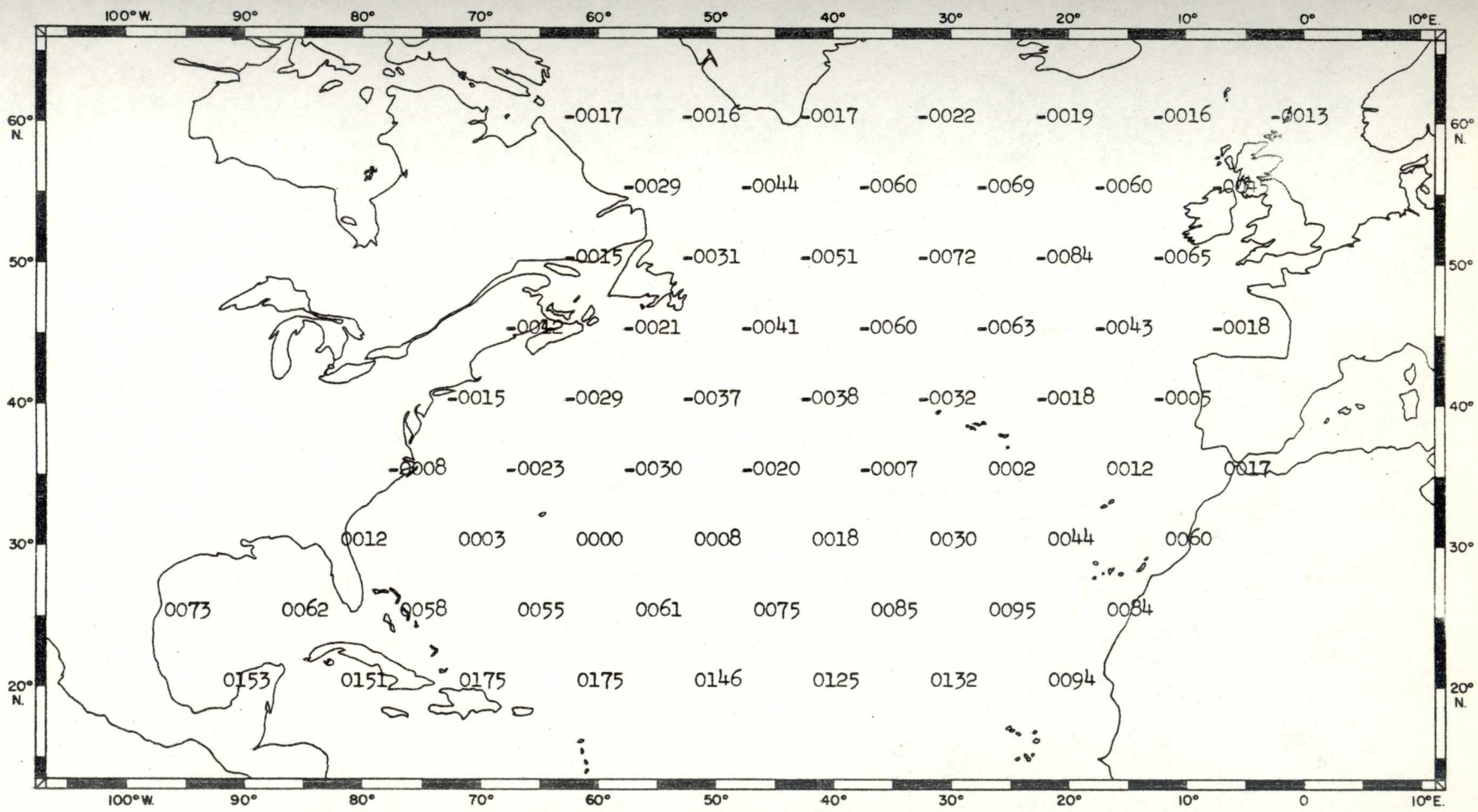


II. Meridional Component of Ekman Transport ANNUAL MEAN 1952



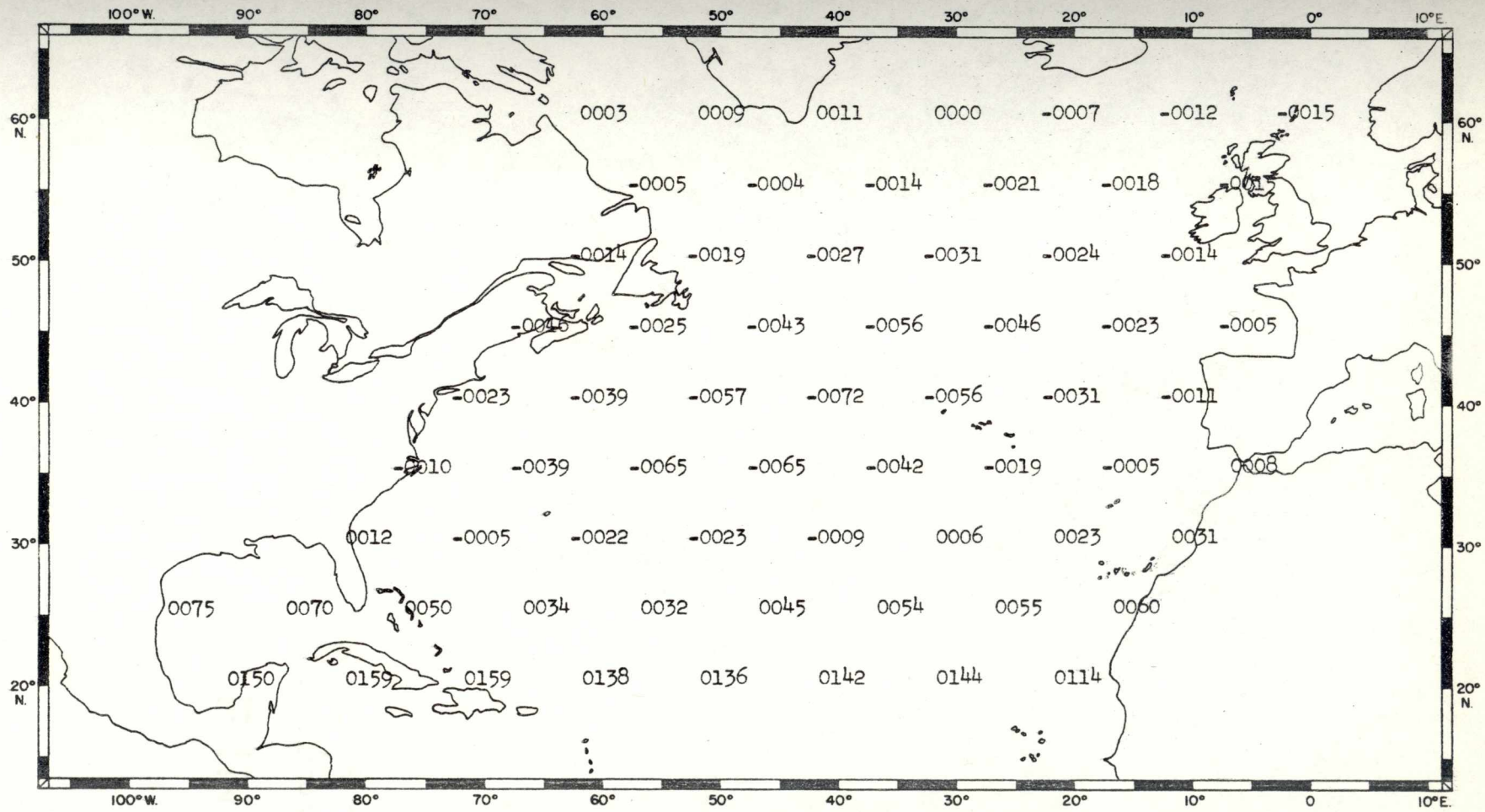
II. Meridional Component of Ekman Transport ANNUAL MEAN 1953

2m Sep 1 Sep 30 1954

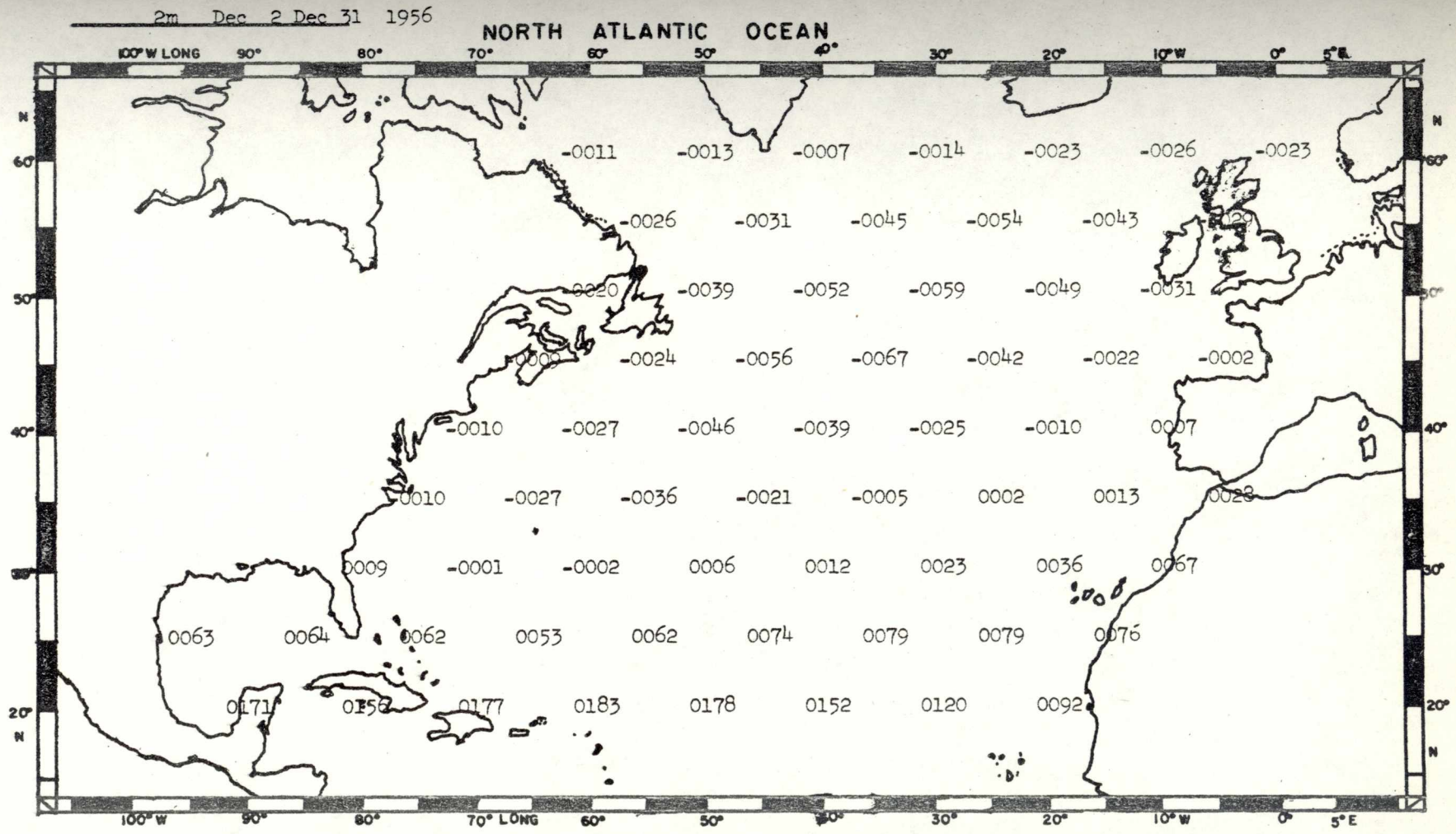


II. Meridional Component of Ekman Transport ANNUAL MEAN 1954

2m Mar 29 Apr 27 1955



II. Meridional Component of Ekman Transport ANNUAL MEAN 1955



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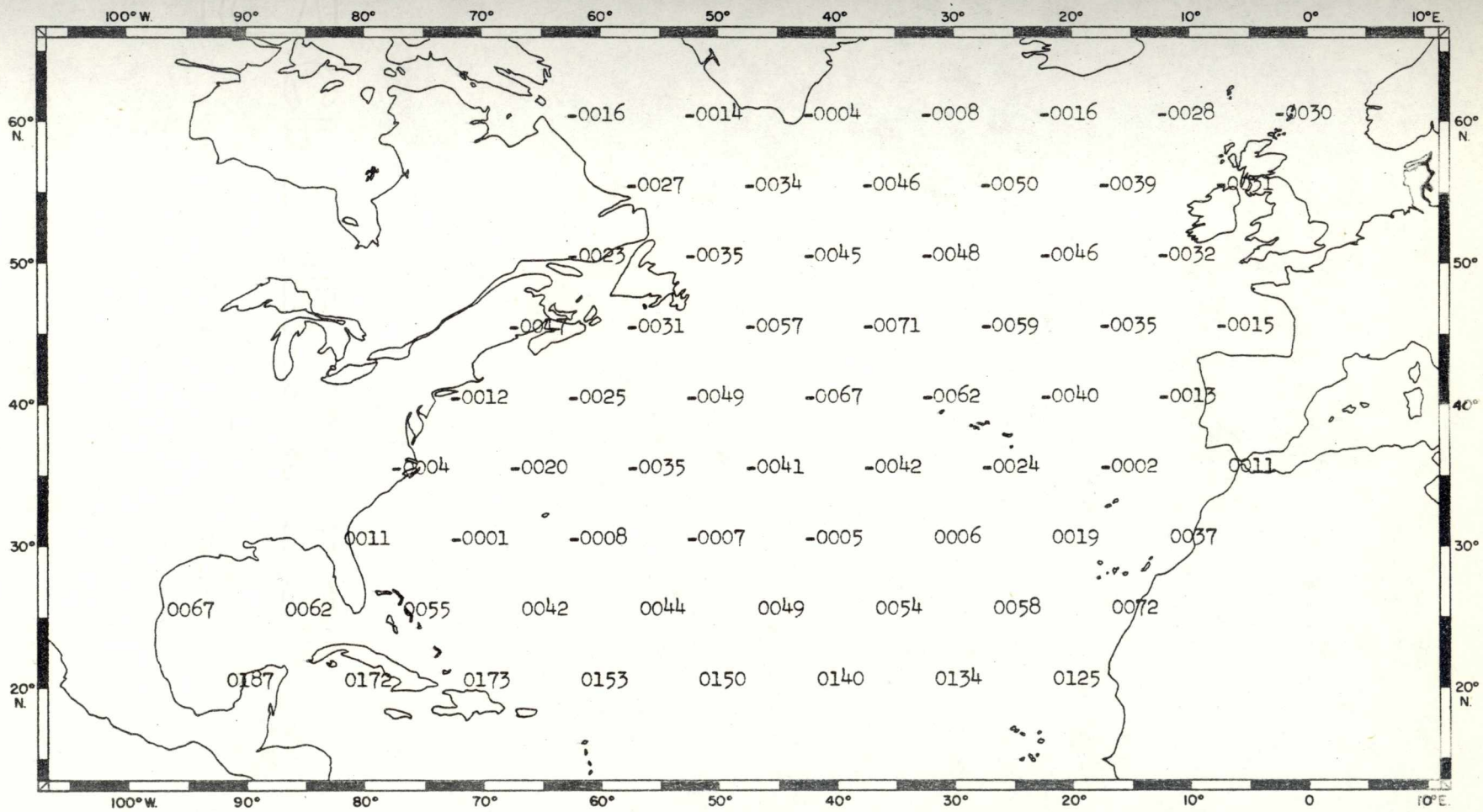
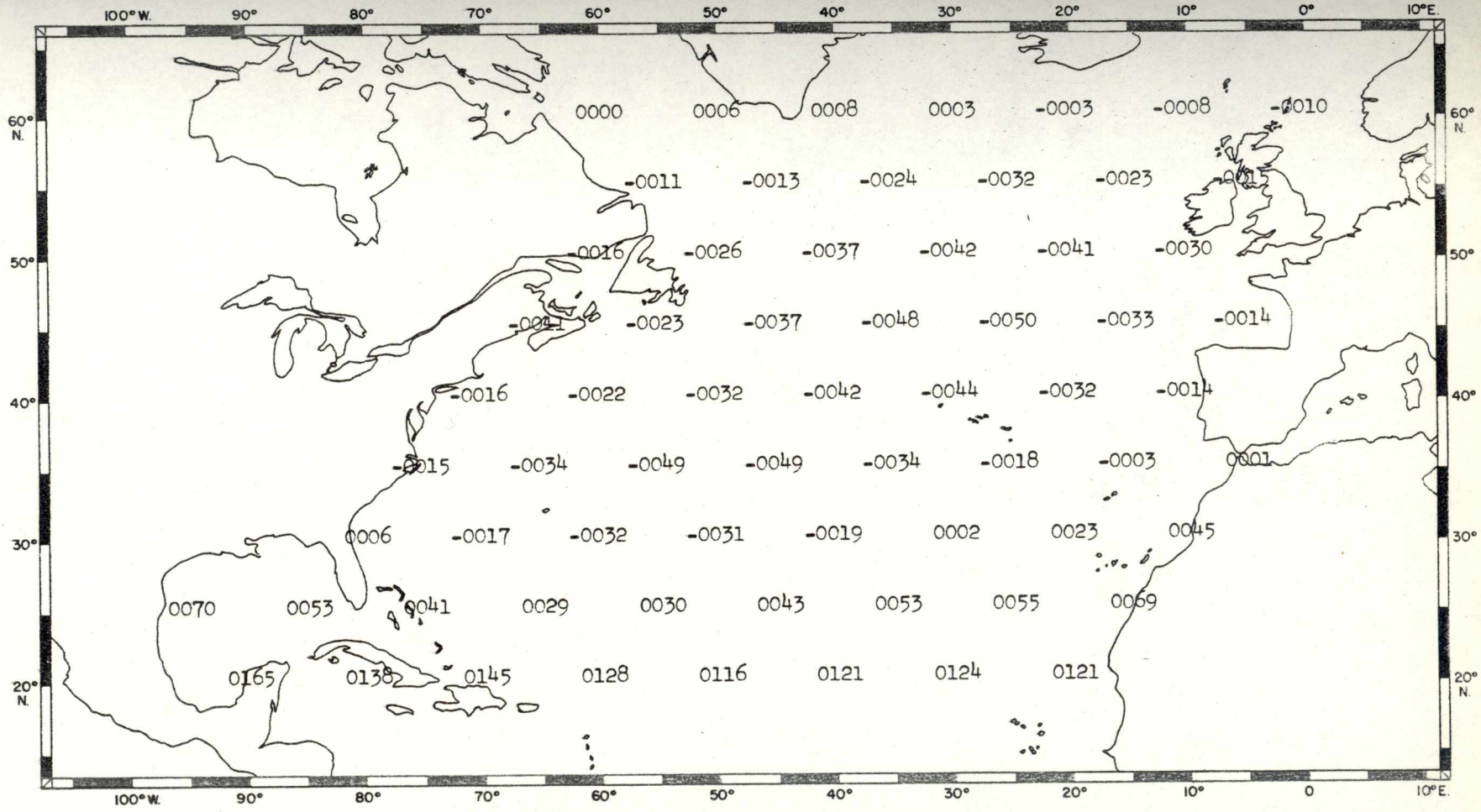
2m Mar 29 Apr 27 1957



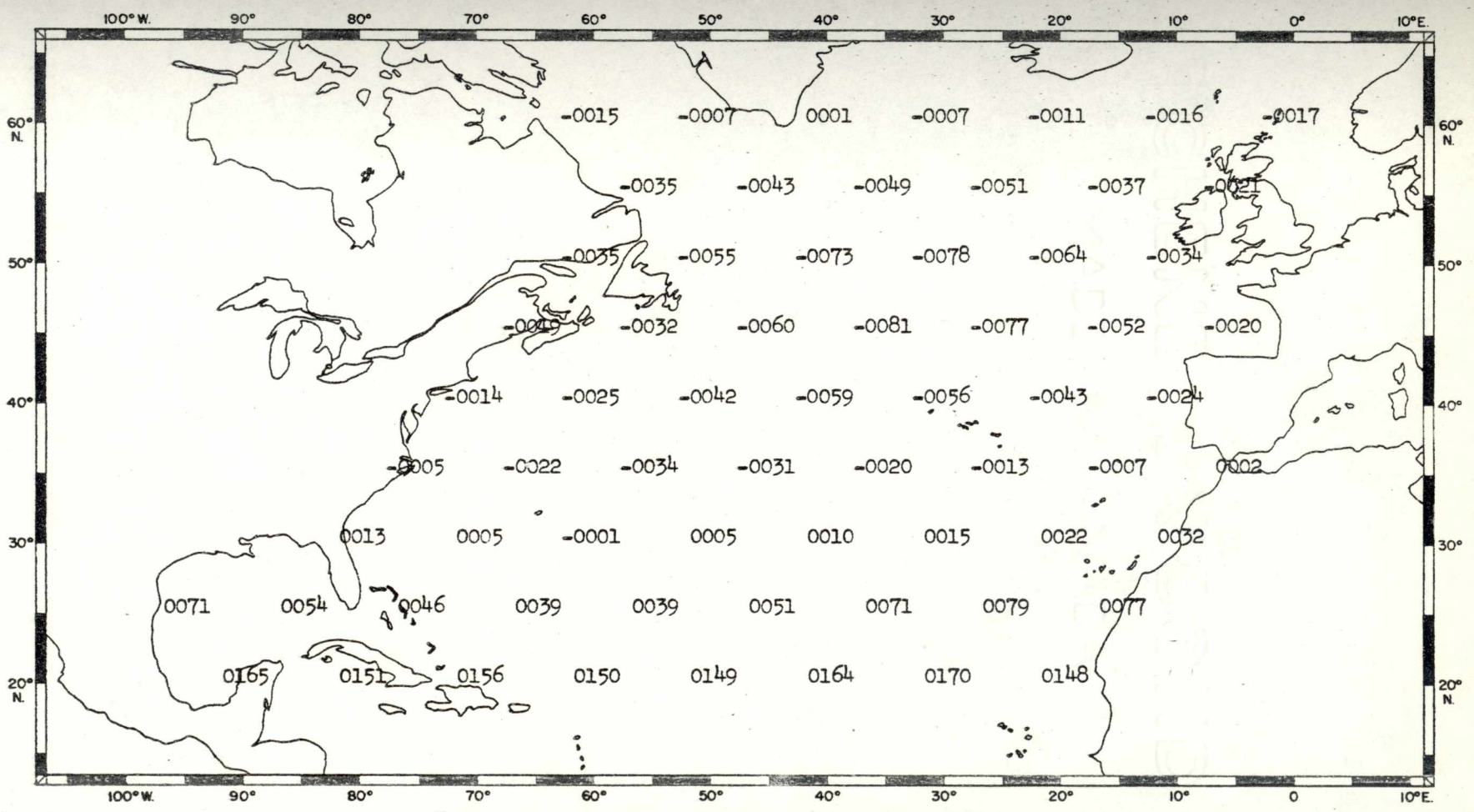
II. Meridional Component of Ekman Transport ANNUAL MEAN 1957

2m Nov 30 De 29 1958

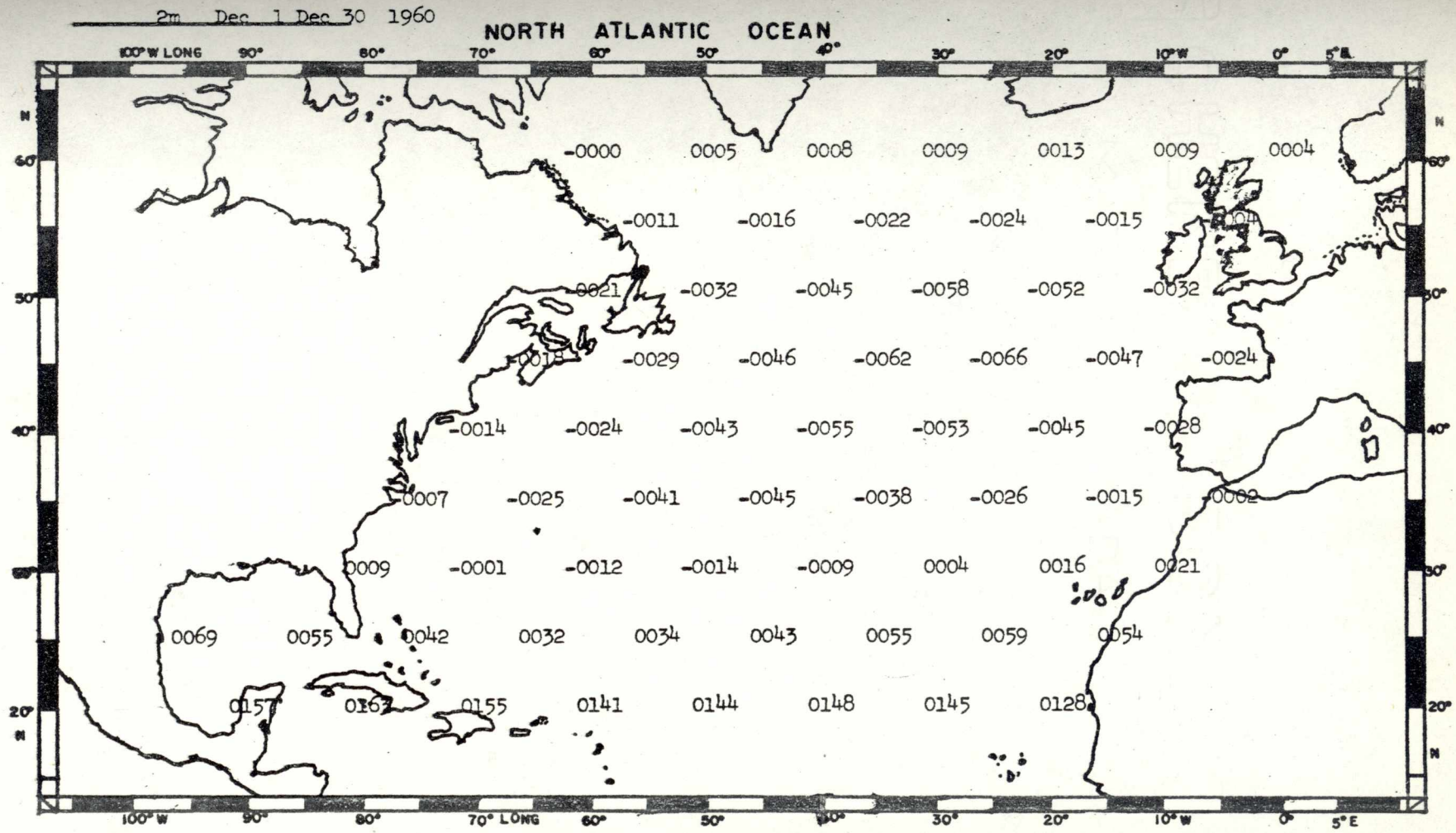


II. Meridional Component of Ekman Transport ANNUAL MEAN 1958

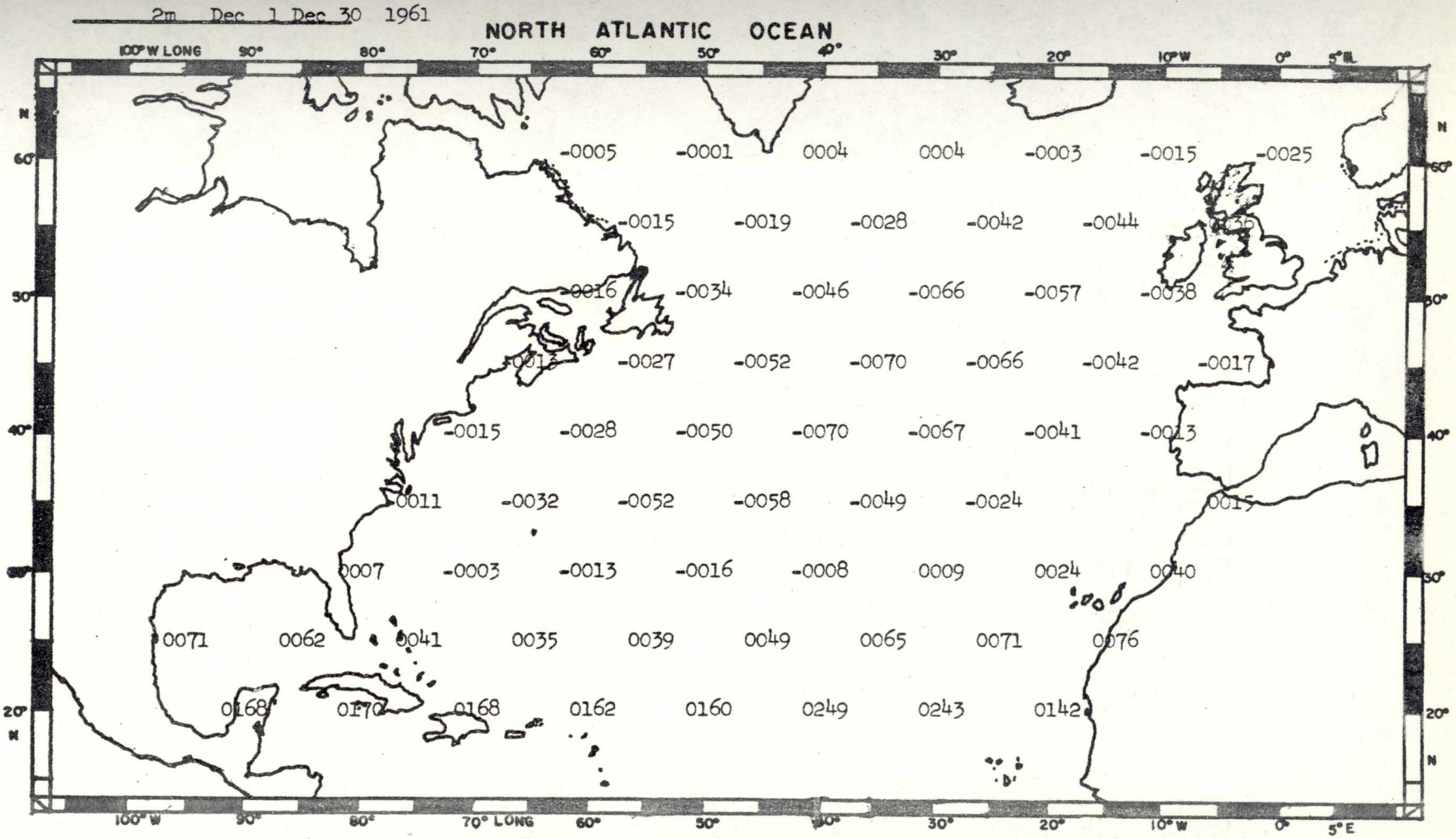
2m Nov 29 Dec 28 1959



II. Meridional Component of Ekman Transport ANNUAL MEAN 1959

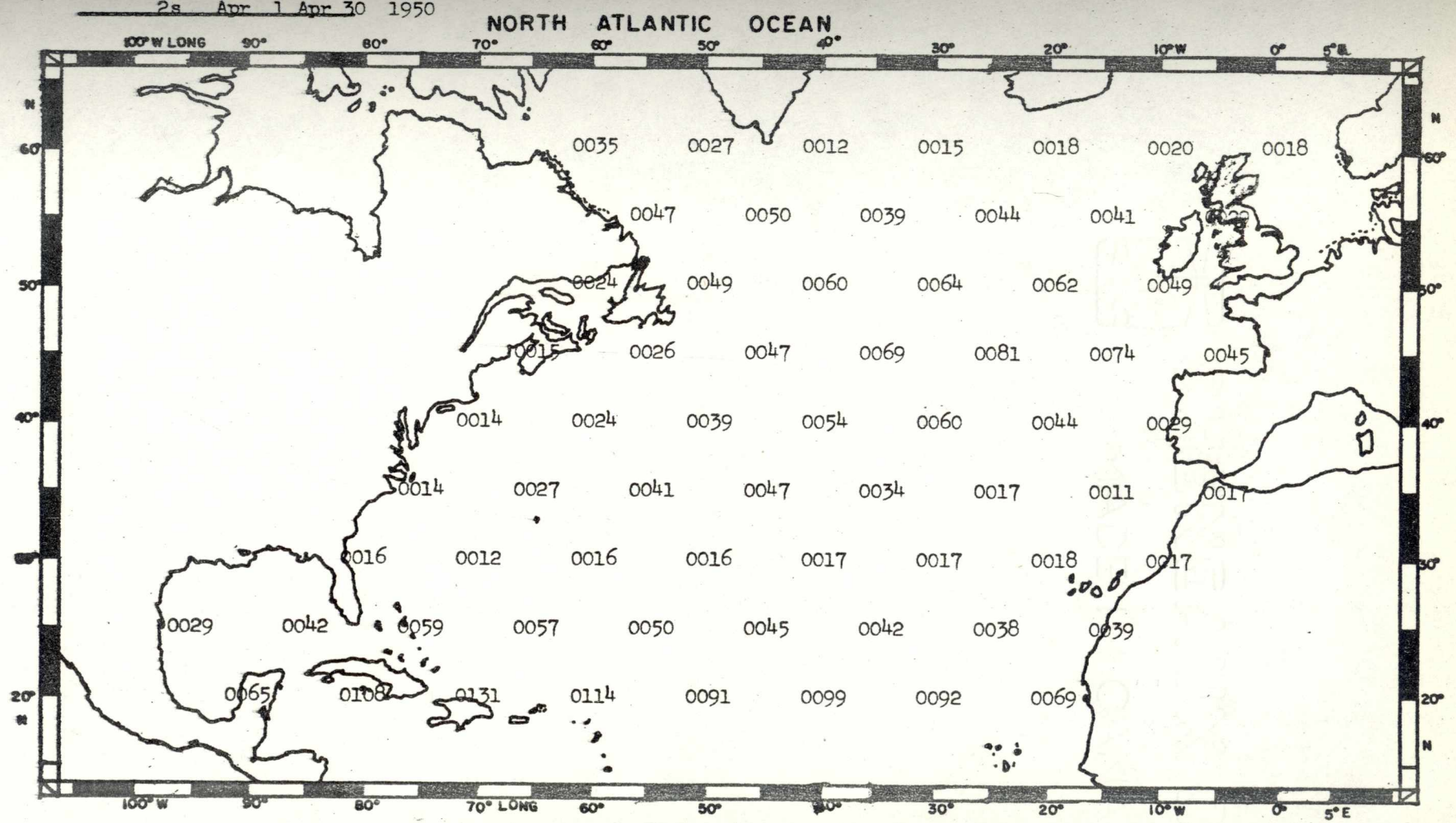


II. Meridional Component of Ekman Transport ANNUAL MEAN 1960



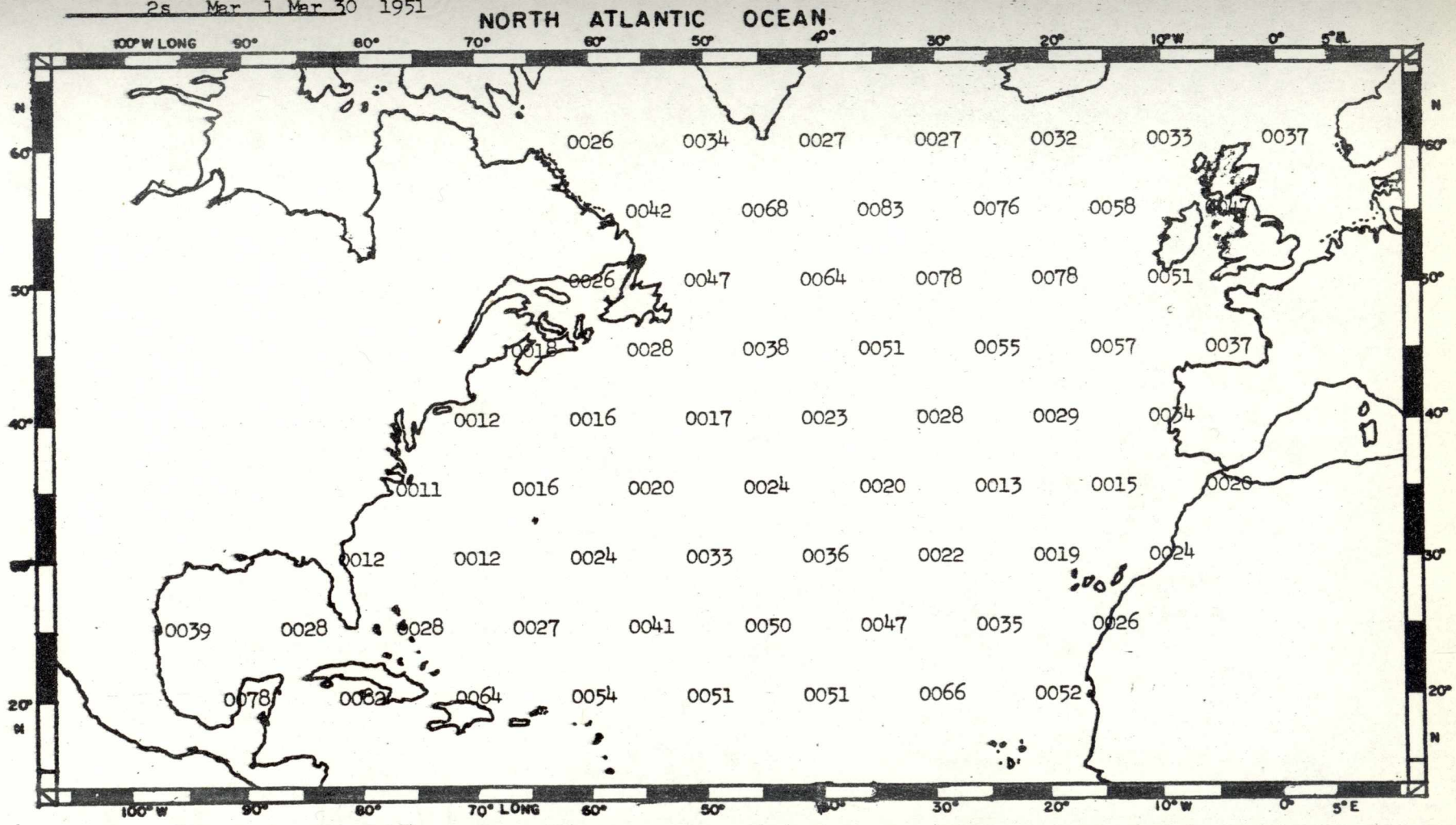
II. Meridional Component of Ekman Transport ANNUAL MEAN 1961

2s Apr 1 Apr 30 1950



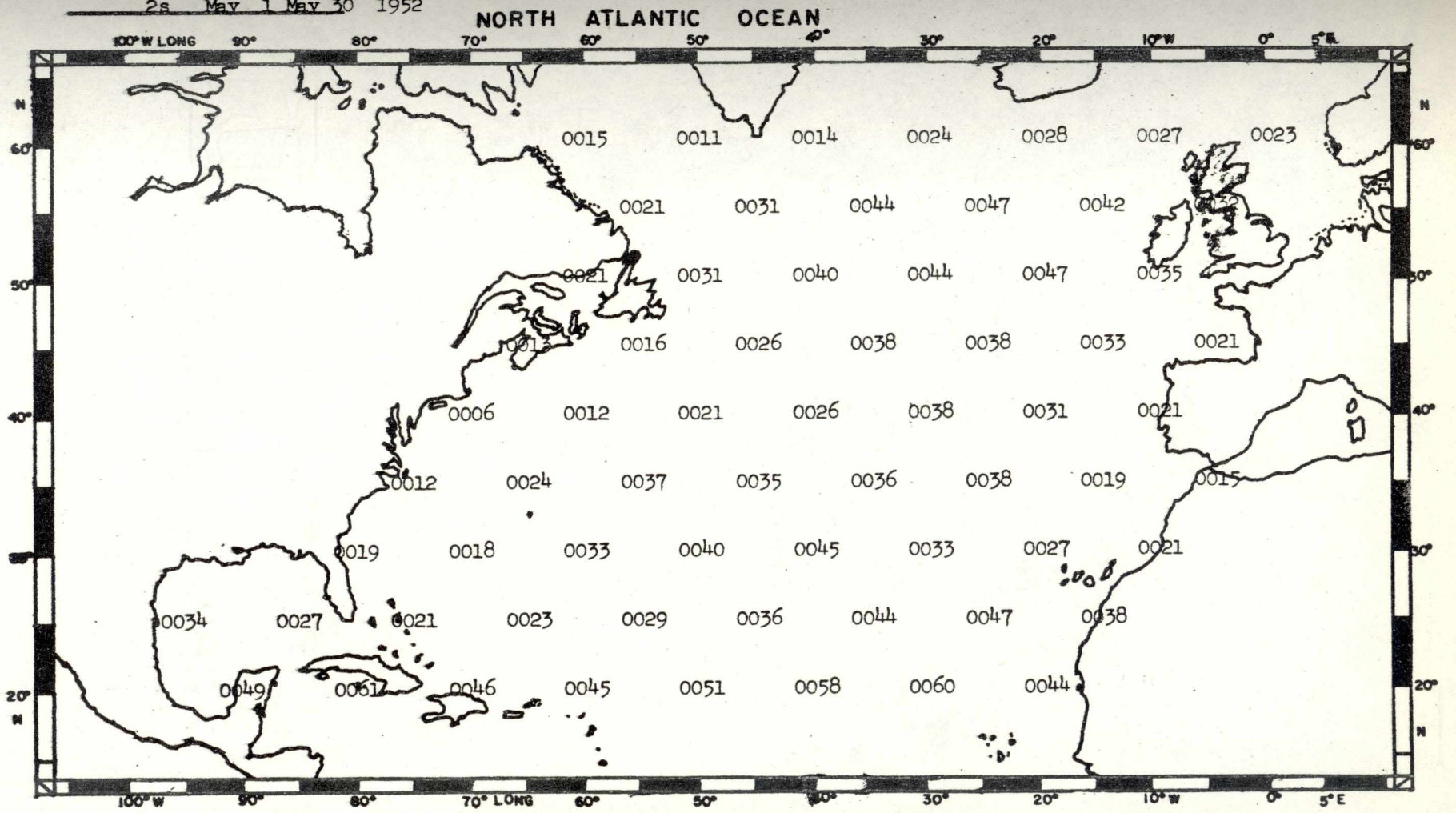
II. Meridional Component of Ekman Transport STANDARD DEVIATION 1950

2s Mar 1 Mar 30 1951



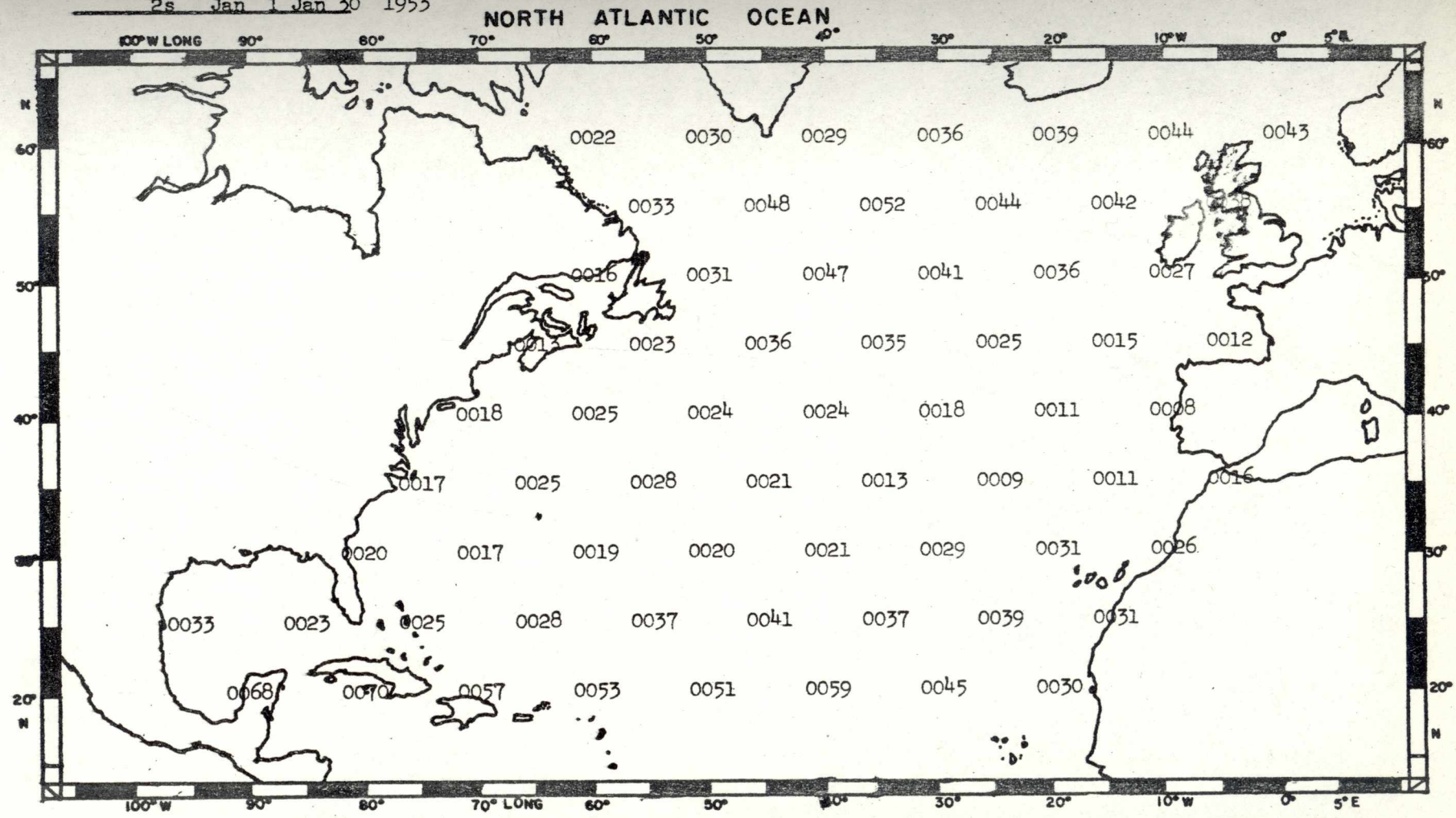
II. Meridional Component of Ekman Transport STANDARD DEVIATION 1951

2s May 1 May 30 1952



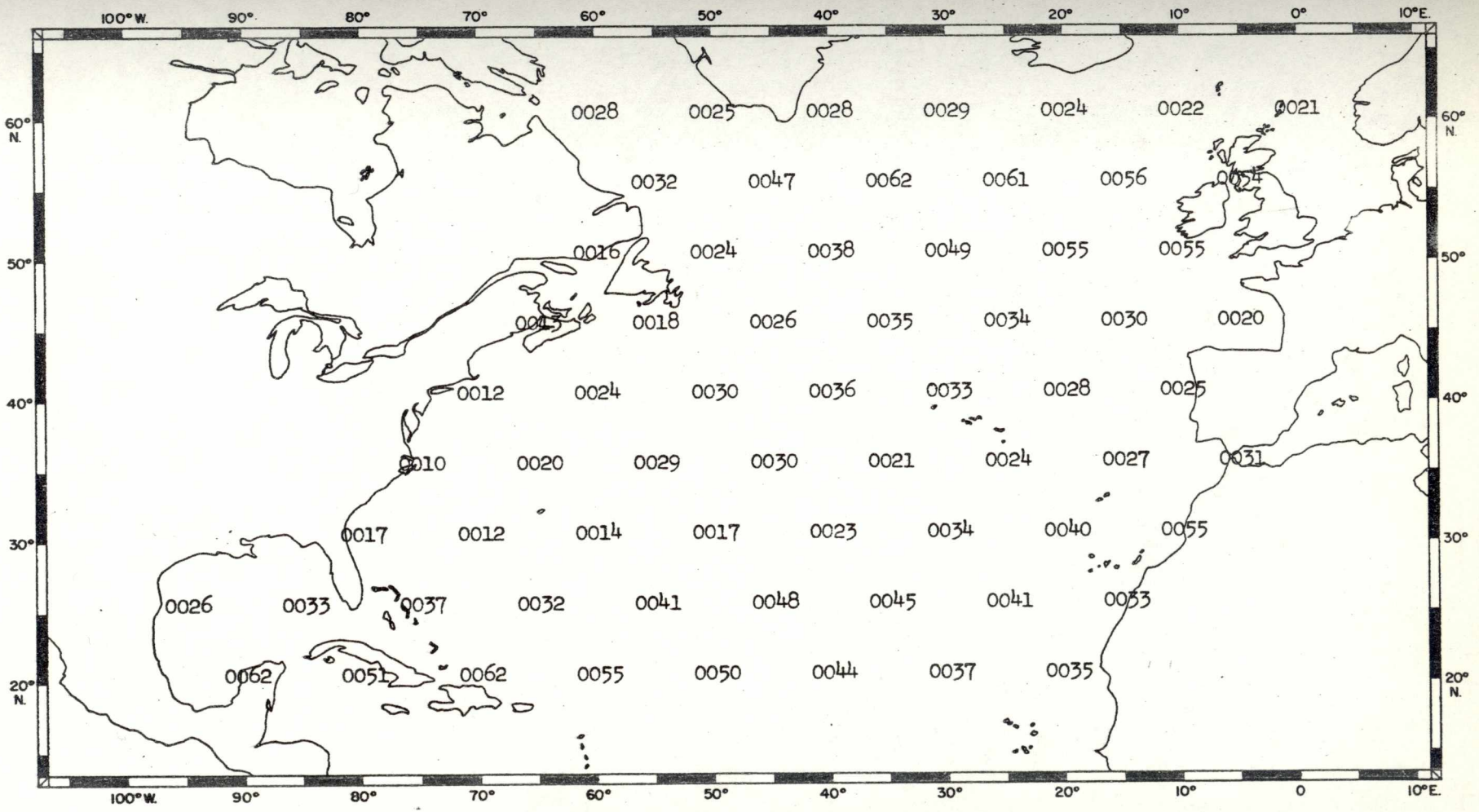
II. Meridional Component of Ekman Transport STANDARD DEVIATION 1952

2s Jan 1 Jan 30 1953



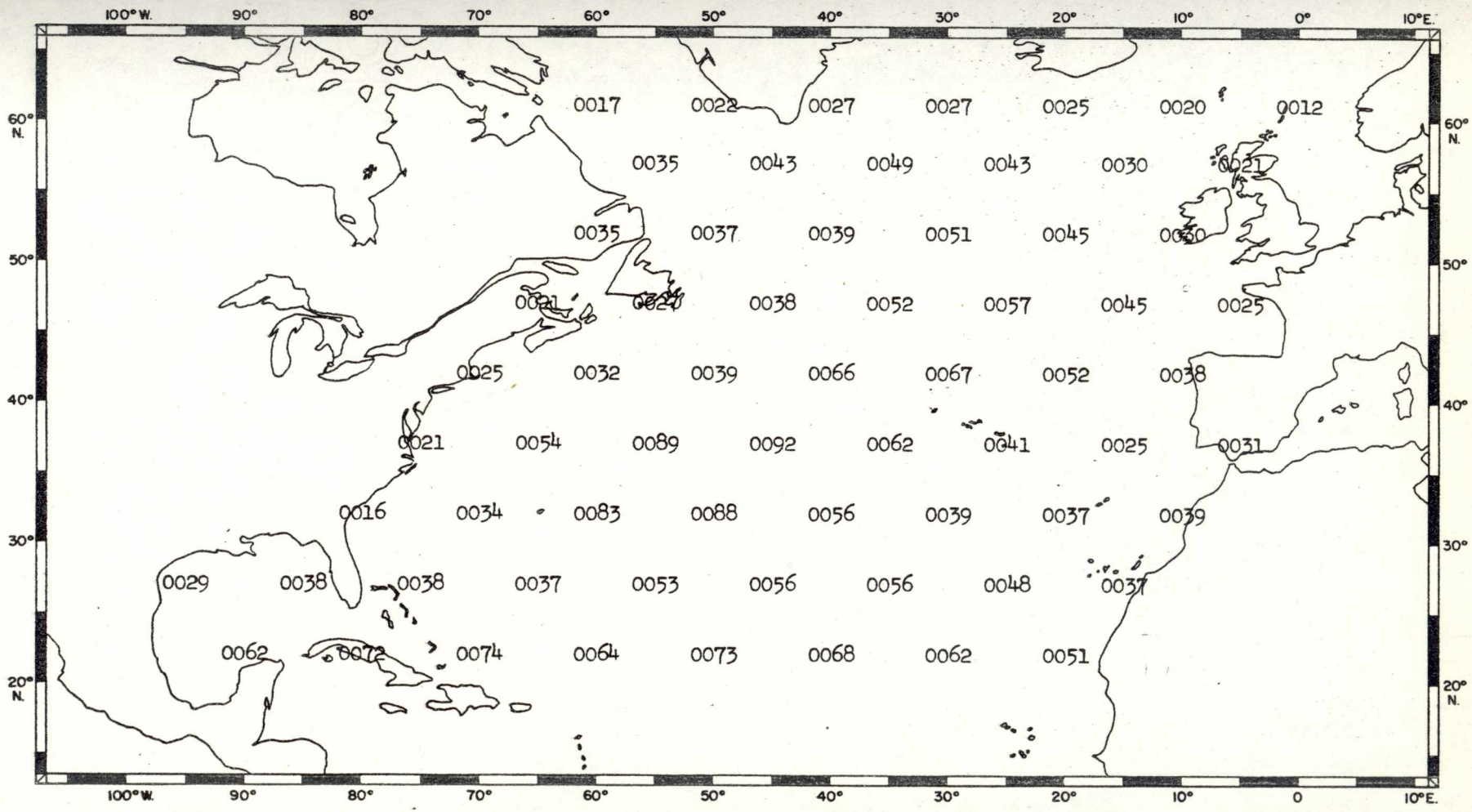
II. Meridional Component of Ekman Transport STANDARD DEVIATION 1953

2s Sep 1 Sep 30 1954



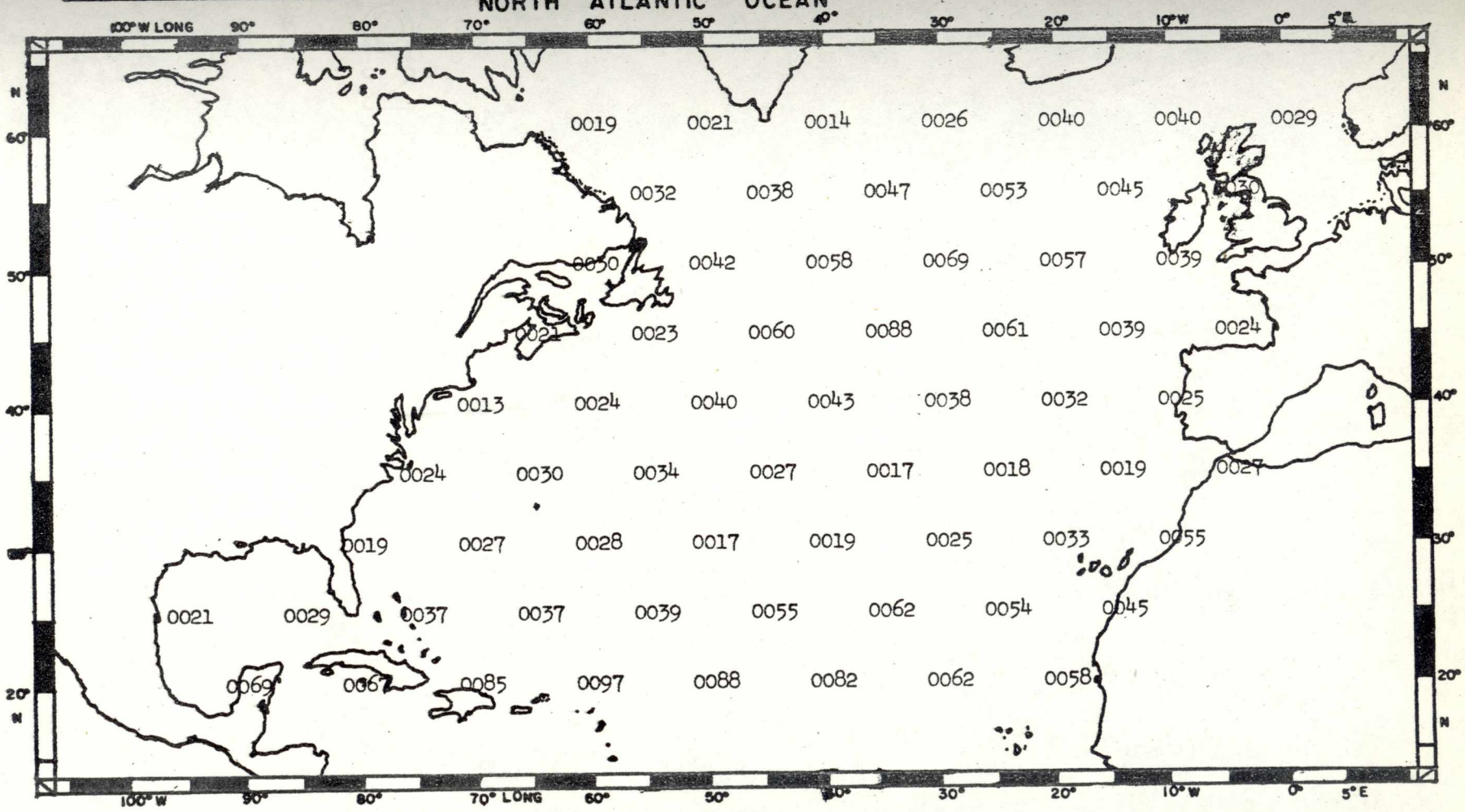
II. Meridional Component of Ekman Transport STANDARD DEVIATION 1954

2s Mar 29 Apr 27 1955



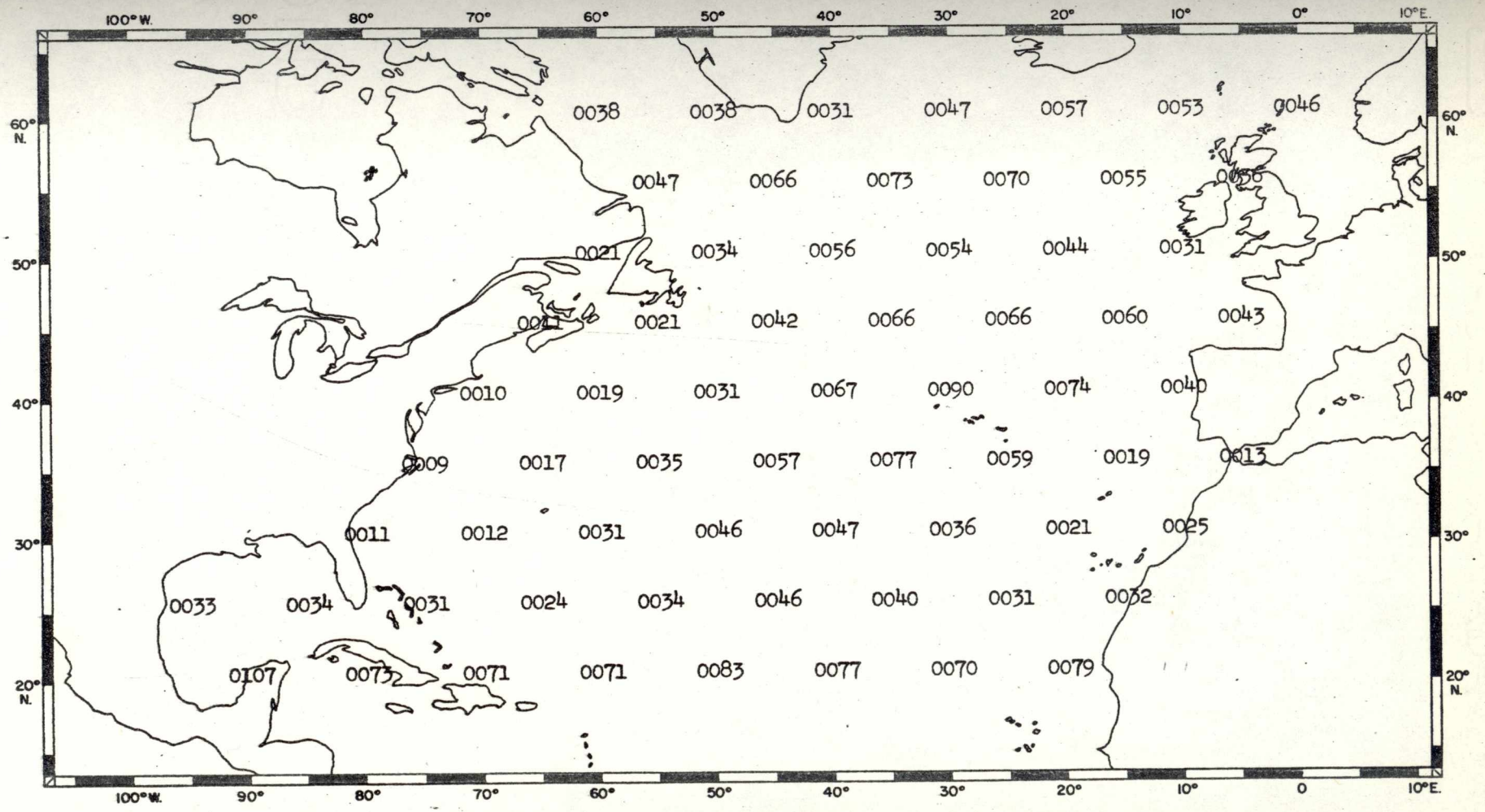
II. Meridional Component of Ekman Transport STANDARD DEVIATION 1955

2s Dec 2 Dec 31 1956



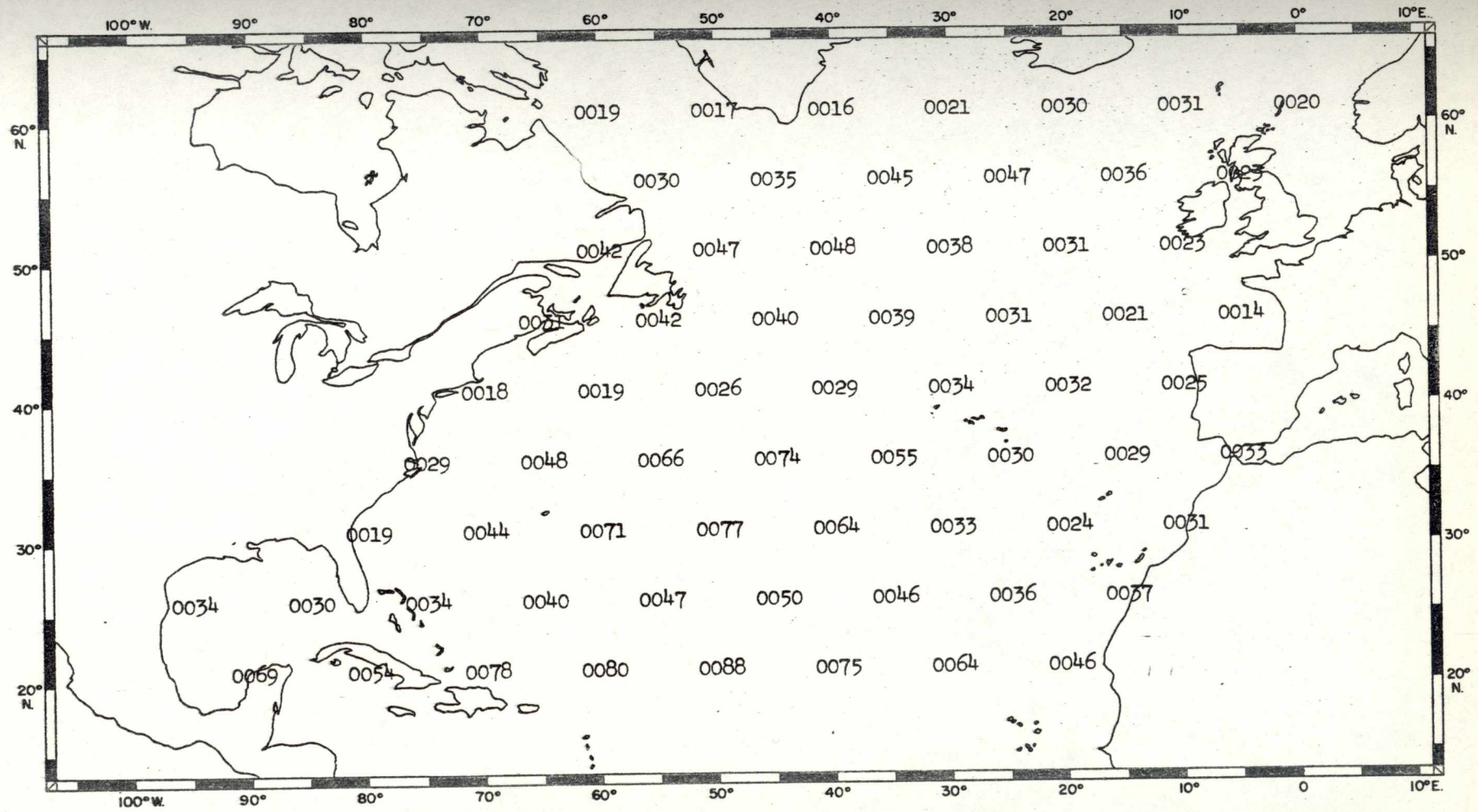
II. Meridional Component of Ekman Transport STANDARD DEVIATION 1956

2s Mar 29 Apr 27 1957



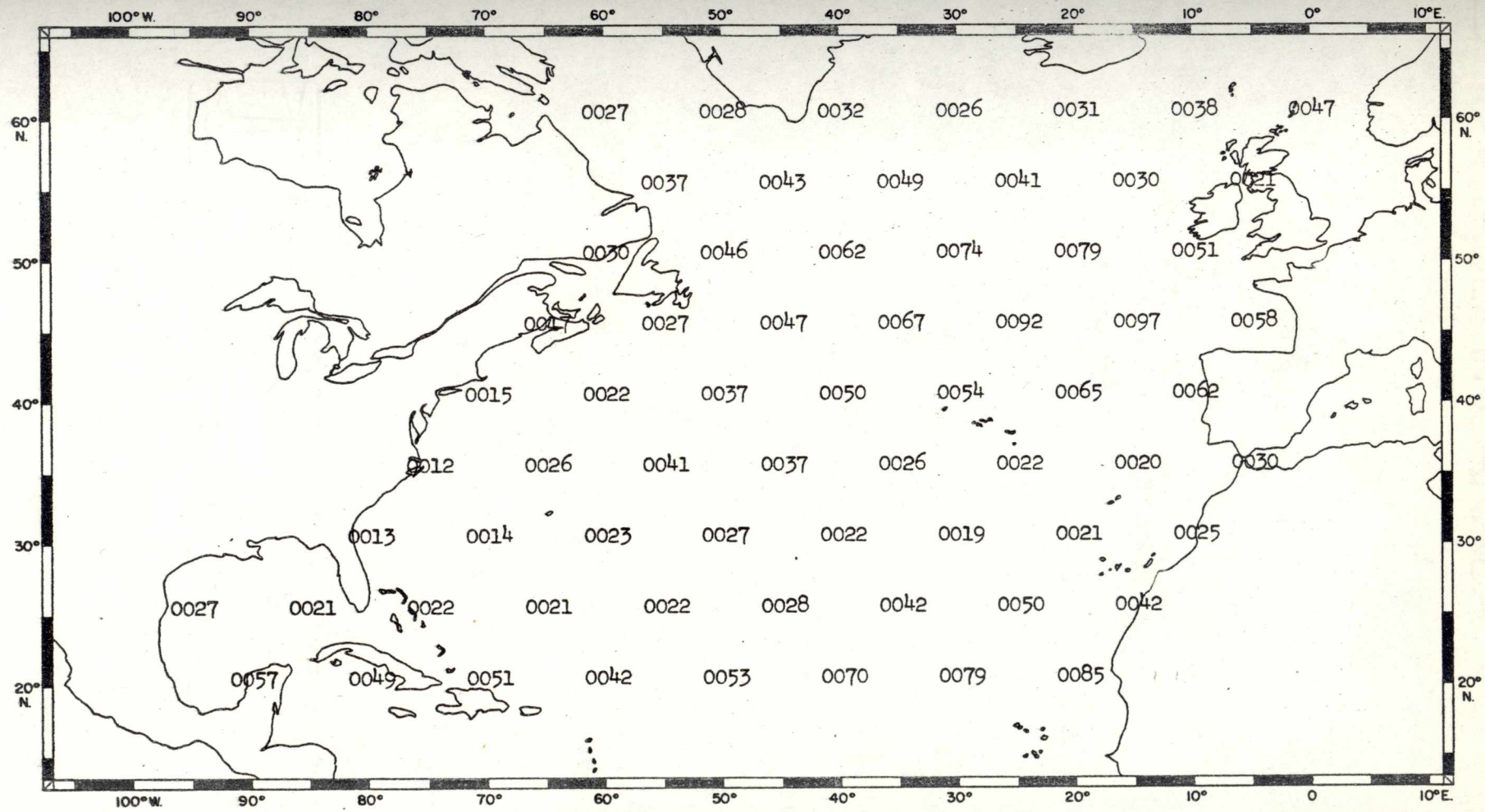
II. Meridional Component of Ekman Transport STANDARD DEVIATION 1957

2s Nov 30 De 29 1958



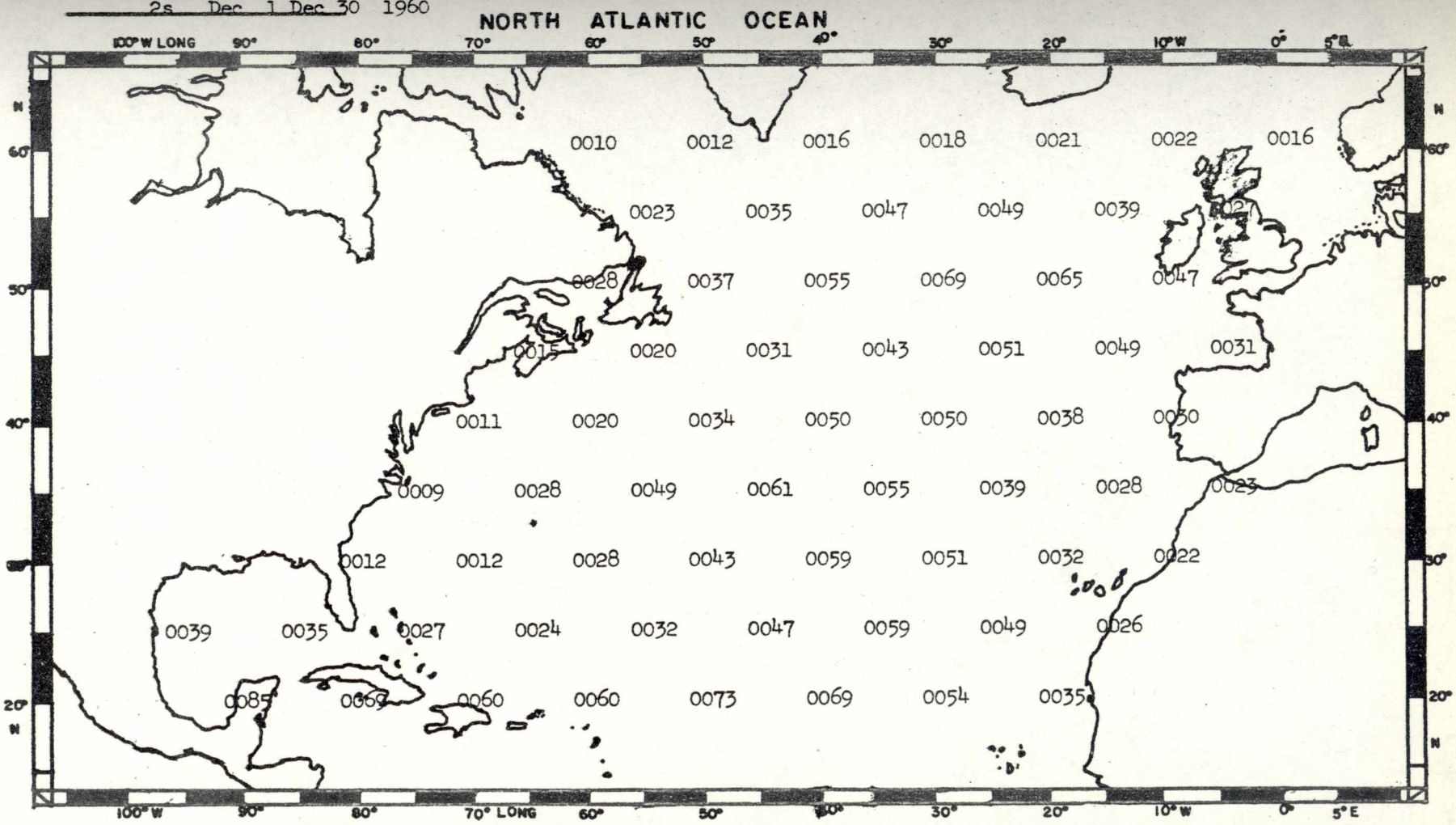
II. Meridional Component of Ekman Transport STANDARD DEVIATION 1958

2s Nov 29 Dec 28 1959



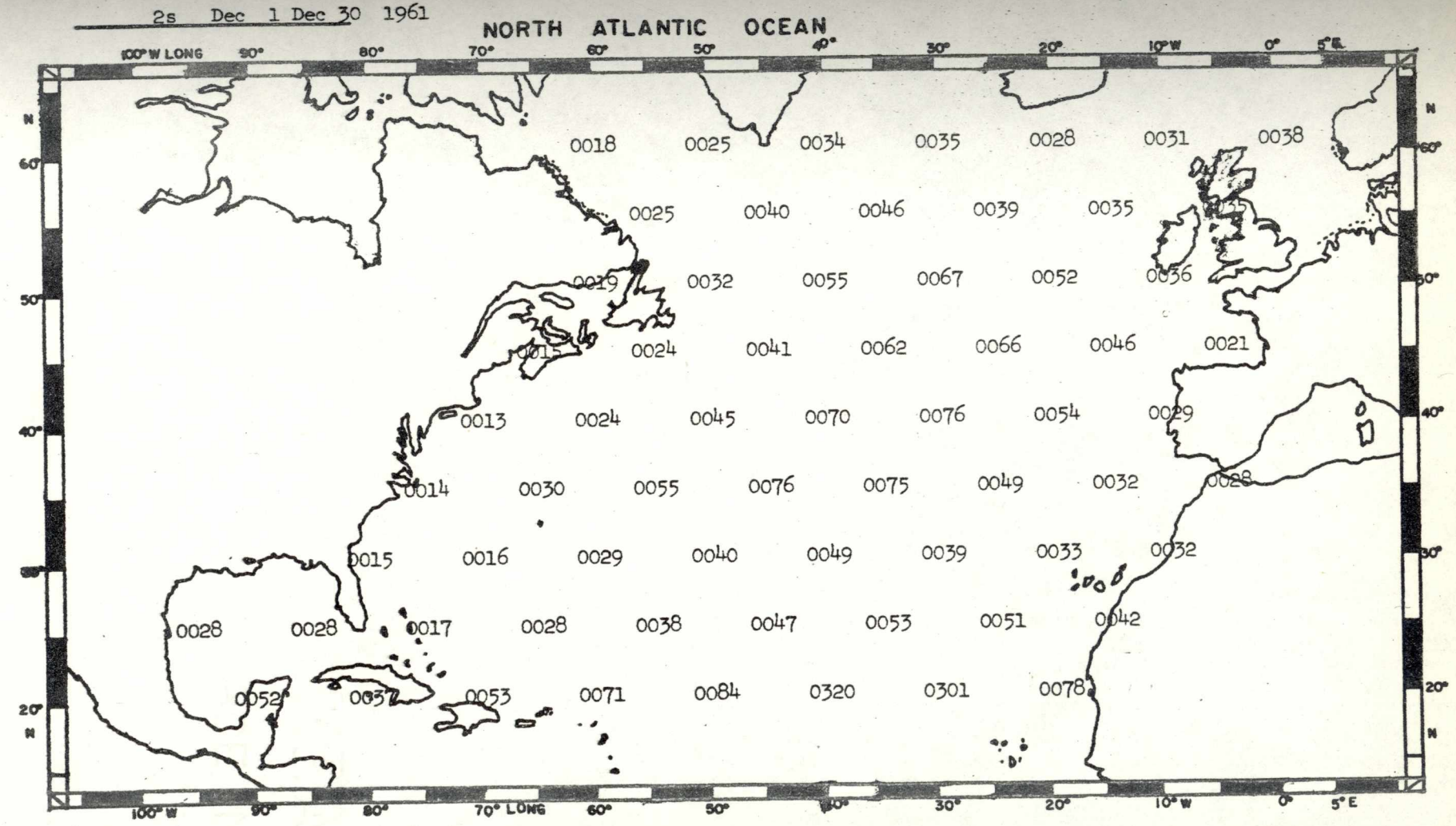
II. Meridional Component of Ekman Transport STANDARD DEVIATION 1959

2s Dec 1 Dec 30 1960



II. Meridional Component of Ekman Transport

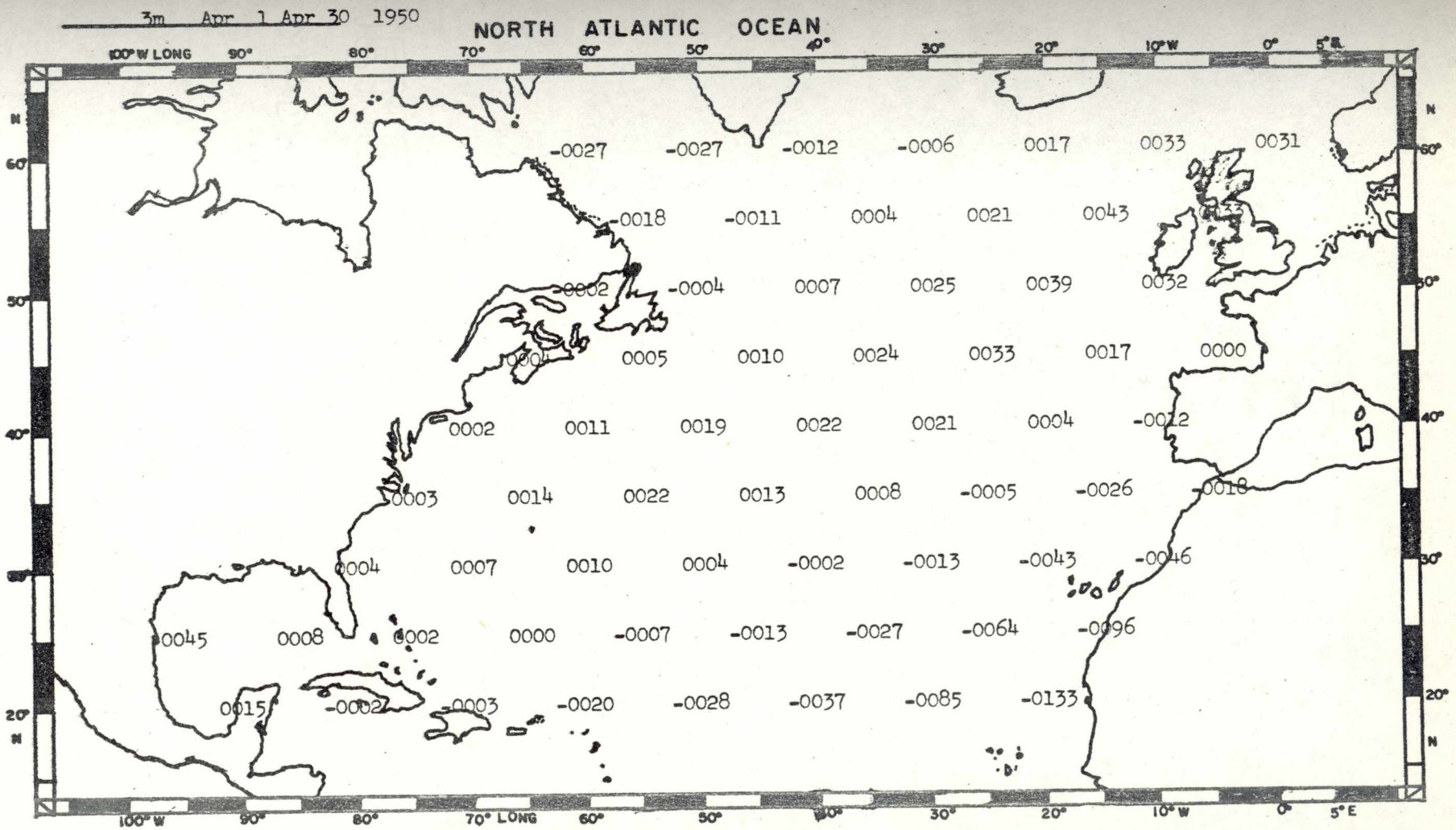
STANDARD DEVIATION 1960



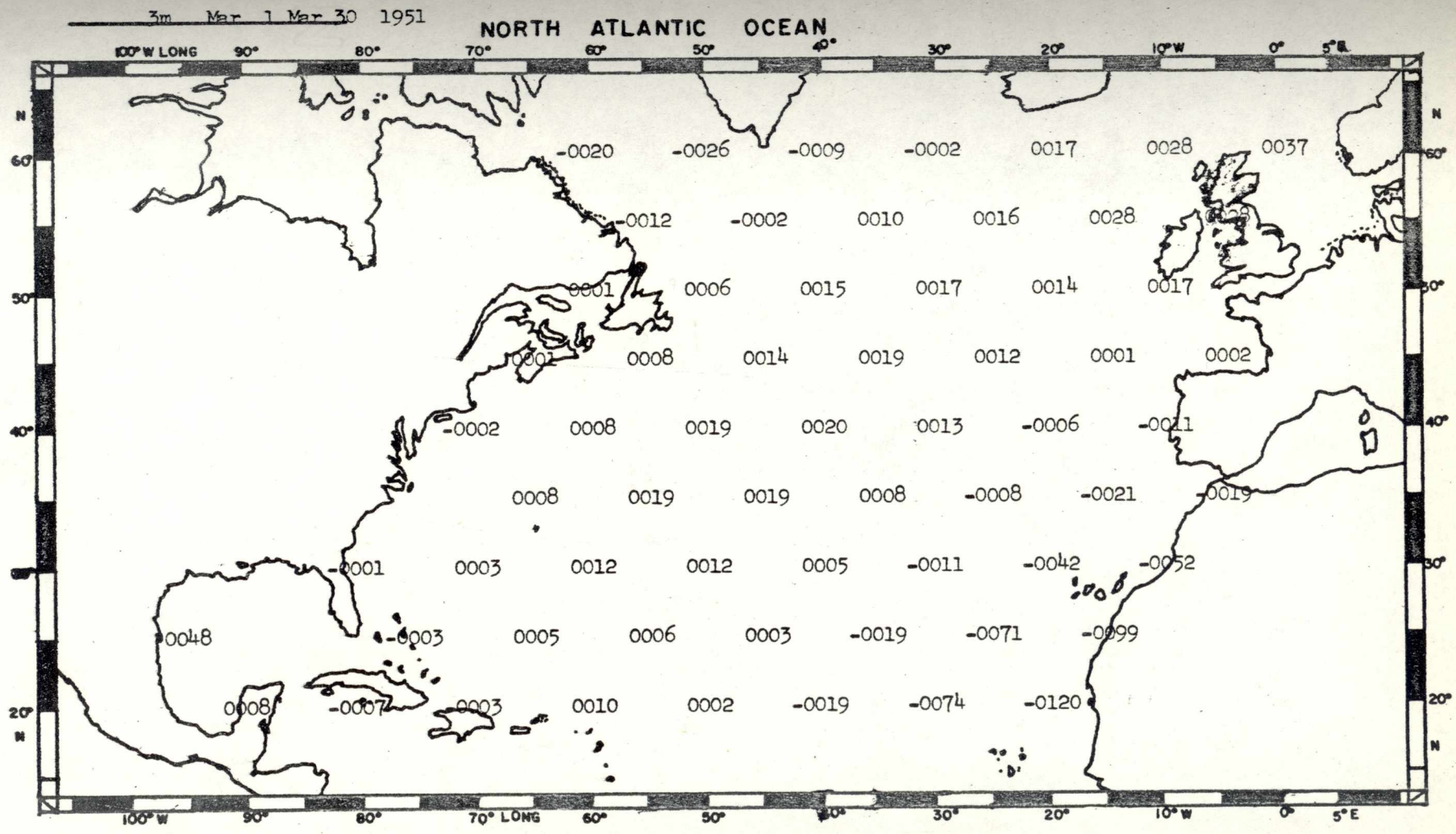
II. Meridional Component of Ekman Transport STANDARD DEVIATION 1961

Section III

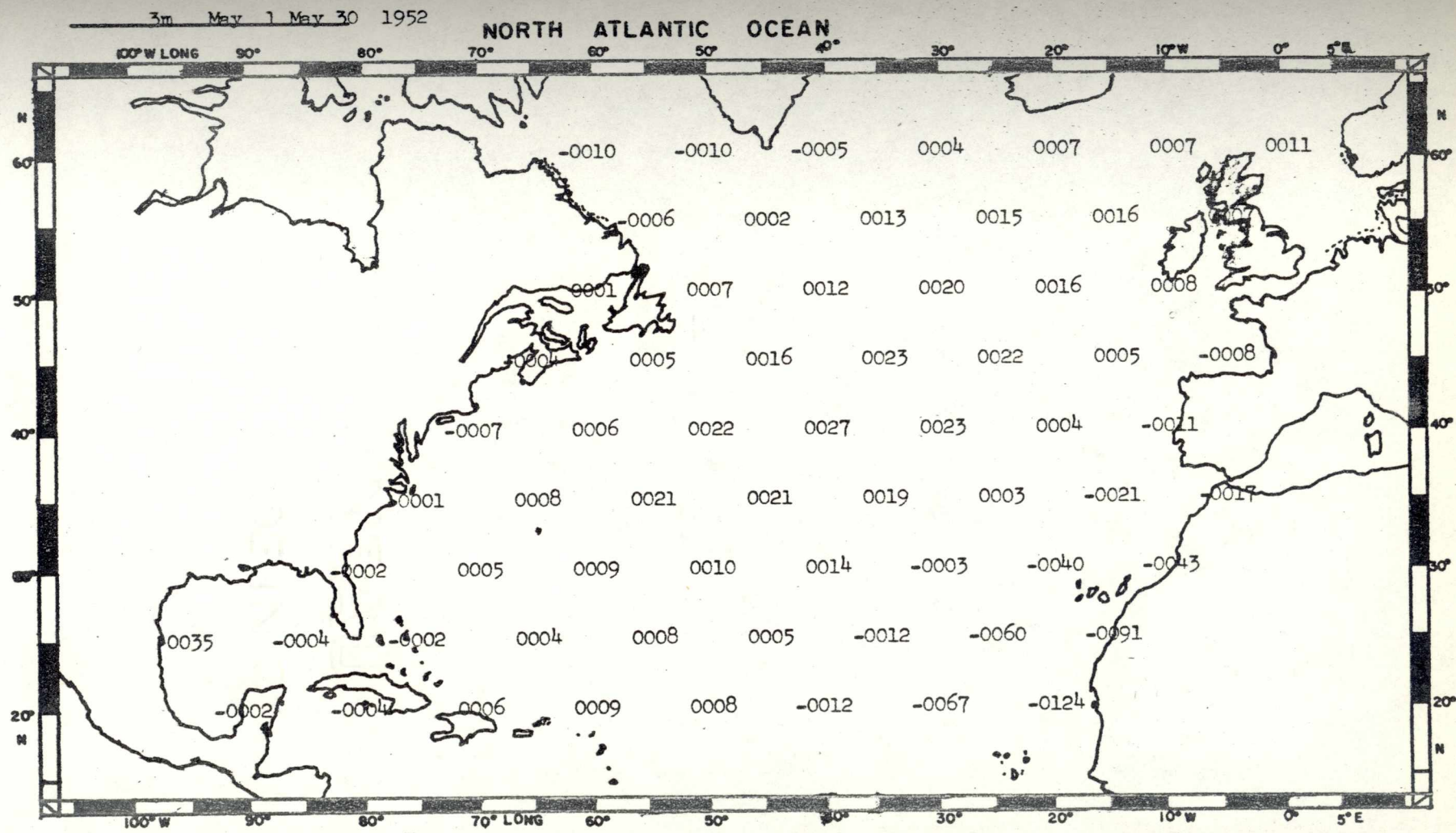
Zonal Component of Ekman Transport



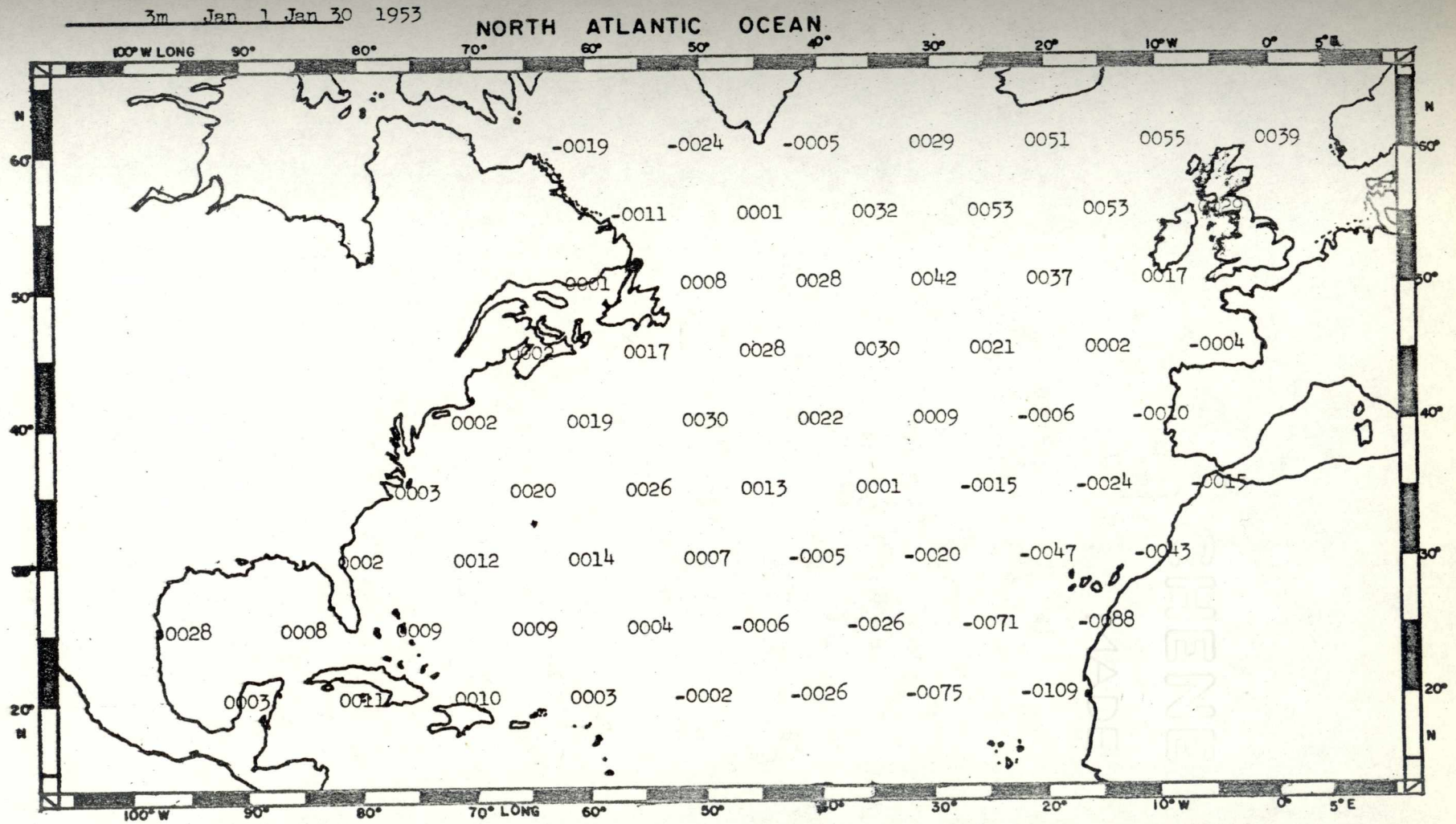
III. Zonal Component of Ekman Transport ANNUAL MEAN 1950



III. Zonal Component of Ekman Transport ANNUAL MEAN 1951



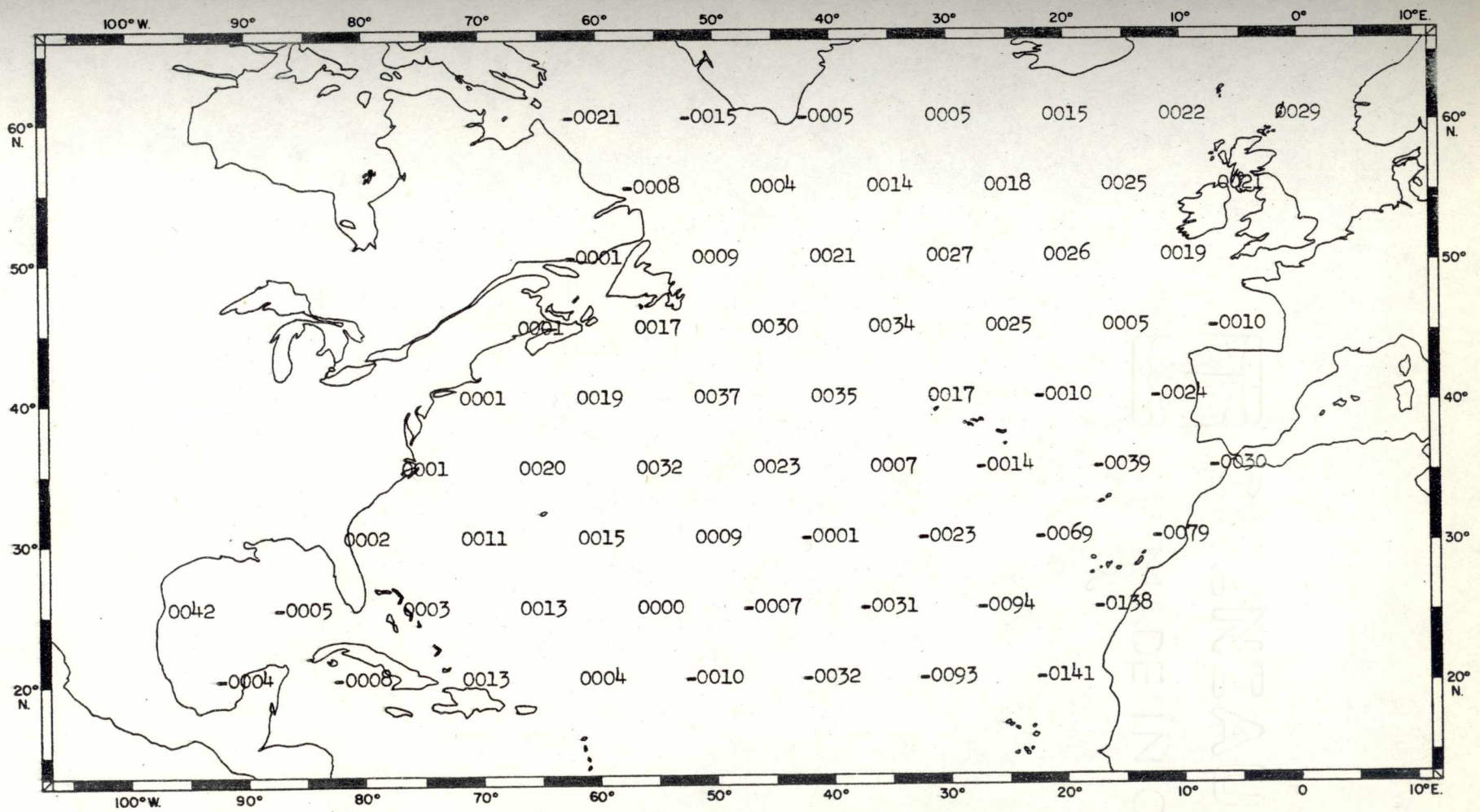
III. Zonal Component of Ekman Transport ANNUAL MEAN 1952



III. Zonal Component of Ekman Transport

ANNUAL MEAN 1953

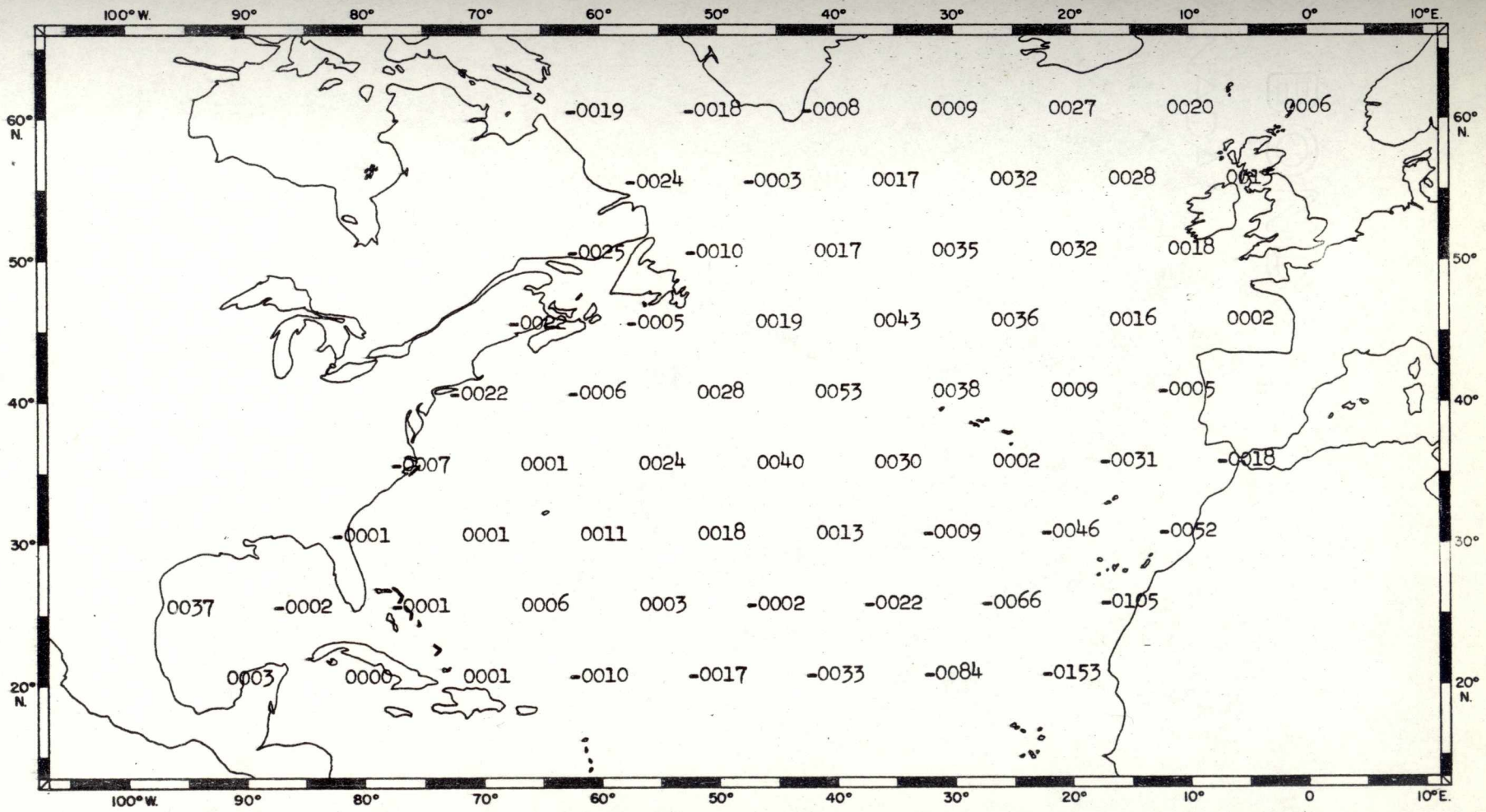
3m Sep 1 Sep 30 1954



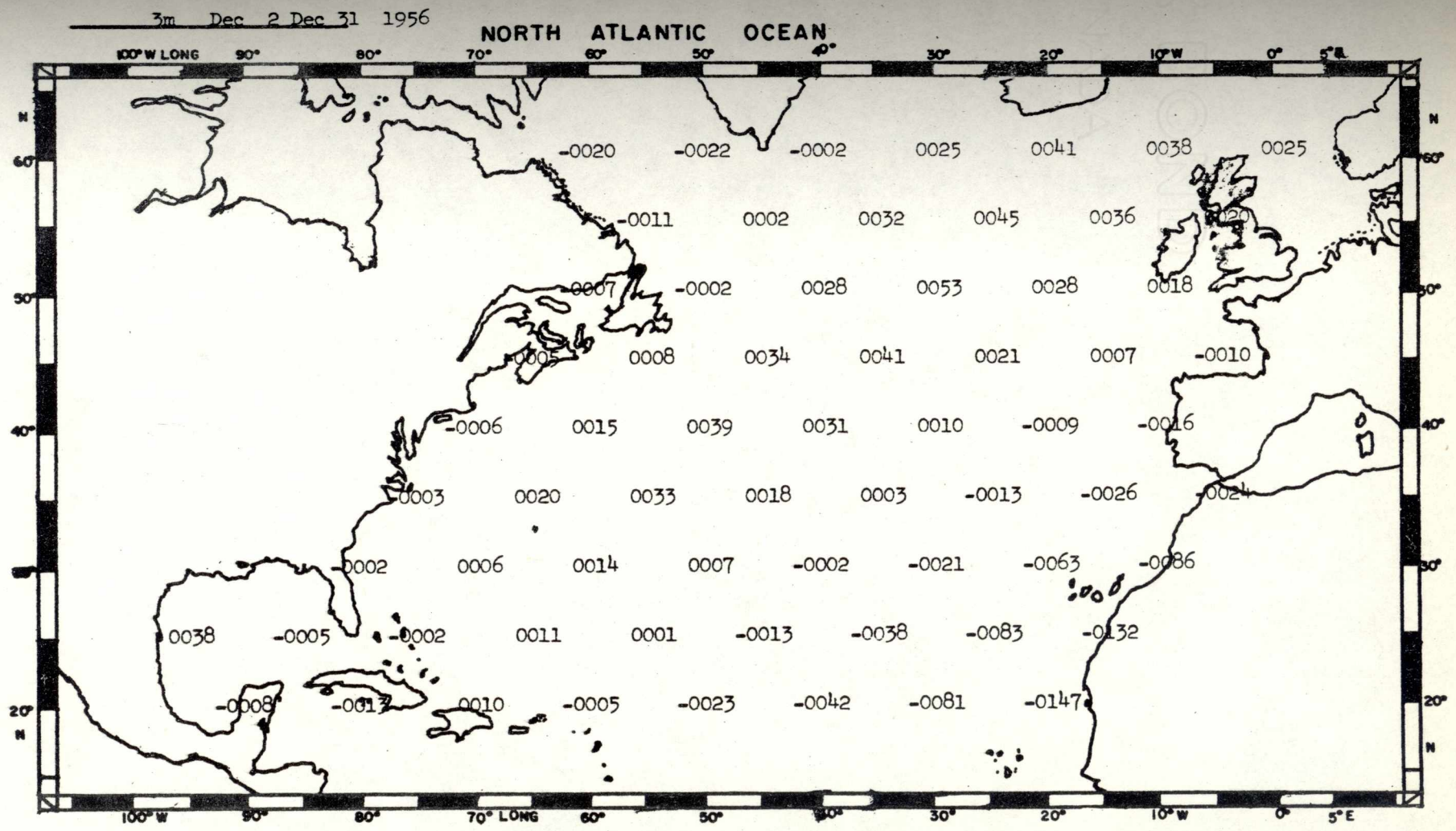
III. Zonal Component of Ekman Transport

ANNUAL MEAN 1954

3m Mar 29 Apr 27 1955

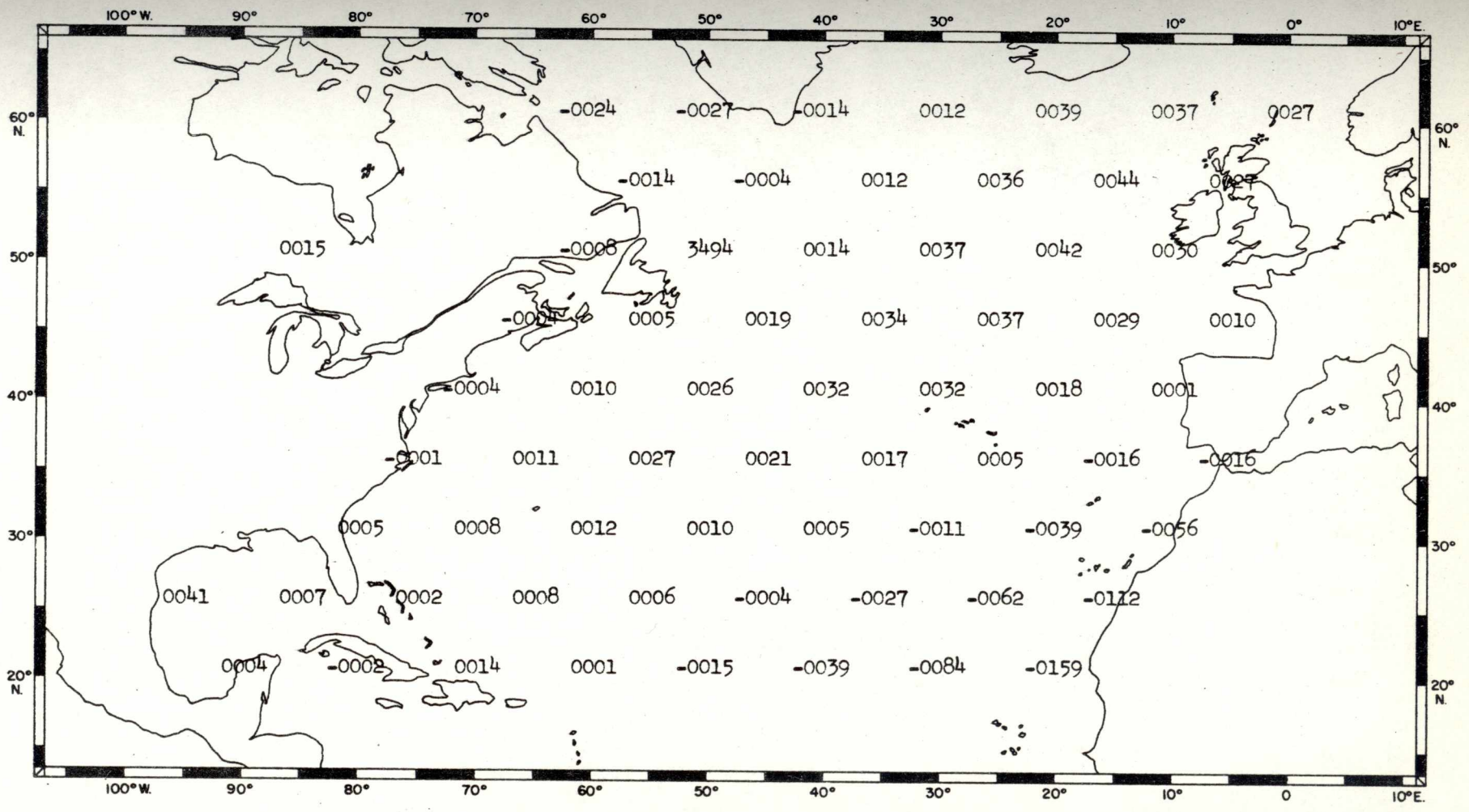


III. Zonal Component of Ekman Transport ANNUAL MEAN 1955



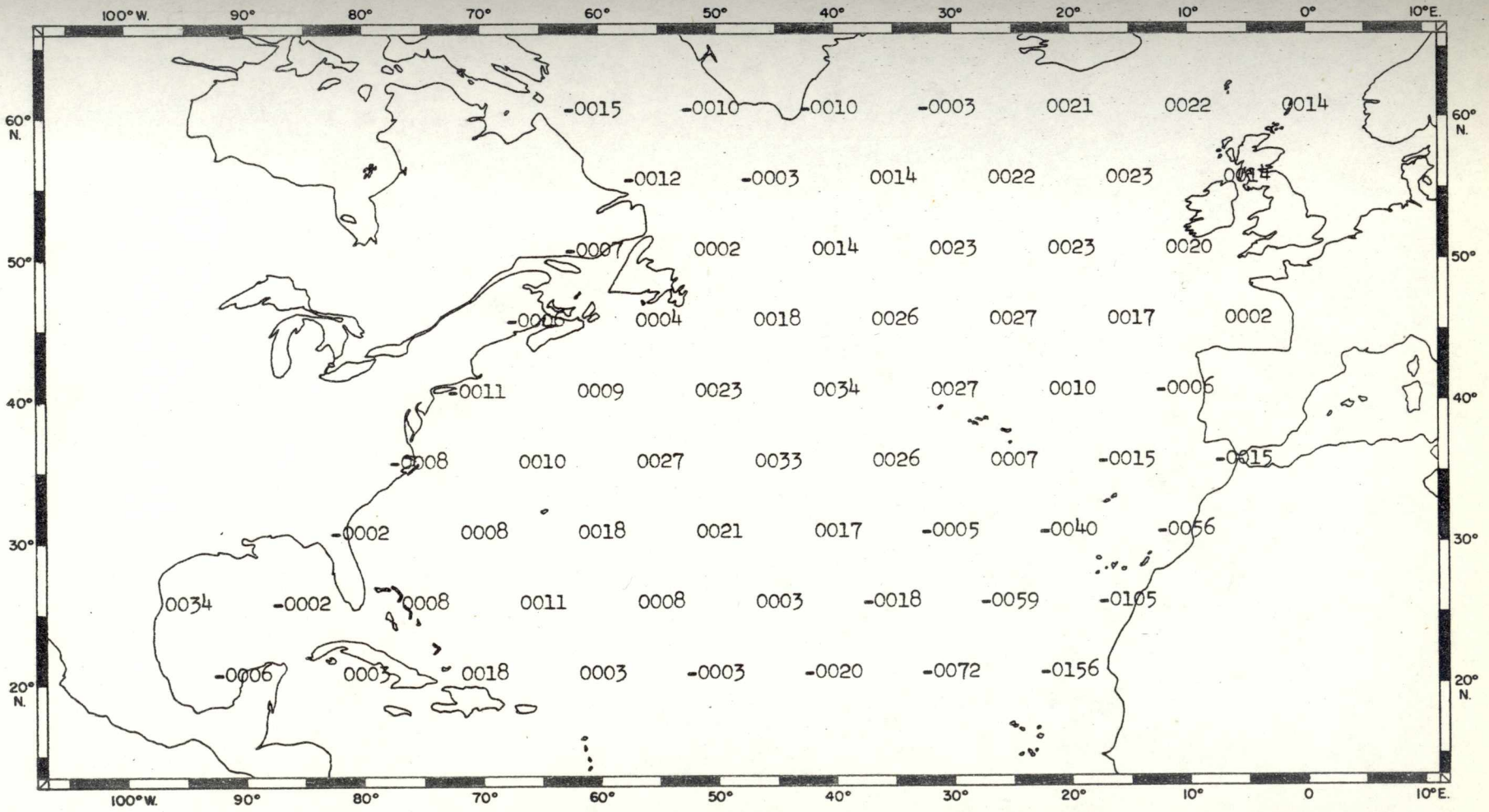
III. Zonal Component of Ekman Transport ANNUAL MEAN 1956

3m Mar 29 Apr 27 1957



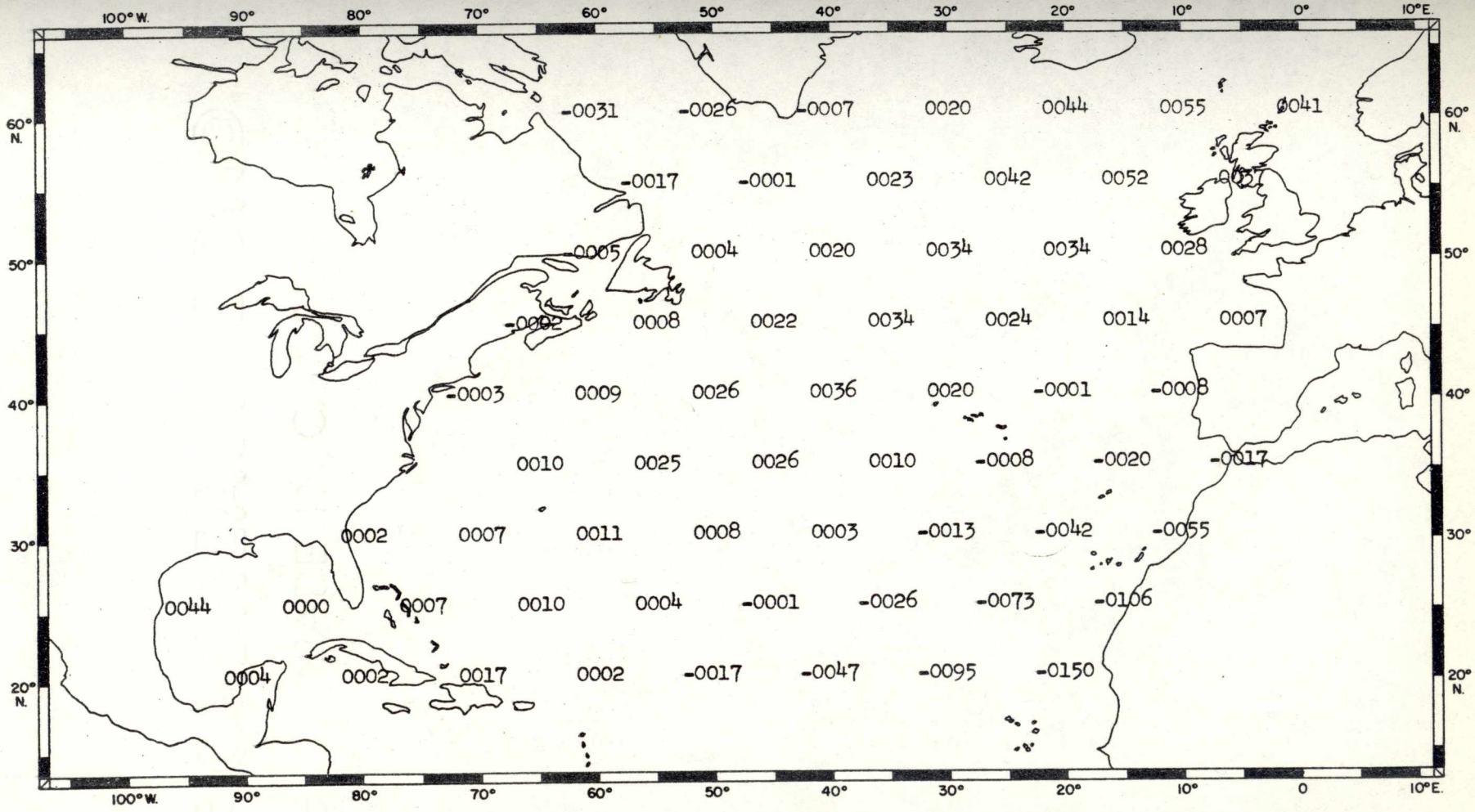
III. Zonal Component of Ekman Transport ANNUAL MEAN 1957

3m Nov 30 De 29 1958

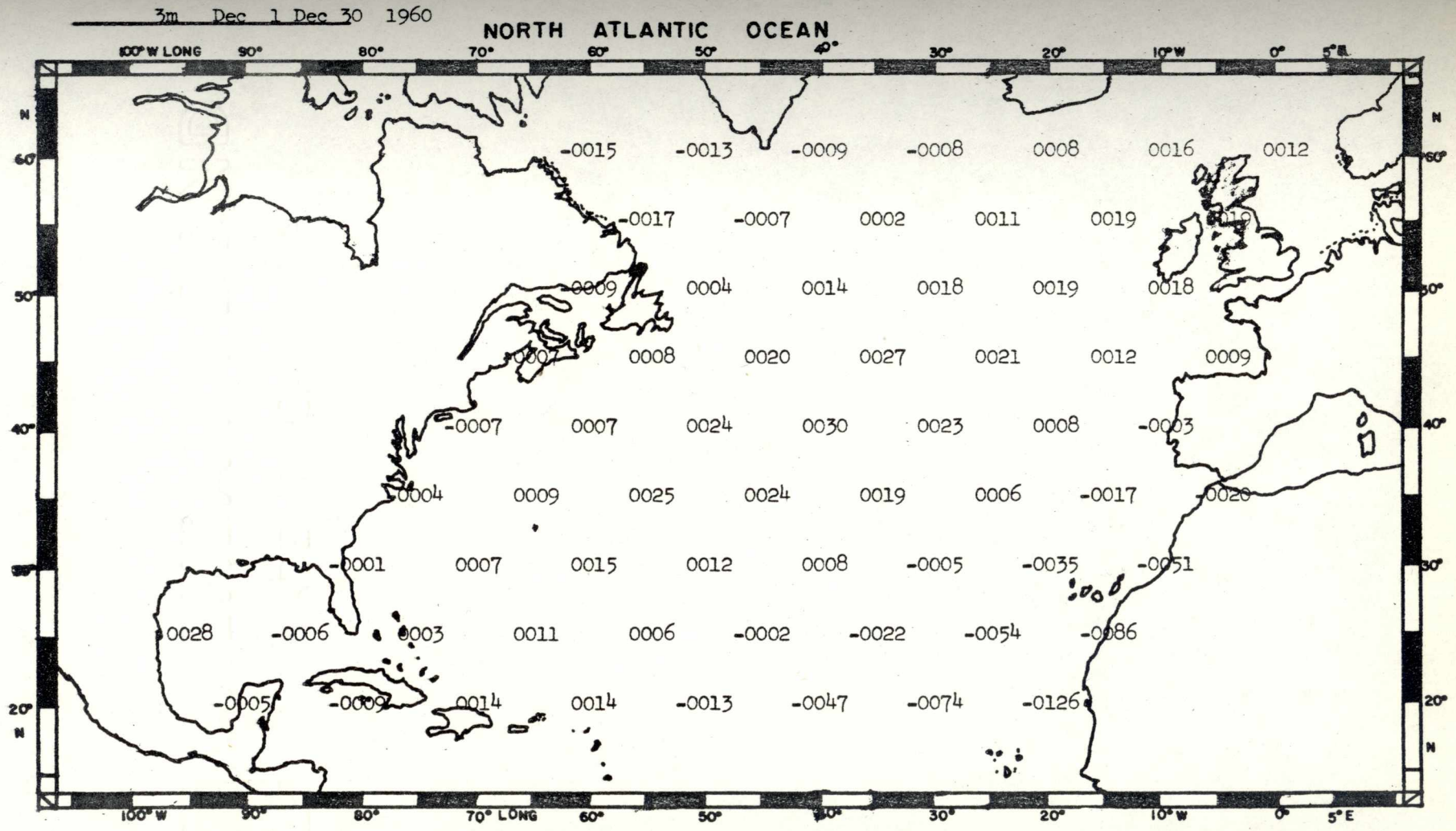


III. Zonal Component of Ekman Transport ANNUAL MEAN 1958

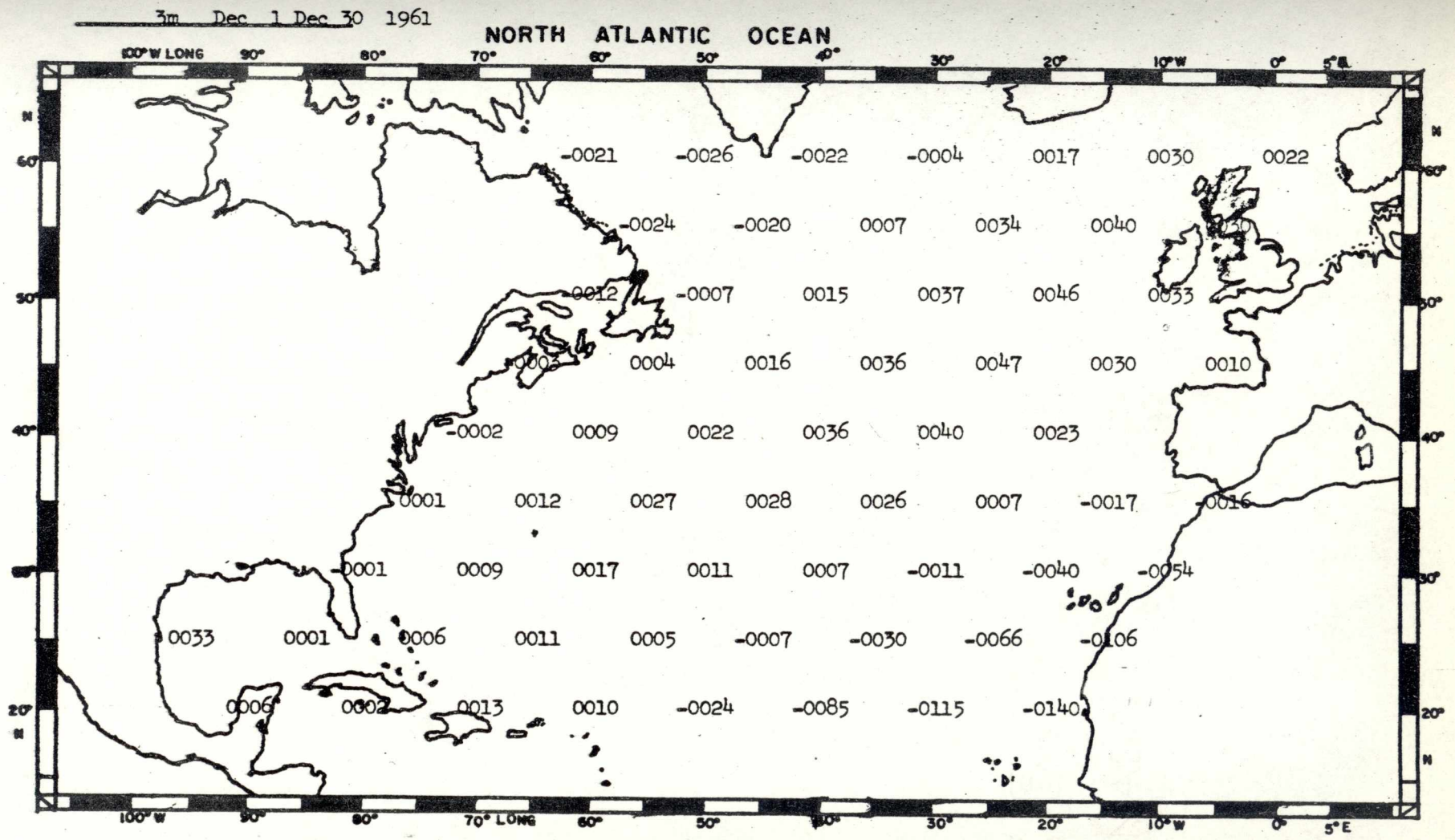
3m Nov 29 Dec 28 1959



III. Zonal Component of Ekman Transport ANNUAL MEAN 1959

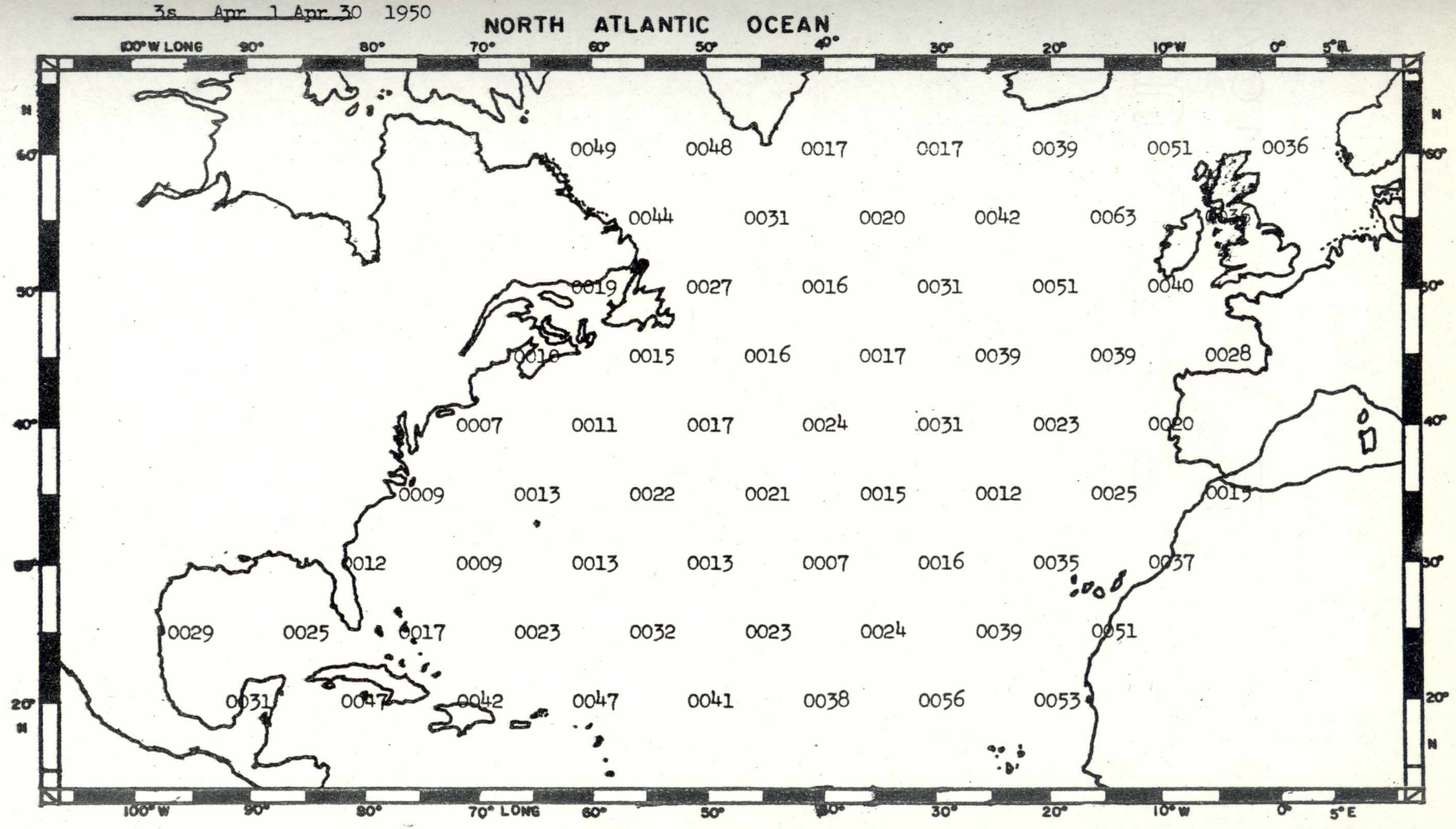


III. Zonal Component of Ekman Transport ANNUAL MEAN 1960



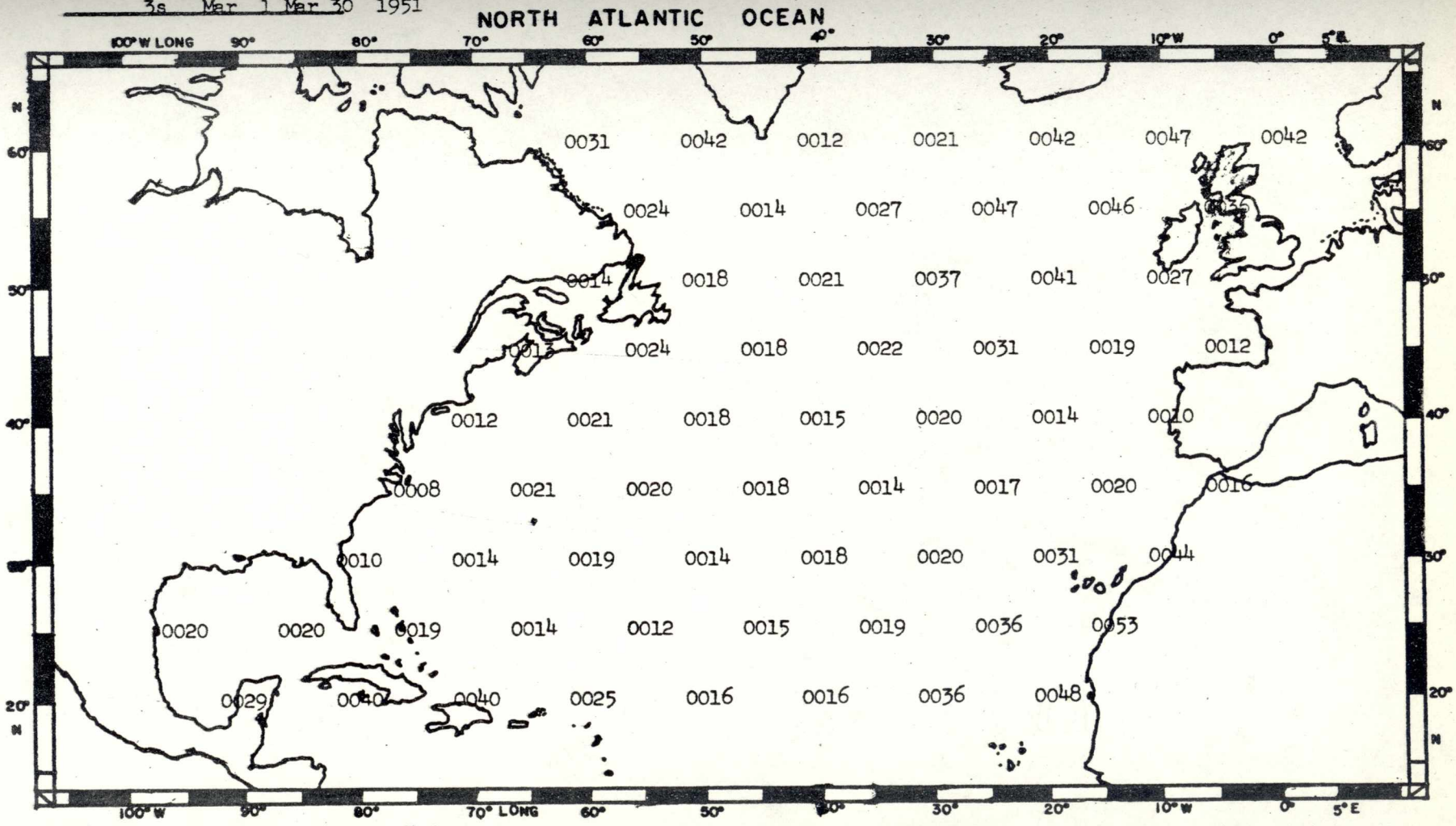
III. Zonal Component of Ekman Transport ANNUAL MEAN 1961

3s Apr 1 Apr 30 1950



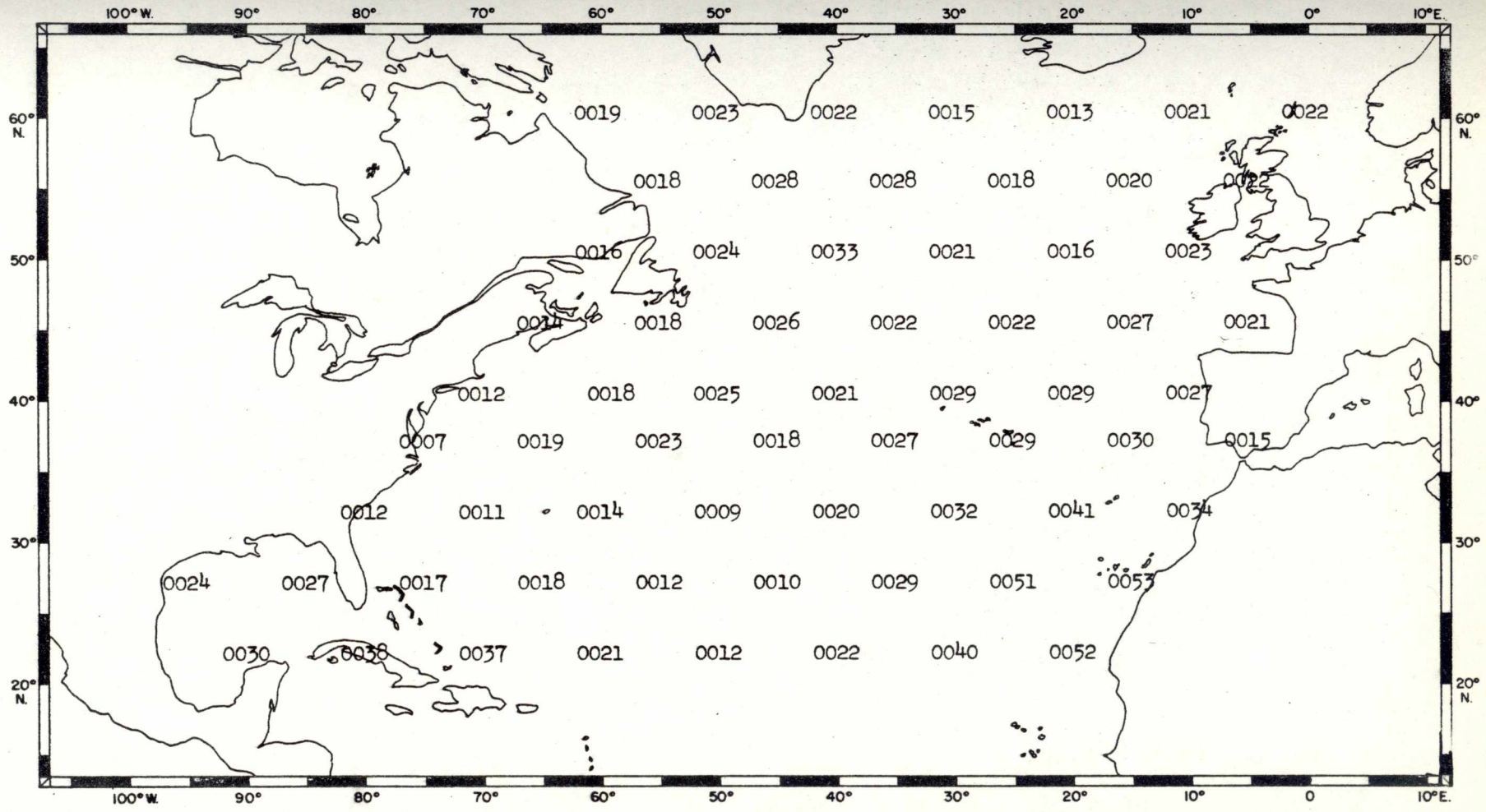
III. Zonal Component of Ekman Transport STANDARD DEVIATION 1950

3s Mar 1 Mar 30 1951

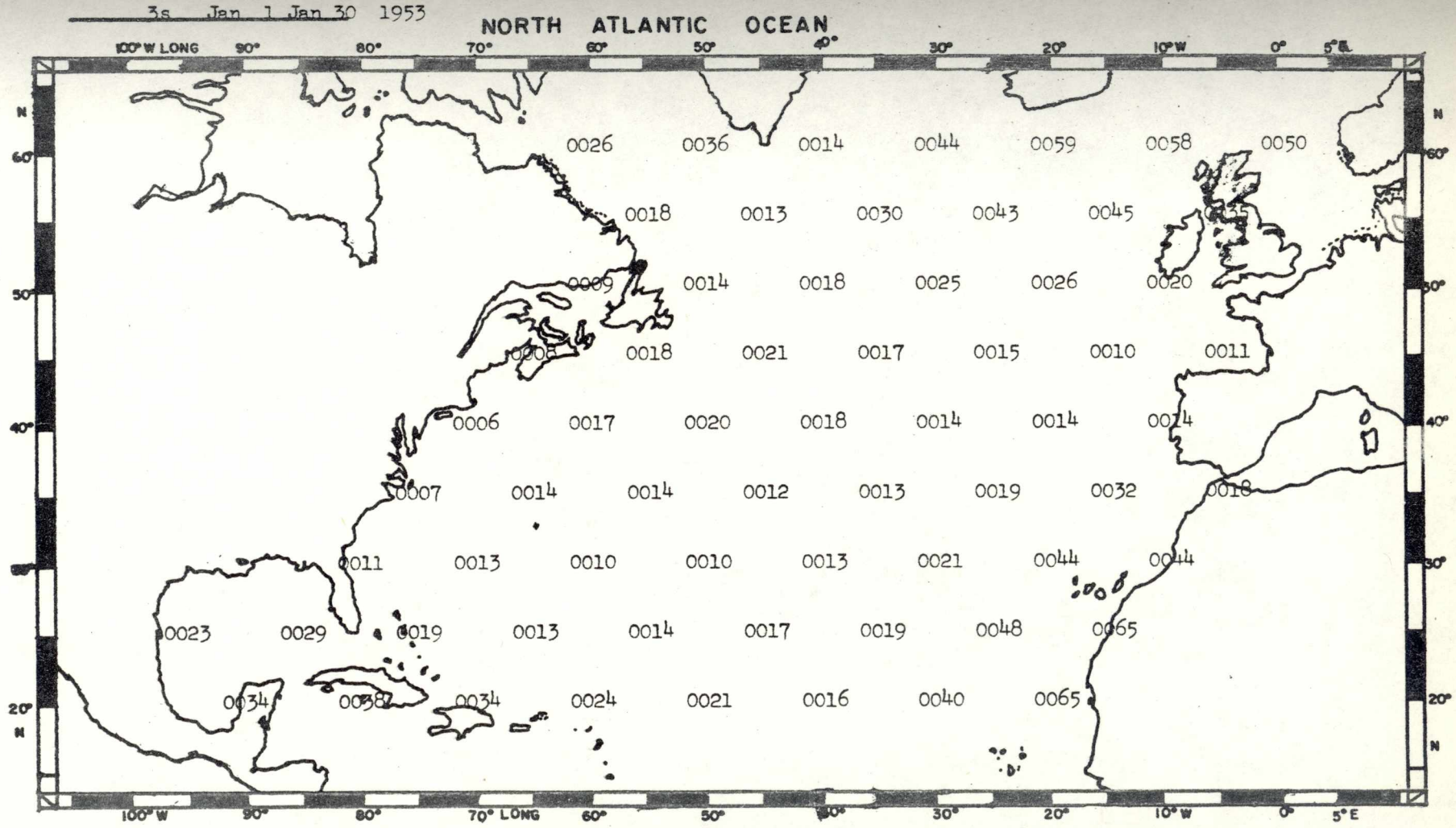


III. Zonal Component of Ekman Transport STANDARD DEVIATION 1951

3s May 1 May 30 1952

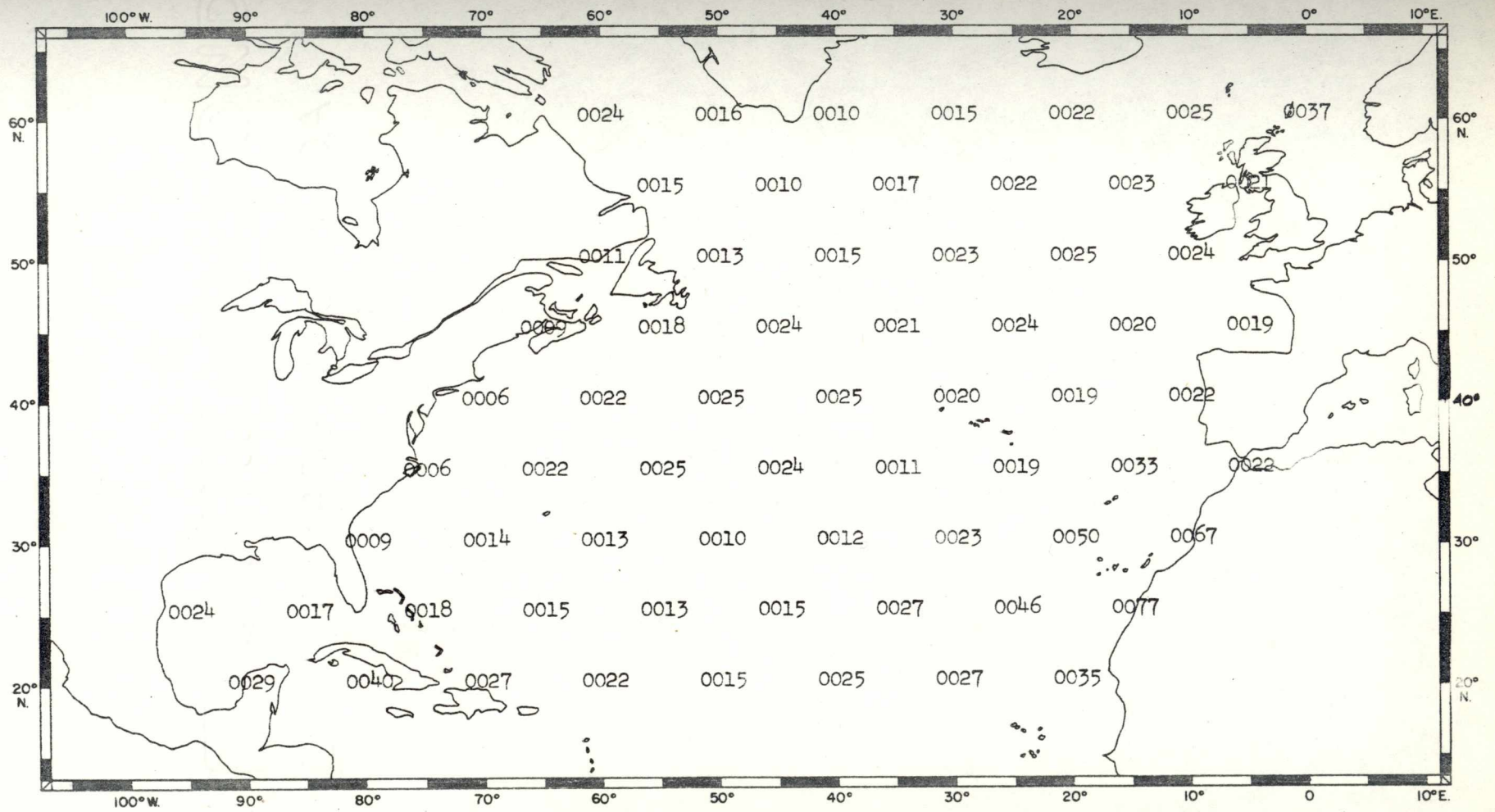


III. Zonal Component of Ekman Transport STANDARD DEVIATION 1952



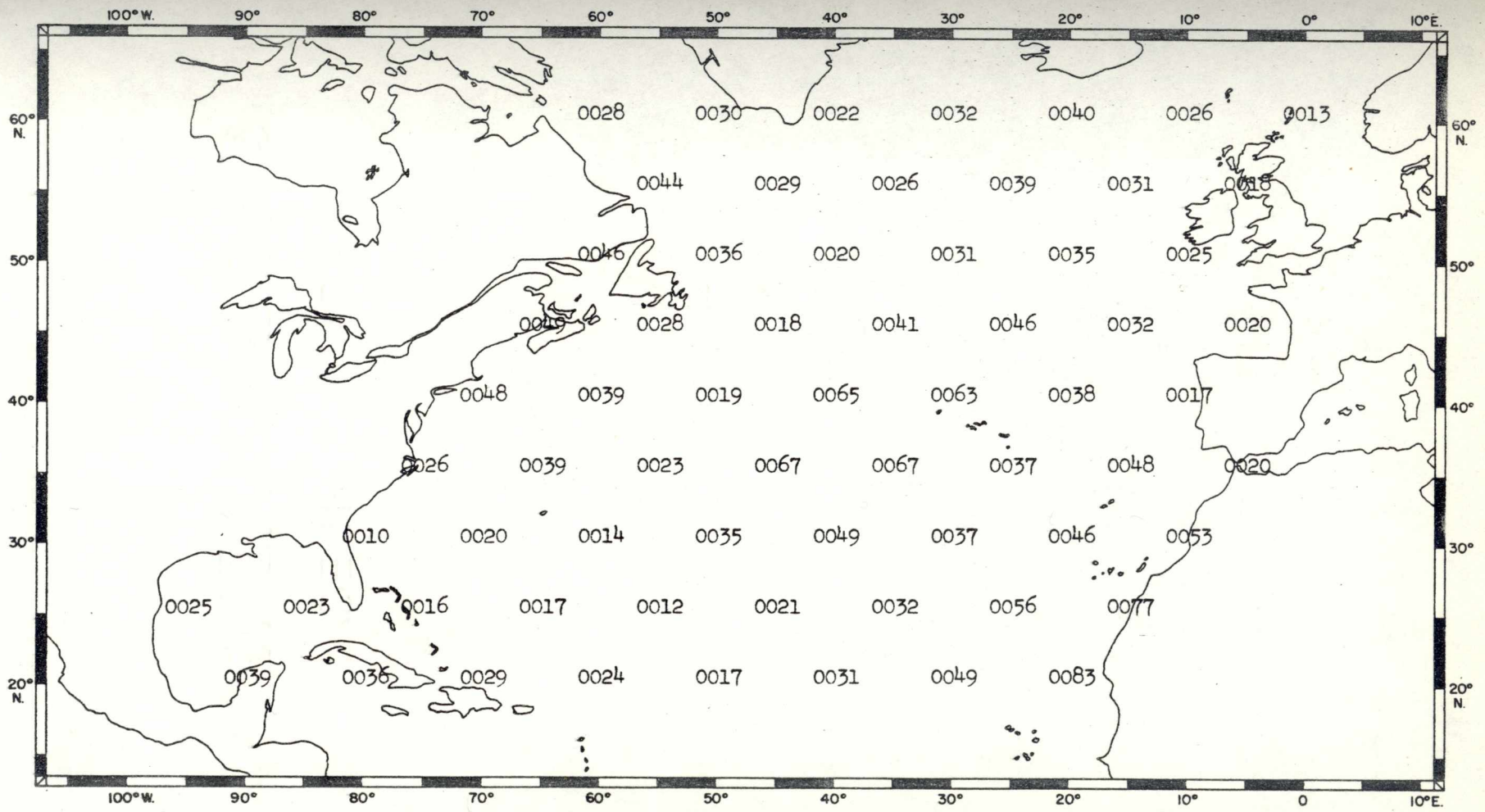
III. Zonal Component of Ekman Transport STANDARD DEVIATION 1953

3s Sep 1 Sep 30 1954



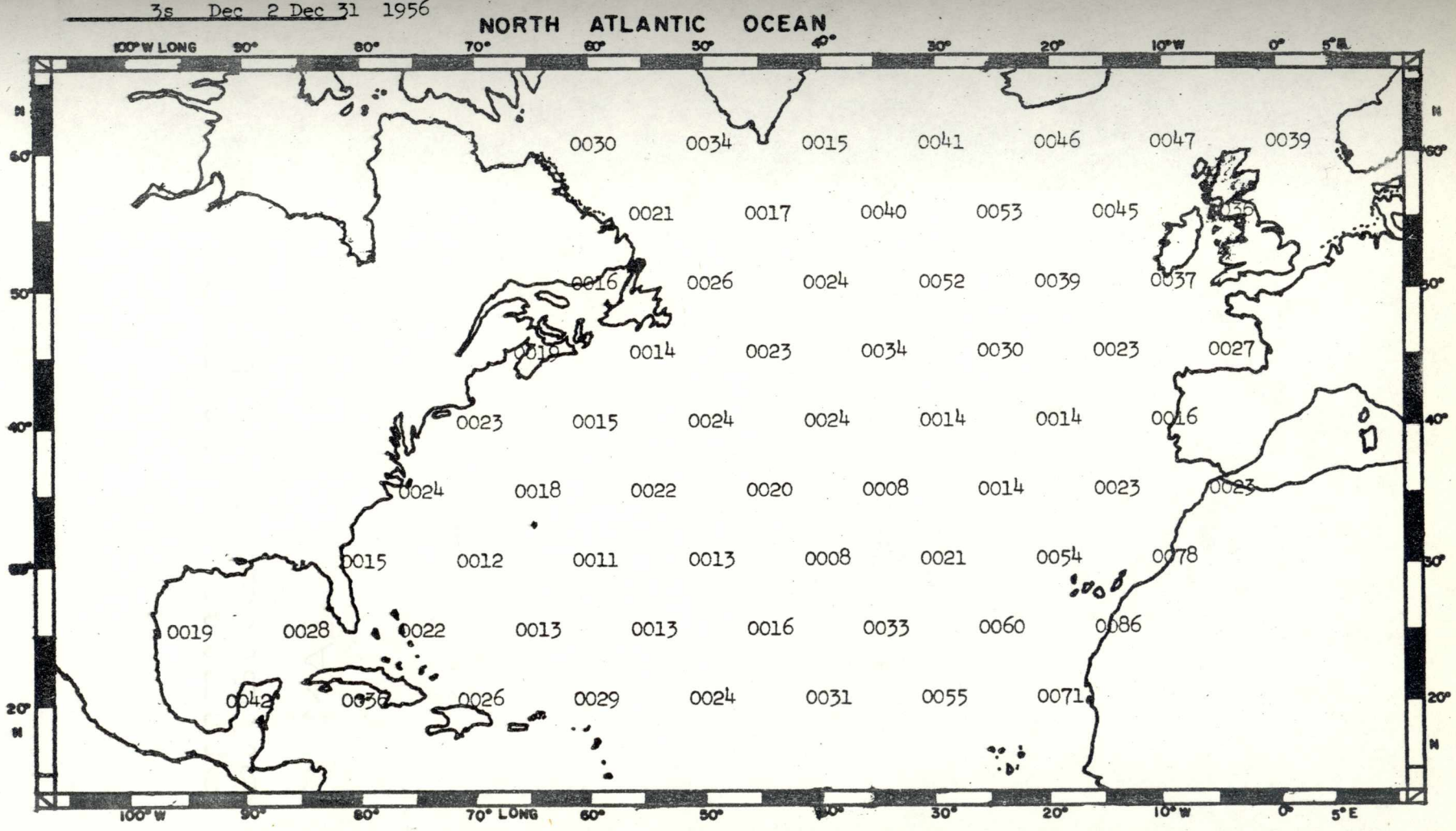
III. Zonal Component of Ekman Transport STANDARD DEVIATION 1954

3s Mar 29 Apr 27 1955



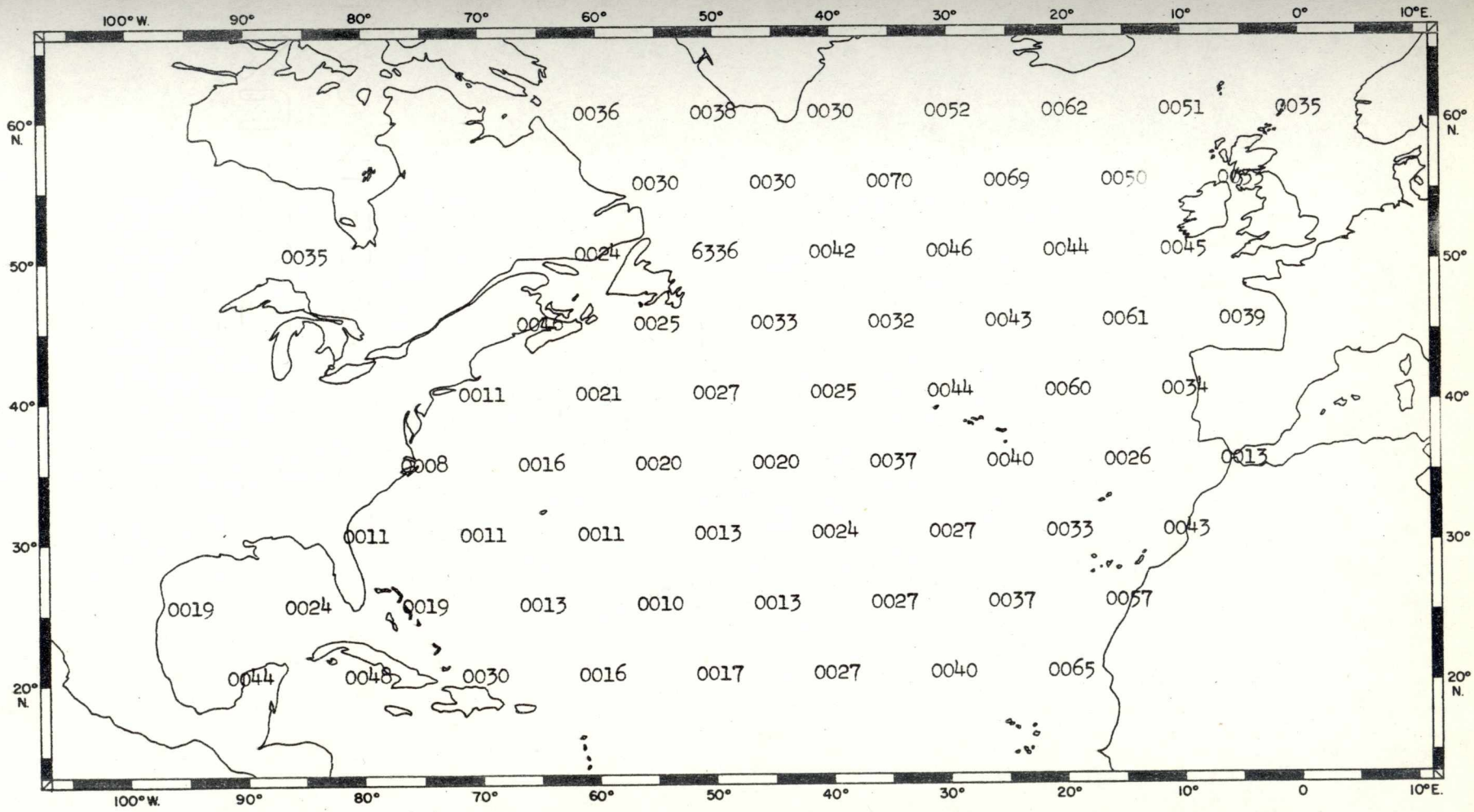
III. Zonal Component of Ekman Transport STANDARD DEVIATION 1955

3s Dec 2 Dec 31 1956



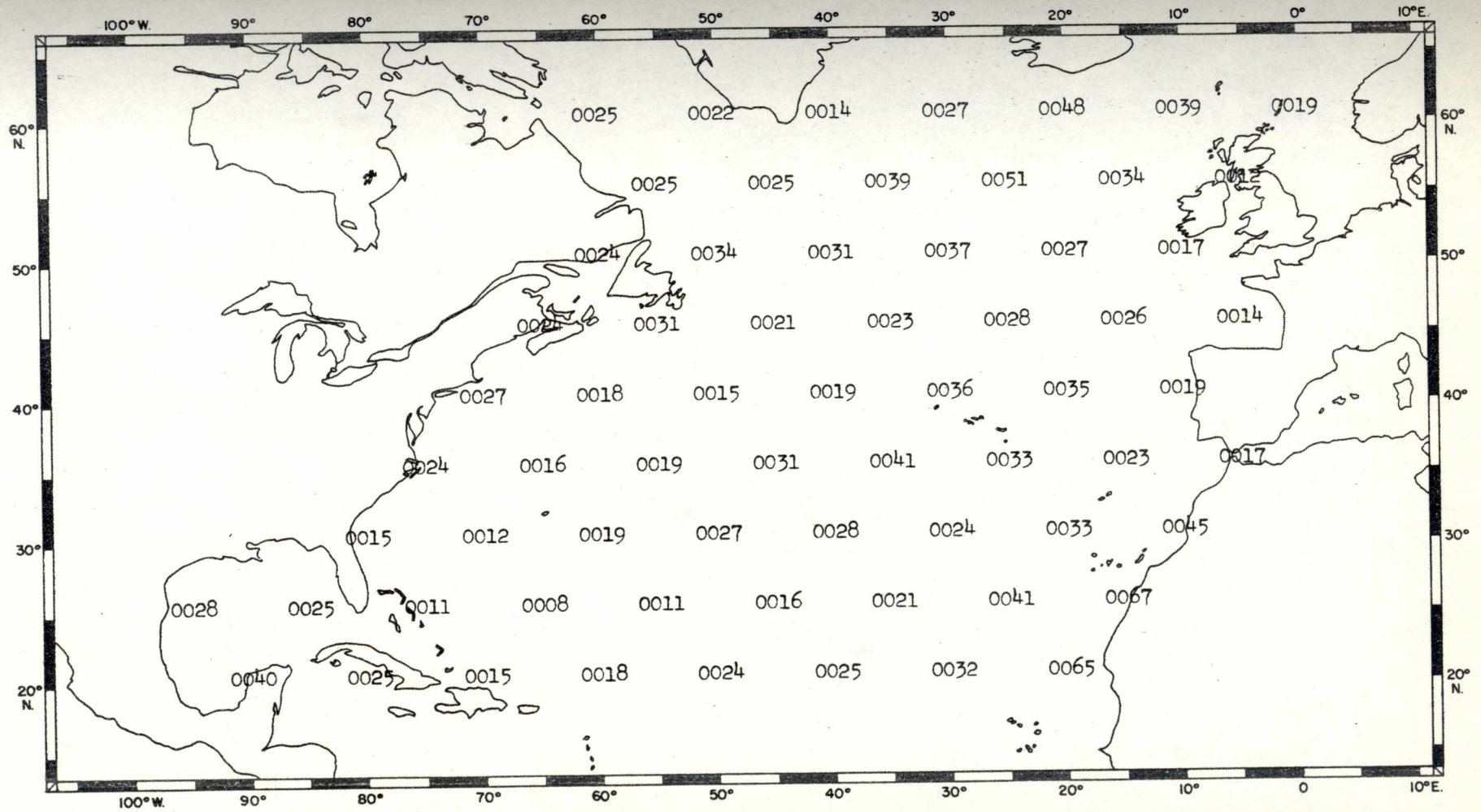
III. Zonal Component of Ekman Transport STANDARD DEVIATION 1956

3s Mar 29 Apr 27 1957



III. Zonal Component of Ekman Transport STANDARD DEVIATION 1957

3s Nov 30 De 29 1958



III. Zonal Component of Ekman Transport STANDARD DEVIATION 1958