Texas A&M University

Department of

OCEANOGRAPHY

ON THE QUESTION OF LOW-LEVEL CLOUD RESPONSE TO THE TEMPERATURE FIELD OF THE SEA SURFACE

by

James E. Arnold

September 1968

Office of Naval Research
Contract Nonr 2119(04)

Project NR 083-036
A&M Project 286-13
Ref. No. 68-20T

Funded by
National Aeronautics and Space Administration
through the
Office of Naval Research

Research Conducted through the
Texas A & M Research Foundation
COLLEGE STATION, TEXAS

Texas A&M University
Department of Oceanography
College Station, Texas 77843

Research conducted through the
Texas A&M Research Foundation

A&M Project 286-13

ON THE QUESTION OF LOW-LEVEL CLOUD RESPONSE TO THE TEMPERATURE FIELD OF THE SEA SURFACE

by

James E. Arnold

September 1968

Project 286 is sponsored by the Office of Naval Research [Project NR 083-036, Contract Nonr 2119(04)]. The Project 286-13 portion is operated through funding provided by the Spacecraft Oceanography Project of the Naval Oceanographic Office and is part of the National Aeronautics and Space Administration's Earth Resources Survey Program.
The work reported herein is of a preliminary nature and the results are not necessarily in final form.

TABLE OF CONTENTS

ABSTRACT

Weekly averages of wind and air-sea temperature differences from ship reports averaged over four-degree quadrilaterals, revealed that increased wind velocities required larger air-sea temperature differences to maintain a maximum cloud amount at low cloud levels for spring and summer cases. During winter the situation was reversed with increased wind velocities requiring less air-sea temperatures to maintain above average cloud amounts. This was also reflected in the individual ship reports. A similar examination of cloud amounts at low levels and the air-sea temperature difference gave some indication that at least a 1C change in air-sea temperature difference was required to produce a change of 1/8 coverage in the low cloud field.

Simple correlation coefficients between low clouds and air-sea temperature differences, wind, and dewpoint depression were small, with the correlation between clouds and wind being the highest with a value of 0.57. There was an indication that in specific cases the influence of moisture and air-sea temperature difference was greater than would be indicated in the simple correlation coefficients.

A seasonal trend of total cloud amount over the Gulf of Mexico from February to August existed in both ship and satellite data. Maximum cloudiness was observed in winter and summer, and a cloud minimum in April and May. The minimum cloud period reflected the presence of the subtropical high and the associated atmospheric subsidence rather than significantly decreased instability in the surface layers.

LIST OF TABLES

LIST OF FIGURES

ON THE QUESTION OF LOW-LEVEL CLOUD RESPONSE TO THE TEMPERATURE FIELD OF THE SEA SURFACE

INTRODUCTION

A sea surface with large temperature gradients and localized cold and warm spots would be expected to have an influence on the marine cloud field. This is in fact observed in at least extreme cases of heating and cooling of the marine boundary layer. Satellite photography of the Atlantic Seaboard has shown that a cloud-free area is frequently present over the cooler shelf water on the western side of the Gulf Stream as well as considerable enhancement of the cloud field over the Gulf Stream itself. As another example, Lake Okechobee in central Florida is frequently an area of minimum cloud activity during the daytime hours when convection over the adjacent land mass is at a maximum. Roll (1965) also cites a case of cumulus development over turbid, excessively heated water in the Gulf of Bengal, reported by Isaacs. Cumulus cloud fields appear to be enhanced over warm water areas as examination of Gemini photography over the Gulf of Mexico has shown. Under favorable atmospheric conditions, i.e., under conditions of weak synoptic-scale convergence and adequate moisture, Arnold (1967) found good agreement between negative air-sea temperature differences (sea warmer than the air) and the marine cloud field during the spring. The reverse characteristic, i.e., stratus clouds in warm moist air over cold water, is also observed. Stratus clouds off the coast of California and Chili fall into this category. Since cloud fields in cool air over warm water are most applicable when examining the marine cloud layer over the Gulf of Mexico, the remaining discussion will be limited to convection resulting from heating at the lower boundary.

HEAT TRANSFER AND CONVECTION

The transfer of heat and moisture to the atmosphere is a function of the gradients of temperature and humidity in the atmosphere near the surface as well as the wind stress on the surface and the eddy coefficients for heat (K_s, cm^2sec^{-1}) and water vapor (K_e, cm^2sec^{-1}). In the first few meters above the ocean, sensible and latent heat transfers can be expressed as:

$$Q_s \doteq -\rho C_p K' \frac{\partial T}{\partial z} \qquad \text{Sensible heat} \qquad (1)$$

$$Q_e \doteq -\rho L K_e \frac{\partial q}{\partial z} \qquad \text{Latent heat} \qquad (2)$$

The stress on the ocean surface can be defined as:

$$\tau = K_m \frac{\partial u}{\partial z} \ (\text{dyn cm}^{-2}) \qquad (3)$$

where K_m is the eddy coefficient for momentum (cm^2sec^{-1}), under assumption that $K_m = K_s = K_e$, 1 and 2 can be reduced through their differential form to:

$$Q_s = \rho C_p C_D (T_s - T_a) u_a \qquad (\text{erg cm}^{-2}\text{sec}^{-1}) \qquad (4)$$

$$Q_e = \rho L C_D (q_s - q_a) u_a \qquad (\text{erg cm}^{-2}\text{sec}^{-1}) \qquad (5)$$

where:

C_p = Specific heat of air at constant pressure (erg gm^{-1}°C^{-1})

ρ = Density of the air (gm cm^{-3})

C_D = Drag coefficient (nondimensional)

T_s = Temperature of the sea (°K)

T_a = Temperature of the air at height z (°K)

L = Latent heat of condensation (erg gm^{-1})

q_a = Specific humidity of air at height z (nondimensional)

q_s = Specific humidity at the sea surface (nondimensional)

z = Height (cm)

u_a = Wind speed at height z (cm sec^{-1})

In this form it is easy to see that the sensible and latent heat fluxes are dependent on the wind speed and the gradient of temperature or humidity. It should be pointed out that strictly speaking the drag coefficient changes slightly with stability and wind speed. Garstang (1967) has defined a relationship between the drag coefficient at 6 meters and the wind speed at the same level and the Bulk Richardson number, R_b (the gradient Richardson number applied at a point), based on observations as:

$$C_6 = (1.46 + 0.07\bar{U}_6 - 4.2R_B) \times 10^{-3} \qquad (6)$$

It can be seen that the wind speed and stability act in opposing directions on the heat transfer described in equations 4 and 5.

In the cases of cool air flowing over a warm ocean area, the resultant heat transfer into the atmosphere will have a tendency to increase the instability in the lower layer and place more moisture in the marine boundary layer. The expected result would then be an increase of convection due to thermal instability and a gradual lowering of the convective condensation level due to the moisture increase at the surface. If the convection exists on a sufficiently large scale, the development of an oceanic cloud field in response to surface conditions of heat and moisture flux would be expected.

The problem of uniform heating at the lower boundary of a liquid resulting in convective overturning has been treated in classic papers by Rayleigh, Jeffreys, Pellew and Southwell and others, as cited by Saltzman (1962). In gases the tendency for the motion of the resultant circulation cell is such that initially the flow is directed toward the region of highest viscosity. Since in the atmosphere, viscosity increases with increasing temperature, the flow is directed down in the center of the cell and upward along the edges when the layer is heated from below. Departures from the idealized laboratory state result in the atmosphere due to differences between eddy motion and molecular processes existing in the laboratory models.

The Rayleigh criterion for the onset of convection in a compressible fluid, involving molecular processes, requires that the ratio

$$\frac{G(\Gamma-\zeta)h^4}{T(K\gamma)}$$

exceed some critical value, stated by Priestly (1959) as 1,100, where

Γ = Adiabatic lapse rate (°C cm^{-1})

ζ = Lapse rate in the fluid (°C cm^{-1})

h = Depth of the fluid (cm)

g = Gravity (cm sec^{-2})

T = Mean temperature of the fluid (°K)

K = Thermal conductivity (erg cm^{-1}sec^{-1} °C^{-1})

γ = Molecular viscosity (cm^{2}sec^{-1})

Although there are inherent complications in applying the Rayleigh criterion to the atmosphere, the concept of the Rayleigh number to examine the effects of the terms involved is useful. Essentially what transpires is that the viscous drag counteracts the buoyancy force and resists overturning. In addition, if the thermal conductivity is high in the lower layers of the atmosphere the air cannot become sufficiently buoyant to become unstable. The depth of the layer also becomes critical as it enters to the fourth power. It is also important to note that ($K\gamma$) is a function of scale since turbulence increases its magnitude. It follows then that conditions which favor convection at one scale inhibit it at another. Also apparent is that the onset of convection, or its maintenance, is dependent on interrelated factors. The problem of utilizing the Rayleigh number as such in the atmosphere is emphasized by Priestly (1959). He examined the Rayleigh criteria for the onset of convection noting that in the atmosphere a pre-existing wind and turbulence condition must be considered. Substituting the turbulent counterparts for the kinematic and molecular conductivity, the Rayleigh criteria was expressed in terms of a Richardson criteria. The result was that the derived critical Richardson number differed greatly from the known -0.03 value usually associated with the onset of free convection. The implication of this comparison is that the criterion specified by the Rayleigh number is not necessarily the relevant one when the onset of free convection is considered under conditions of wind. Once convection and resulting condensation begin, additional heat terms contribute to the system, further modifying the motion.

Hubert (1966) examined satellite photographs over oceanic area cellular convection was occurring. The most common mode of organized convection present was of the open cell type expected from the previous discussion. Closed cells, i.e., with motion upward in the center and down along the cell edges, was most commonly observed in cases of weak heating with small values of $(T_a-T_s)u_a$. While closed cells and consequent maximum cloud cover were associated with a relatively narrow range of conditions, open cells were found over a wide range of wind speeds and temperature differences.

Alterations of the Benard-type cellular convection due to uniform wind shear has been described by Avsec (1939). He noted that as the convective layer was heated from below and simultaneously subjected to a weak shear in the vertical, rolls and transverse polygonel cells were observed. Tsuchiya and Fujita (1967) noted a similar effect in the monsoons over the Sea of Japan. Well-defined longitudinal rolls were present in wind shears greater than 7×10^{-3} sec^{-1} changing to transverse bands for shears between 5 and 7×10^{-3} sec^{-1}. Cellular convection was observed for wind shears less than 5×10^{-3} sec^{-1}. Hubert (1966) also gives examples of longitudinal rolls in the cloud field in areas of strong surface heating and wind shear. The distance between rolls (D) is proportional to the depth of the convective layer (h), according to Scorer (1958), through the relationship

$$D = 2.7h \tag{7}$$

This implies that as the convective layer becomes deeper, as it usually does downwind, the spacing increases until some critical depth is reached where the vertical shear is small enough to allow three-dimensional cellular convection.

In the marine atmosphere in the Trade Wind zone, the level below the cloud base to the surface can be divided into three basic regions according to Roll (1965): a superadiabatic region, a homogeneous layer where potential temperature and mixing ratio are relatively constant with height, and a transition layer where the moisture lapse rate increases while the temperature profile is more stable than in the layer below. Observations in the Trades by Malkus (1958) indicate that cloudy situations were characterized by an approach of the top of the homogeneous layer to the condensation level. In the absence of clouds, the height of the homogeneous layer was distinctly less than for cloudy cases. Since the extent of the homogeneous layer and convective modes at its base are dependent of fluxes initiated in the lower or superadiabatic layer, an examination of convective processes in this region is illuminating in the overall consideration of cloud occurrence.

In the layer near the surface, the convective region may be described in terms of the stability length defined by Monin and Obokhov (1954) as:

$$L = \frac{c_p T\, u_*^3}{gkH} \qquad \text{(cm)} \qquad (8)$$

where:

T = Mean absolute air temperature near the surface (°K)

u_* = Friction velocity (cm sec^{-1})

k = von Karman constant (nondimensional)

H = Flux of heat (erg cm^{-2}sec^{-1})

g = Gravity (cm sec^{-2})

For heights less than $z \doteq 0.03\ |L|$ forced convection dominates and the heat flux is a function of the Richardson number:

$$R_i = \frac{g(d\bar{\theta}/dz)}{\theta(d\bar{u}/dz)^2} \tag{9}$$

where $\bar{\theta}$ is the mean potential air temperature.

This implies that the heat flux decreases with height. In the region defined by $0.03<\frac{z}{L}<1$, both forced and free convection exist while for heights of $z \doteq |L|$ and larger essentially free convection exists and buoyancy is the governing factor. This latter region comprises the homogeneous layer in the marine atmosphere.

Examination of the behavior of the L with wind speed and heat flux utilizing

$$u_* = (C_D)^{1/2}u \tag{10}$$

reveals that L increases with increasing wind or decreasing heat flux. Since the input into the homogeneous layer, and thus its structure, is influenced by the height and zones of transition present such a tendency could be important in the appearance of convection elements and their associated cloud fields.

In view of the criterion necessary for the establishment of convection in the uniformly heated lower boundary, the influence of shear in modifying the convection modes, and the parameters describing the regimes of heat transfer in the marine atmosphere, it is not unexpected that the convection patterns observed in the atmosphere often differ from their laboratory counterpart. Scorer (1951) comments that, in fact, there is no reason why overheating or overcooling should not occur in the atmosphere. In this respect, Jeffreys (1928) shows that besides the dimensions and properties of the boundary, the additional assumption that the motion will only just take place is required in order to obtain cell size.

Malkus and Stern (1953) and Stern and Malkus (1953) examined the production of cumulus clouds in response to a point source of heat at the surface. After observing the production of cumuli over and downwind from small oceanic islands, a model was developed which described the air flow over the island in terms of heat mountain causing a vertical distortion of the streamlines. In cases where the air flow was distorted vertically to the point that air parcels were raised from their upwind height to condensation level over the thermal mountain, small cumuli were created.

Malkus (1956) extended the heat mountain concept derived over heated islands to observed cumulus clouds over warm spots on the ocean surface. The height of the thermal mountain created by the warm spot was expressed as

$$M = \frac{\tau}{\Gamma - \zeta} \tag{11}$$

where:

M = Maximum height of the mountain (cm)

τ = Effective island temperature excess (°C)

Γ = Adiabatic lapse rate (°C cm^{-1})

ζ = Undisturbed lapse rate (°C cm^{-1})

Due to lapse conditions in the Trade Wind region, the height of the equivalent mountain in kilometers is approximately one-half the temperature excess in degrees Celsius. Examination of the cloud field over an oceanic region of varying water temperature revealed that clouds, when present, were always associated with warm spots on the ocean and were frequently best developed on the downwind boundary where the surface temperature gradient was the steepest. The general conclusion was that the spots of warm water with temperature excesses of even a few tenths of a degree could give equivalent hills high enough to permit air in the subcloud layer to reach the level of condensation.

In addition then to the convective modes expected from uniformly heating the atmosphere from below and the effects of wind shear, convective processes resulting in the appearance of a cloud field should be expected from local sources, i.e., warm water patches.

Localized modification of the surface wind profile may also lead to small-scale convergence and the production of cloud elements. Since the shape of the adiabatic wind profile near the surface is given by

$$\frac{\partial u}{\partial z} = \frac{u_*}{kz} \tag{12}$$

changes in the friction velocity, u_*, may lead to changes in the wind profile. Since the friction is dependent on the stability of the air through equations 6 and 11, the shear and/or the wind velocity should increase as the heat flux or bulk Richardson number increases. In fact, acceleration of the wind is noted in observational data taken by Regula over warm oceans and illustrated by Roll (1965). Low level convergence may result from the locally induced discontinuity in the wind profile. It is possible then that flow of air over a temperature gradient on the ocean surface, if the gradient is sharp enough, could be sufficient to enhance convection. Once the convective clouds appear their continued life is dependent on environmental conditions existing in the cloud layer. Excessive dryness or large wind shears as well as synoptic scale stability are known to inhibit cloud development.

CONVECTION AND THE SEA SURFACE FROM COMMERCIAL SHIP DATA

In the previous section, the various modes of convection expected as a response of the atmosphere's marine layer to the sea surface were discussed. It should be pointed out that other causes of atmospheric convection exist. Local convergence patterns may develop in mesoscale-systems initiated in the atmosphere due to the overall synoptic conditions. Frontal systems in a specfic region will greatly enhance convection in the lower layers regardless of the sea-surface temperature. In the present chapter, where weekly averages are treated, the effect individual fronts have on the cloud field is minimized. The cloud field has also been found to be dependent on the upper level synoptic patterns with clouds being favored when general low level convergence is topped by upper level divergence. Equally important is the fact that low level clouds tend to be suppressed by the existence of upper level convergence and low level divergence (Riehl and Malkus, 1965). In the current study, the various atmospheric and sea-surface parameters--air temperature, sea temperature, wind, dewpoint depression, clouds, etc., were examined in the Gulf of Mexico utilizing commercial ship reports. This was accomplished by dividing the Gulf of Mexico into four-degree quadrilaterals (see Figure 3) and obtaining averages of reported parameters at one-week intervals for 25 weeks in 1967. Because the shipping routes in the Gulf extend from either the Florida or Yucatan Channel to specific ports, usually in Louisiana or Texas, commercial ship reports tend to be along two lines rather than scattered randomly over the entire area of interest.

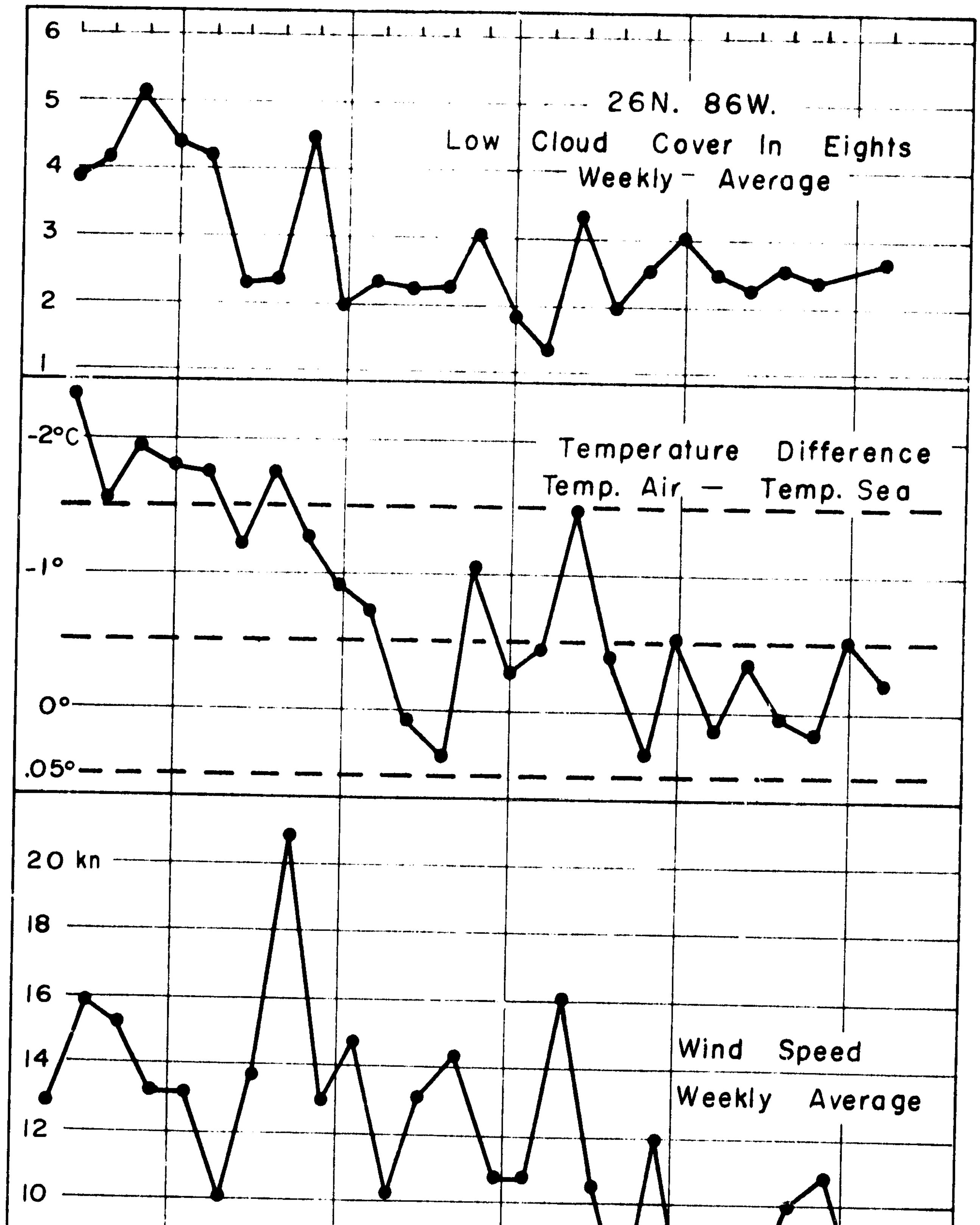
There is also a definite seasonal difference in the number of ships in the Gulf with a typical winter week having 160 reports while a typical summer week may have over 250 reports. For specific dates corresponding to week numbers, the reader is referred to Appendix A.

Two of the quadrilaterals with larger numbers of ship reports are sufficient to show the typical trend of cloud, air-sea temperature difference, and wind for northern and southern Gulf areas. Data for quadrilateral 7 are shown in Figure 1. As can be seen, the weekly average cloud amount is greatest during the early weeks, averaging approximately 4/8 cloud cover. By weeks 11 to 16, corresponding to 9 April to 20 May 1967, the low cloud amount reaches a minimum averaging just slightly more than 2/8 coverage. From late May through the summer, the cloud amount increases slightly. The temperature difference between the air and the sea is at a maximum, as would be expected, during the winter months decreasing from a difference of more than two degrees Celsius during early February to the sea being colder than the air during weeks 12 and 13, 16-29 April 1967. For the remainder of the period, the air-sea temperature difference is slightly negative (sea warmer than air), on the average, but does have two weeks where the differences gets as large as one degree. As was the case with the low cloud cover and air-sea temperature differences, the average wind velocity decreases from winter to summer. The winter average wind velocity was approximately 14 knots while the summer average is closer to 8 knots. Examination of the trends of air-sea temperature differences and wind in relation to the amount of low clouds reveals that, on a weekly average basis, the clearest association between increasing clouds and increases of the other two parameters

Fig. 1. (a) Weekly average low cloud cover determined from commercial ship reports in a four-degree quadrilateral, no. 7, centered at 26N, 86W. The time period extends from 6-12 February to 23-29 July 1967.

(b) Weekly average air-sea temperature difference, in degrees Celsius, determined from commercial ship reports in a four degree quadrilateral centered at 26N, 86W. Negative values mean sea is warmer than air.

(c) Weekly average wind speed (kn) determined from commercial ship reports in a four-degree quadrilateral centered at 26N, 86W.

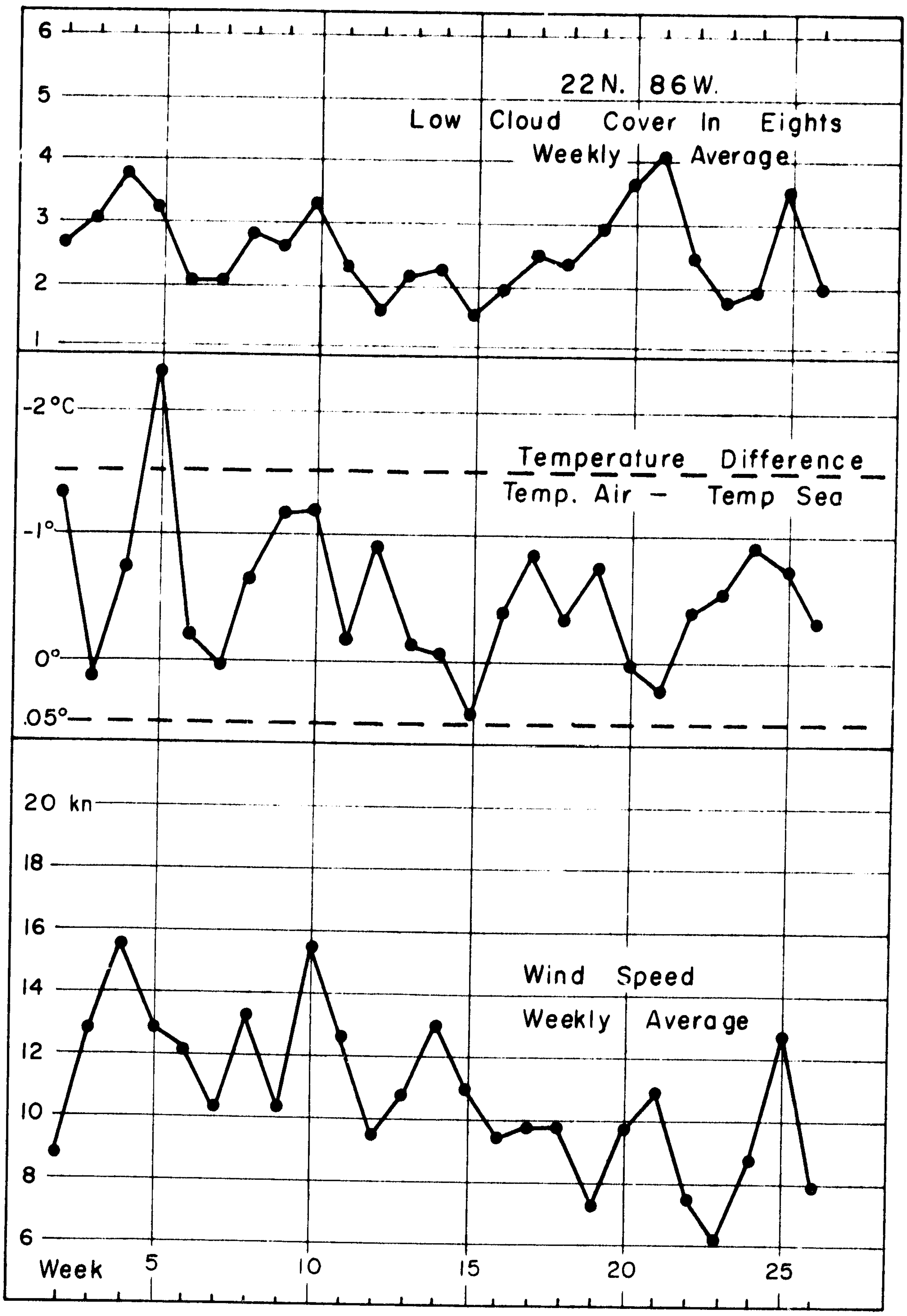


26N. 86W.
Low Cloud Cover In Eights
Weekly Average
6
5
4
3
2
1
Temperature Difference
Temp. Air — Temp. Sea
-2°C
-1°
0°
.05°
20 kn
18
16
14
12
10
8
6
Wind Speed
Weekly Average
Week
5
10
15
20
25

Fig. 2. (a) Weekly average low cloud cover determined from commercial ship reports in a four-degree quadrilateral, no. 12, centered at 22N, 86W. The time period extends from 6-12 February to 23-29 July 1967.

(b) Weekly average air-sea temperature difference, in degrees Celsius, determined from commercial ship reports in a four degree quadrilateral centered at 22N, 86W. Negative values mean sea is warmer than air.

(c) Weekly average wind speed (kn) determined from commercial ship reports in a four-degree quadrilateral centered at 22N, 86W.


22N. 86W.
Low Cloud Cover In Eights
Weekly Average
Temperature Difference
Temp. Air – Temp Sea
-2°C
-1°
0°
.05°
Wind Speed
Weekly Average
20 kn
Week
5
10
15
20
25

are when there are large increases of wind speed, i.e., when frontal activity influenced all the features. This is especially pronounced on weeks 9, 14, 17 and 20.

Data for the southern quadrilateral, number 12, show trends in low cloud, air-sea temperature difference, and wind in much the same manner as did number 7. As can be seen in Figure 2, cloud cover decreased from a maximum of near 3/8 during February to a minimum between weeks 12 and 15, corresponding to 16 April to 13 May. In the case of quadrilateral number 12, the increase in cloud cover following the April to May minimum was greater than in the northern latitude case, actually reaching a period of greater cloud cover during mid-June, weeks 20 and 21, than during the winter weeks.

The air-sea temperature trend in quadrilateral number 12 through the period did not exhibit as pronounced a decrease from winter to summer as did the more northern quadrilateral. It will also be seen that the air-sea temperature differences seemed to go through cycles of about 7-week periods, starting in mid-March, week 7. A comparison between the air-sea temperature cycles and the cloud amount trends shows little relationship on a week-to week basis. The only indication that the cloud field at low levels and the air-sea temperature difference are related, is that in general, greater air-sea temperature differences (more negative) over a period of several weeks were usually associated with greater cloud amounts. As with the northern quadrilateral shown in Figure 1, the southern quadrilateral in Figure 2 shows a reasonable relationship between weeks with higher than average wind speed and increases in the low cloud cover.

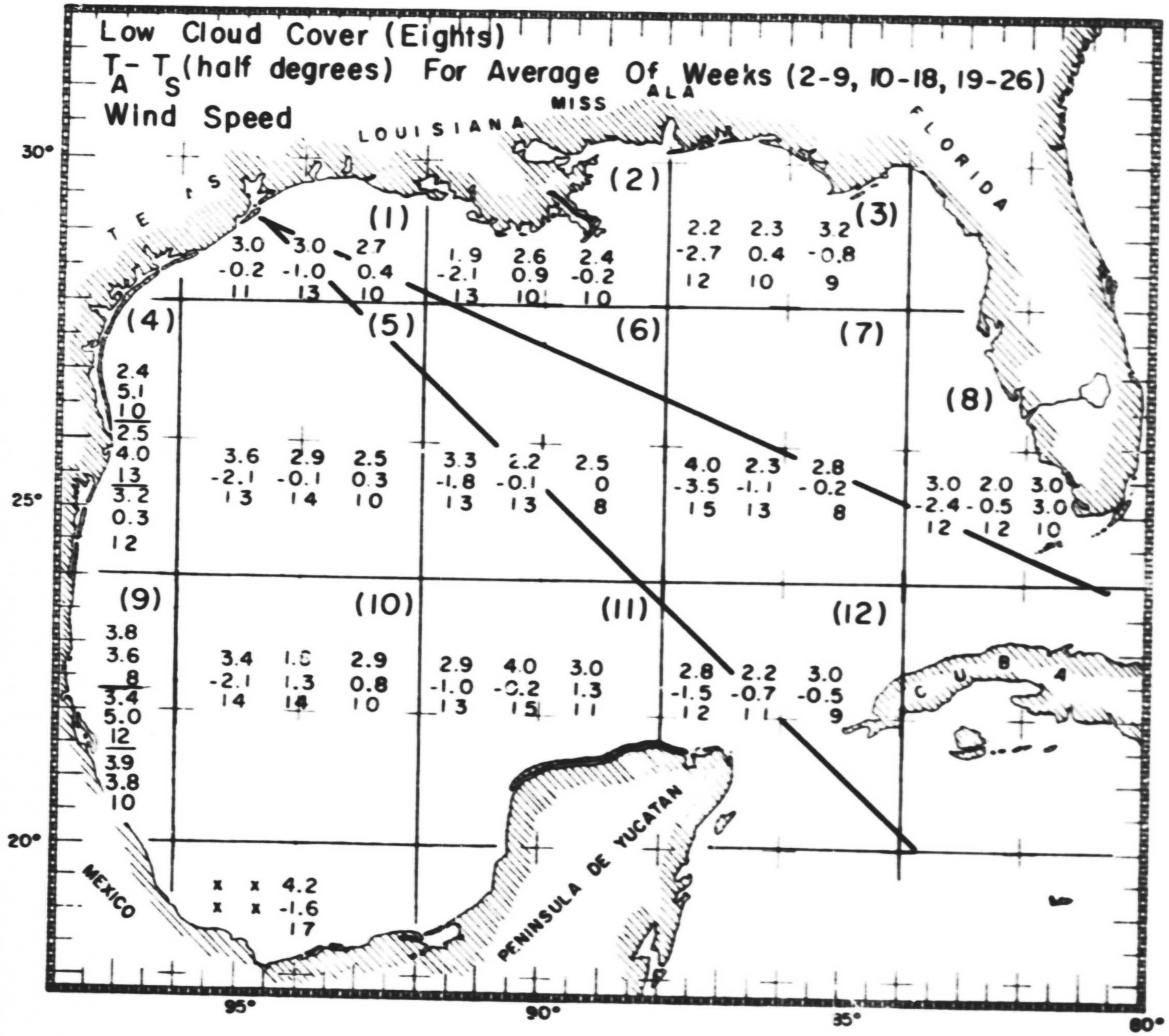
Although the correlation between amount of low cloud cover and surface parameters is somewhat tenuous, on a week-to-week basis, there does seem to be an indication that the seasonal trend of low cloud cover is responding to overall seasonal atmospheric vertical motion patterns, as described by Hastenrath (1968). On the average, in the Gulf of Mexico, divergence in the lower troposphere and convergence in the mid-troposphere is present in the winter half of the year. This is followed in May and June with a tendency for divergence in most of the lower and mid-troposphere and convergence in the upper troposphere. In July and August, convergence dominates between 900 and 700 mb while divergence exists at the 500 mb layer. Simple continuity requires that from winter to sometime in May or June, subsidence exists in and above the cloud layer changing to upward motion during mid-summer. The effect of this vertical motion pattern is seen in the cloud trends shown in Figures 1 and 2. During the winter weeks, when there is a large air-sea temperature difference and high wind velocities, there is a maximum in cloud amount, induced by strong thermal instability but capped by subsidence over the area. By April or May, the air-sea temperature difference has lowered to a maximum of about one degree and the subsidence is capable of overcoming the instability in the lower atmosphere. As a consequence, a cloud minimum is observed during this period. In early summer, the lower atmosphere is subject to a net convergence due to the overall synoptic conditions and with the general characteristic of the sea being warmer than the air, an increase in cloud amount is observed. It is interesting to compare the trends of air-sea temperature difference and relative cloud amounts in the two quadrilaterals in the winter and summer periods. In the northern quadrilateral when the air-sea temperature difference is greatest and significantly larger than in the southern quadrilateral, the cloud amount is also greatest. In the summer period, the situation is reversed and the southern quadrilateral has the largest air-sea temperature differences. It will be noted that the average low cloud amount is correspondingly greater in the southern quadrilateral.

From characteristics of cloud trends shown in Figs. 1 and 2, the 25-week period was broken into three parts. These subperiods consisted of the second to ninth weeks, 6 February to 1 April 1967, during which time the sea was uniformly warmer than the air over the entire Gulf and subsidence was the average mid and lower tropospheric characteristic. The second period extended from weeks 10-18, 2 April to 3 June 1967, and covered a time span when the sea was just slightly warmer than the air and the lower atmosphere was characterized by weak subsidence. The third period extended from weeks 19 to 26, 4 June through 29 July, and like the previous period was characterized with the sea being slightly warmer than the air on the average but with convergence and vertical motion in the lower troposphere. Inspection of Fig. 3 shows that during the winter period, weeks 2-9, the amount of cloud cover (top number in the left-hand group for each quadrilateral) reflects the extent that the sea is warmer than the air (middle number in each group) for the oceanic quadrilaterals. Quadrilaterals that are adjacent to the coast, especially the northern coast, depart from this, as may be expected from the advection of dry continental air into the region.

The lower figure in each group is the wind velocity. Over the entire Gulf, the period from weeks 10 to 18 has a minimum of cloud cover with the exception of quadrilateral number 11. In this quadrilateral it will be noted that in addition to a slightly negative air-sea temperature difference, the wind velocity is higher than for the other quadrilaterals. During the summer period, almost all the coastal quadrilaterals have a cloud cover as high as or higher than during either of the other two periods. The central oceanic quadrilaterals have slightly less cloud cover than their corresponding winter periods or the coastal quadrilaterals in the same season. As before, it is interesting to note that the wind velocity in these central quadrilaterals, numbers 5, 6, and 7, in this case is less than in the surrounding quadrilaterals.

From information presented in Figs. 1-3, it can be seen that there is apparently some correlation between low cloud cover, air-sea temperature difference, and wind speed. Correlation coefficients were computed between clouds and various parameters utilizing weekly averages for each of the five most populated quadrilaterals subdivided into the three periods previously mentioned. These values are presented in Table I.

Fig. 3. Seasonal change of average low cloud cover, air-sea temperature difference (half-degrees Celsius) and wind speed (kn) for each of the quadrilaterals used in subdividing the Gulf of Mexico for averaging purposes. Quadrilateral numbers appear in the upper righthand corner of each area. Data for the period from 6 February to 1 April 1967 (weeks 2-9) appears in the first column of numbers with average low cloud amount at the top, air-sea temperature difference as middle number, and wind speed as bottom number in each column. Column two contains data for the period from 2 April to 3 June 1967 (weeks 10-18) and column contains data for 4 June to 29 July 1967 (weeks 19-26). For example, in quadrilateral 6 (central Gulf) during the period from 4 June to 29 July 1967 the average low-cloud cover for all ship reports in that quadrilateral was 2.5 eighths, the average air-sea temperature difference was 0 Celsius half-degrees, i.e., the air and sea had the same average temperature, and the wind speed was 8 kn. The two straight lines emitting from the Galveston area on the Texas coast are the major shipping lanes and denote regions of maximum data.



Low Cloud Cover (Eights)
$T_A - T_S$ (half degrees) For Average Of Weeks (2-9, 10-18, 19-26)
Wind Speed
TEXAS
LOUISIANA
MISS
ALA
FLORIDA
CUBA
MEXICO
PENINSULA DE YUCATAN
(1)
(2)
(3)
(4)
(5)
(6)
(7)
(8)
(9)
(10)
(11)
(12)
30°
25°
20°
95°
90°
85°
80°

Table I. Simple correlation coefficients between clouds and air-sea temperature difference ($r_{c\Delta t}$), dewpoint depression ($r_{c(t-t_d)}$) and wind (r_{cw}) for three periods.

	Wk 2-9	Wk 10-18	Wk 19-26
$r_{c\Delta t}$	.43	-.11	-.14
$r_{c(t-t_d)}$	-.33	-.08	-.15
r_{cw}	.57	.31	.51
Number of pairs	40	45	40
.05 significance level	.31	.29	.31

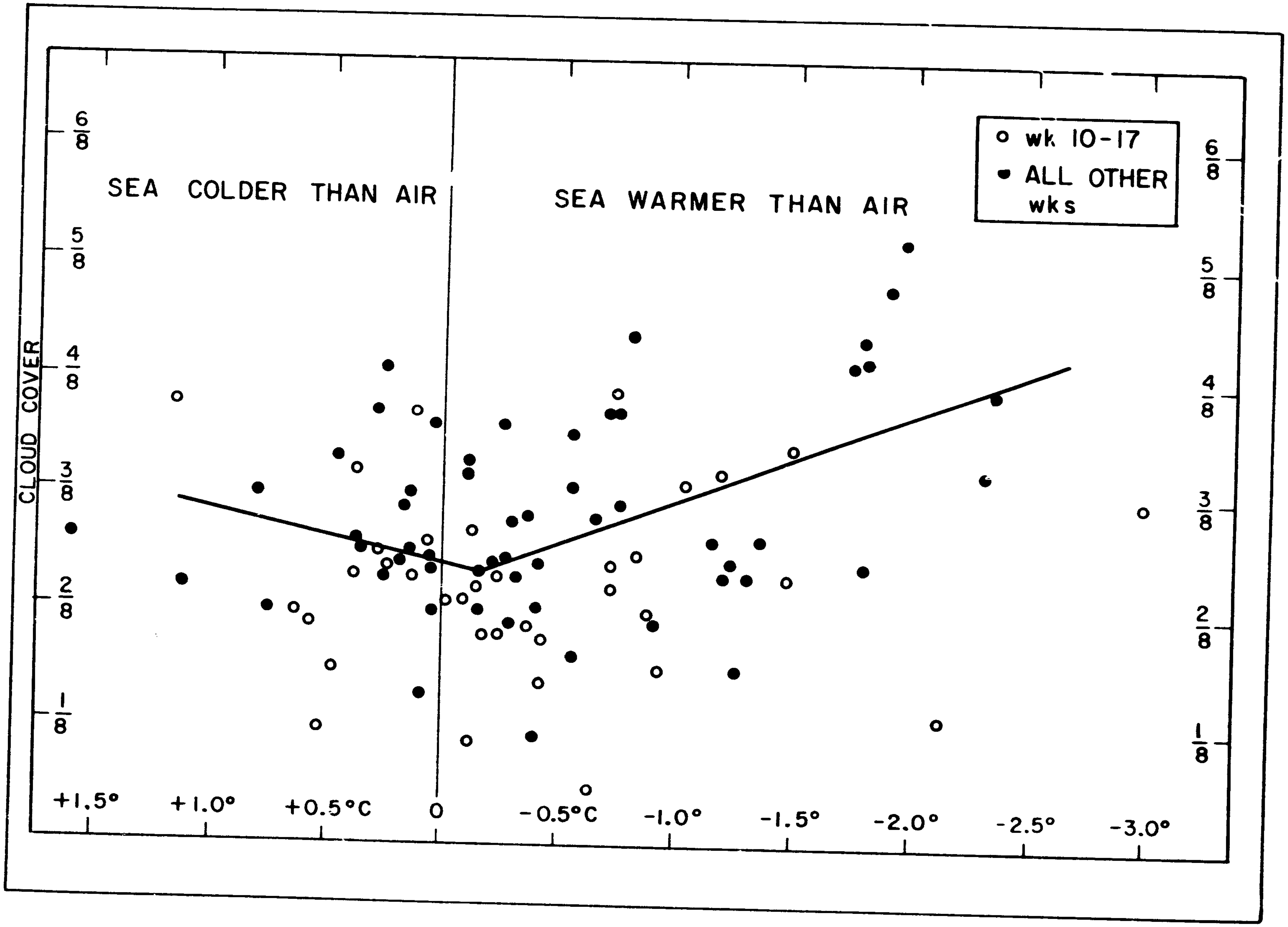
As can be interpreted from the table, the highest correlation between clouds, air-sea temperature difference, dewpoint depression or wind occurred in the winter period. In the latter two periods, the correlation coefficients fell off to insignificant values with the exception of r_{cw}-wind speed. The reversal of the correlation between clouds and air-sea temperature differences for weeks 10-26 is of some interest. Using the correlation coefficient of 0.43 as significant for the period from week 2 to week 9, and it is at the 5 percent level, an expected range of the correlation coefficient for the population can be determined. Based on 40 pairs, the range of the population correlation coefficient should be from 0.29 to 0.56. It is possible then that the reversal of the coefficient in the remaining two periods is significant and that different convective modes are controlling cloud development. The best overall correlation was obtained between clouds and wind velocity as would be expected from examining Figures 1 and 2.

Correlation between low cloud amount and dewpoint depression was weak but in the original data there did seem to be tendency for a reduction in clouds when extremely dry air was encountered. In most cases, the difference had to be considerably in excess of the average dewpoint depression present in the surrounding Gulf at the time. The dewpoint depression itself did not exhibit any pronounced trend through the 25-week examination period as did the other parameters. In the northern part of the Gulf, the dewpoint depression averaged a little less than 5C through the period while in the southern Gulf the difference averaged a little less than 4C.

In spite of the low correlation coefficients between low clouds and the air-sea temperature difference field, the concept that the thermal stability in the lower boundary is important in the convection process, and thus cloud development, is difficult to disregard. As will be shown later, the low simple correlation coefficient is probably due to several factors influencing cloud development in addition to thermal stability. It is more informative to examine a plot of air-sea temperature difference versus low cloud cover than to discuss the small correlation coefficient. Fig. 4 is such a plot with data for four of the most populated quadrilaterals plotted with the intermediate period in open circles and the remaining weeks with solid circles. With some imagination and intuition, it is possible to visualize a trend in the data for the sea warmer than the air values such that a difference in 1/8 cloud cover may result from a temperature change between the sea and air of one degree. Since very few of the points or areas, on the average, have differences as large as this, it could explain in part, the poor correlation coefficient between the two. Data points for the air warmer than the sea are probably due to forced convection and would not necessarily follow the same trend.

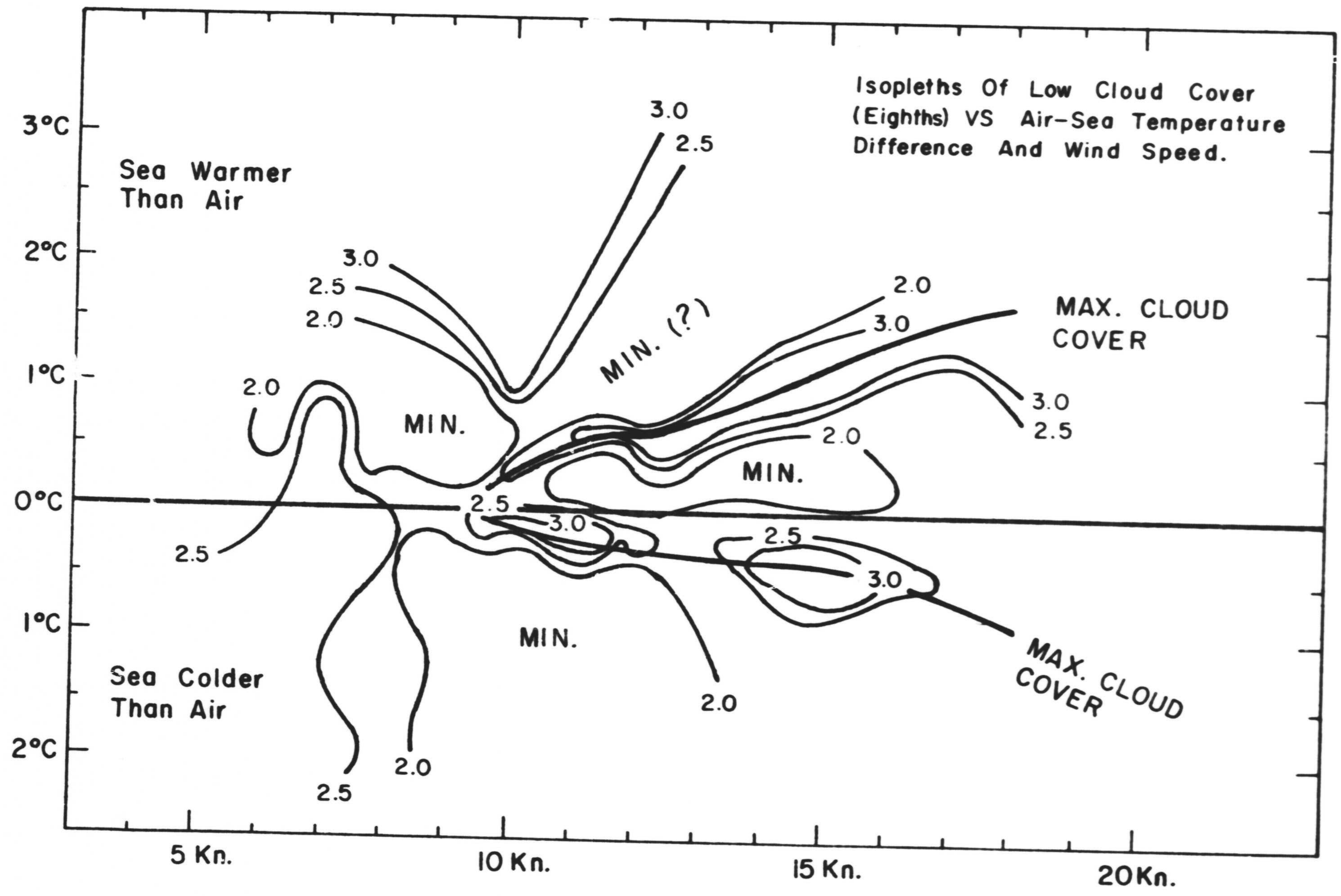
From the discussion in Section II, a relationship between the cloud cover, wind and air-sea temperature difference should exist. Changes in this relationship could result from alterations in the various modes of convection, i.e., from closed versus open cell circulation, from changes in the forced and free convection levels in the boundary layer through the mixing length hypothesis discussed or through changes in the eddy coefficients. Fig. 5 obtained from the analysis of weekly averages of data of four quadrilaterals, omitting winter convection, reveals such a relationship. It can be seen that there are two axes of maximum cloud cover originating at the zero air-sea temperature difference and, for the sea warmer than the air, requiring larger air-sea temperature differences as the wind speed increases to maintain the same average cloud cover. The appearance of a region of minimum cloud cover at high wind velocities and only slightly negative air-sea temperature differences seems to be real at least in the data examined. A possible explaination for the minimum zone could be in the alteration of the eddy transfer coefficients with increasing wind speeds. This could in turn lead to a situation requiring greater heat flux to maintain the convection cells. There is also an axis of maximum cloud cover for cases where the sea is colder than the air and is probably a result of forced convection. Inclusion of the winter data did not alter the overall pattern considerably. The main exception was an indication that the cloud

Fig. 4. Scatter diagram of low cloud cover versus air-sea temperature difference (degrees Celsius) for data from quadrilaterals 6, 7, 11, and 12. Values of cloud amount and air-sea temperature difference are weekly average values for each quadrilateral for each week. Data from weeks 10-17, the period of Gulf of Mexico cloud minimum, are plotted with open circles while all other weeks are plotted as dots.



CLOUD COVER
SEA COLDER THAN AIR
SEA WARMER THAN AIR
o wk 10-17
• ALL OTHER wks
6/8
5/8
4/8
3/8
2/8
1/8
+1.5°
+1.0°
+0.5°C
0
-0.5°C
-1.0°
-1.5°
-2.0°
-2.5°
-3.0°

Fig. 5. Isopleths of low cloud cover in eighths as a function of air-sea temperature difference and wind speed. Data used consisted of weekly averages of the three parameters for each of quadrilaterals 6, 7, 11 and 12 from week 10-26.


Isopleths Of Low Cloud Cover (Eighths) VS Air-Sea Temperature Difference And Wind Speed.
Sea Warmer Than Air
Sea Colder Than Air
MAX. CLOUD COVER
MAX. CLOUD COVER
MIN. (?)
MIN.
MIN.
MIN.
3°C
2°C
1°C
0°C
1°C
2°C
5 Kn.
10 Kn.
15 Kn.
20 Kn.
3.0
2.5
2.0

minimum at wind speeds of 12 knots and air-sea temperature differences of 1 to 2C was eliminated and an average area of 3/8 cloud cover or greater existing throughout the entire upper area of the chart. These winter cases will be discussed in greater detail in the following section.

From the information presented in Figs. 4 and 5, a partial explanation can be given for the problem of relating the oceanic cloud field to any one feature, especially the air-sea temperature difference. First of all, the change of air-sea temperature differences from area to area required to cause a corresponding change in cloud cover is greater, in averages, than is usually observed from day to day. However, sufficient differences do exist. Secondly, the combination of air-sea temperature difference and wind speeds is capable of producing alterations in the cloud cover in a manner such that at a consistent wind speed the cloud cover can vary, depending on the heat flux. Given a constant air-sea temperature difference, changes in wind speed could alter the cloud amount. As was also pointed out previously, the state of the atmosphere above the ocean is also important in the appearance of clouds visible from the ground or in satellite photographs.

Since several investigators, particularly Garstang (1964), have examined the diurnal trends of air-sea temperature differences, cloud cover, pressure and wind speed, it is of interest to show the variation of these parameters as obtained from the ship reports in the Gulf of Mexico. For consistency, the same periods have been used in this analysis as in the previous discussion. The diurnal variation of air-sea temperature difference is illustrated in Fig. 6a. It can be seen that during the weeks beyond week 10, 2 April, the sea was warmer than the lower atmosphere by approximately 0.6C at 0600 local and was about 0.5C colder than the atmosphere at the time of the local noon observation. During the winter period, weeks 2 to 9, the sea was warmest in relation to the air at local midnight decreasing to about 0.6C warmer than the air by local noon. The low level cloud cover shown in Fig. 6b did not reflect the inferred change in low level stability to any great degree. In fact, the maximum cloud amount was observed at times when the sea was colder than the air. It is possible that the midnight minimum is due to darkness and poor cloud visibility but even the early morning observations during the spring and summer months do not show a significant increase in cloud amounts corresponding to the air-sea temperature differences. In interpreting this trend, however, one must also consider the data presented in Fig. 5. The diurnal pressure wave is presented in Fig 6c as pressure differences between observation times. The magnitude of the wave was about 2 mb during the winter and spring but altered in shape for the summer period. If the pressure wave is interpreted as a zone of maximum pressure propagating from east to west causing an increase in wind velocity as the wave approaches and a decrease of wind velocity as the wave passes, zones of convergence and divergence can also be visualized. The resultant effect on cloud cover would be one of increasing cloud cover between 1600 local time and 2200 local time, by darkness, and between 0400 and 1000 local time. Decreases in cloud cover due to local divergence should be observed between 2200 local time and 0400 local time

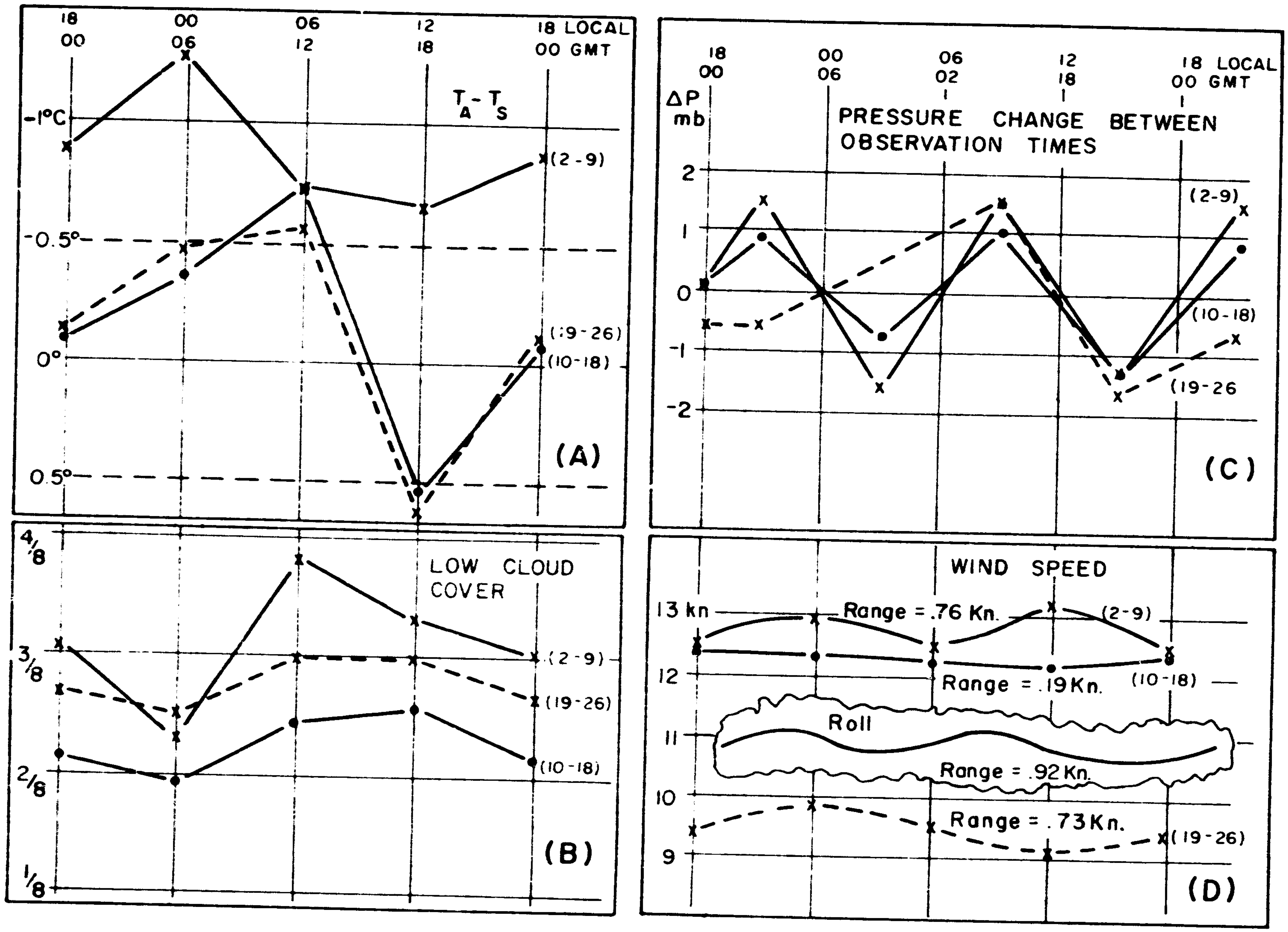
Fig. 6. Diurnal variation, observed from averages of each observation time (00, 06, 12, 18 GMT), over the entire Gulf of Mexico for the periods of weeks 2-9, 10-18, 19-26, of:

(a) Temperature of the air minus temperature of the sea in degrees Celsius for each observation time

(b) Low cloud cover in eighths for each observation time

(c) Pressure change from one observation time to the next in mb

(d) Average wind speed at each observation time and the range of wind speed observed. Inset is diurnal variation of wind speed from Roll (1965) for the Trade Wind zone.



18 00
00 06
06 12
12 18
18 LOCAL 00 GMT
$T_A - T_S$
-1°C
-0.5°
0°
0.5°
(2-9)
(19-26)
(10-18)
(A)
4/8
3/8
2/8
1/8
LOW CLOUD COVER
(2-9)
(19-26)
(10-18)
(B)
ΔP mb
PRESSURE CHANGE BETWEEN OBSERVATION TIMES
18 00
00 06
06 02
12 18
18 LOCAL 00 GMT
2
1
0
-1
-2
(2-9)
(10-18)
(19-26
(C)
WIND SPEED
13 kn
12
11
10
9
Range = .76 Kn.
(2-9)
Range = .19 Kn.
(10-18)
Roll
Range = .92 Kn.
Range = .73 Kn.
(19-26)
(D)

and 1000 and 1600 local time. A cloud suppressing or enhancing mechanism in addition to the air-sea temperature difference trend throughout the day gives a better explanation of the diurnal trend of the observed cloud amount than either independently. The actual variation of the wind at the different observation times does not appreciably reflect the diurnal pattern expected from the previous discussion of the pressure wave. As can be seen from Fig. 6d, there is almost no diurnal variation for the period of week 10 to 18. The diurnal variation of the wind for the winter period from week 2 to 9 most closely corresponds to the pressure wave while the summer period, week 19 to 26, has a wind maximum at local midnight. This decreases to a single minimum at local noon. The diurnal variation of the wind speed in the Trades according to Kuhlbrodt and Reger from Roll (1965) has been included in Fig. 6d to illustrate where maximums and minimums occur based on more complete observations.

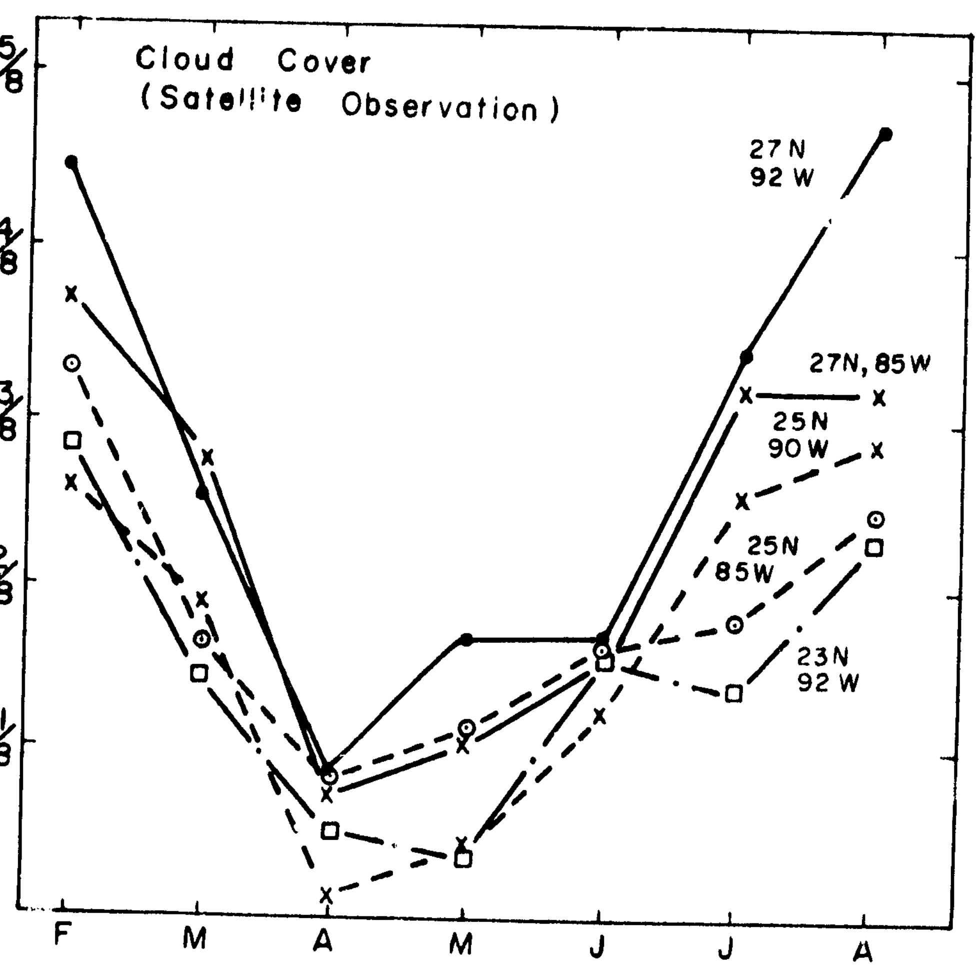
METEOROLOGICAL SATELLITE OBSERVATIONS OF THE GULF CLOUD FIELD

Observation of the cloud distribution of the earth can be accomplished utilizing the orbiting meteorological satellites. The ESSA series of satellites provides photographs over much of the earth's surface taken at approximately local noon on each pass or orbit as the satellite revolves about the earth. Because of the resolution of the camera and television vidicon system there is a tendency to overestimate the amount of cloud cover present when the cloud field consists of a large number of well developed cells. There is a tendency to underestimate the cloud cover when there are only poorly developed clouds with large areas of clear air between the clouds. Separation between low and middle or high clouds is often difficult or impossible from the photographs alone. To overcome the ambiguity between cloud layers or level of the predominant cloud field, surface observations and cloud form or structure as seen in the satellite photograph are used. In the present investigation, satellite observations were used to examine the variation of cloud cover at given points over the Gulf of Mexico and to determine the forms of response of the cloud field to air-sea temperature differences and horizontal temperature gradients on the ocean surface.

Initially it was hoped that some correlation could be found between the cloud cover over a given area and the temperature change in the surface water. The basic premise for this inquiry was that cloud cover at the lower levels, i.e., cumulus forms, were the result of increased instability due to the sea temperature being warmer than the atmosphere and that greater cloud amounts occurred simultaneously with higher wind speeds. The expected result was that the ocean should heat at a slower rate in the areas of large cloud cover due to decreased solar insolation and increased mixing of the surface water. With the data available, this did not seem to be the case. Frequently the ocean surface temperature continued to increase even though the cloud cover increased considerably over a period of two or three weeks. A highly probable reason for this result seems to be that the prevailing horizontal advection dominated the heating processes in the area examined.

Variations of the total cloud amount determined from satellite observations (ESSA III) for areas within the quadrilaterals partitioned off for the ship report averages followed trends from week to week similar to those described using averages of cloud amounts reported by the ships. The satellite observations of cloud amounts were averaged into corresponding monthly averages from February through August and are presented in Fig. 7 for five data areas. As can be seen, the trend from a winter maximum to a spring minimum and back to a summer maximum is much more pronounced that that obtained from ship reports alone. This difference is in part due to total cloud amount appearing in Fig. 7 as opposed to just low cloud amount in Figs. 1 and 2. The difference between the low cloud amount and total cloud amount in the ship report averages, however, was usually less than 1/8 coverage on a week-to-week average. The tendency to overestimate and underestimate cloud amounts from the satellite photographs also contributes to the enhancement of the seasonal trend shown in Fig. 7. The average amount

Fig. 7. Average total-cloud amount (monthly) for five points in the Gulf of Mexico determined from satellite (ESSA III) photographs. Cloud amounts were estimated for a two-degree-latitude diameter circle about the central point.


Cloud Cover
(Satellite Observation)
27 N
92 W
27N, 85 W
25 N
90 W
25 N
85 W
23 N
92 W
5/8
4/8
3/8
2/8
1/8
F
M
A
M
J
J
A

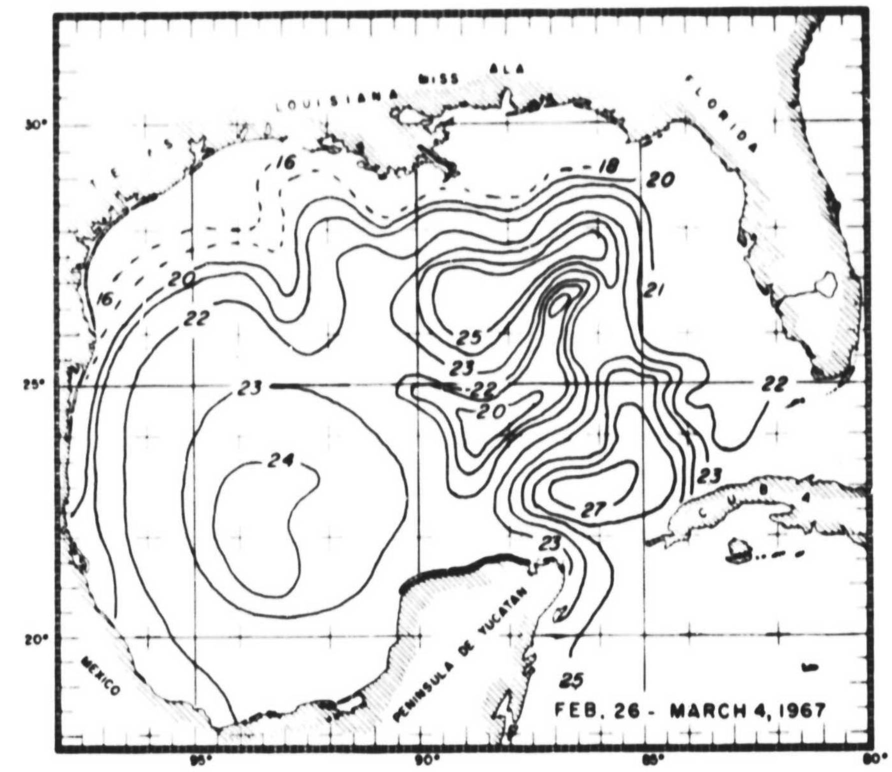
of clouds in each area for each month reflects to some extent the temperature gradients surrounding the specific location for which cloud estimates were made. Both of the areas in the northern Gulf (27N) are near or within the warm water tongues and pronounced gradients illustrated in section III. The area at 25N, 90W, or in the central Gulf is usually a region of minimum temperature gradient on the surface water while the area at 23N, 92W is near the temperature gradients induced by the current maximum in the southern Gulf. The proximity to surface temperature gradients permits air flowing over cold water, relatively speaking, to arrive at an area where the water is significantly warmer thus increasing the low level instability.

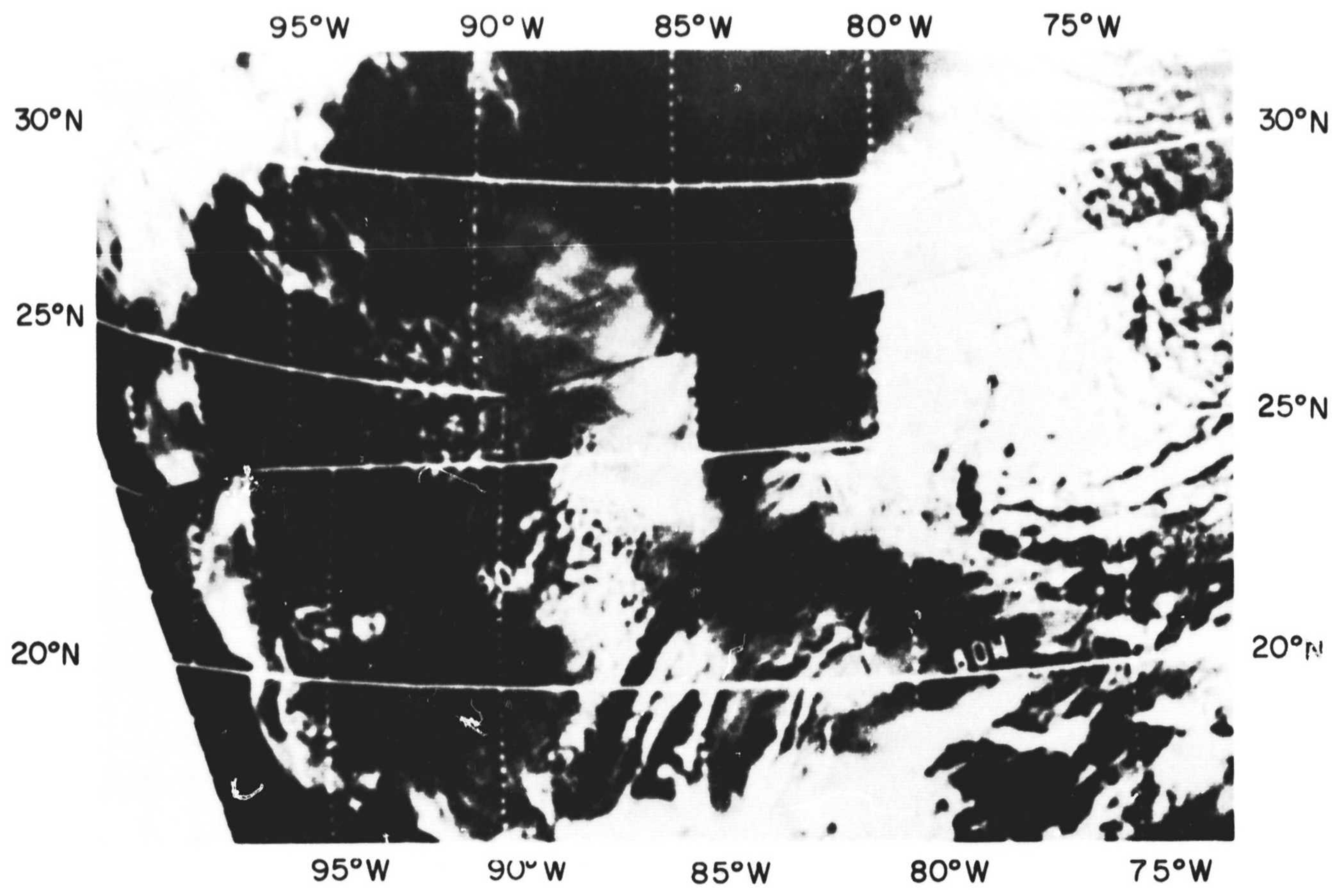
The response of the low-level cloud field to the ocean surface temperature and various atmospheric parameters can be best illustrated by examining representative individual cases. Two examples illustrating winter and spring situations, periods when the response of the cloud field seemed to be best correlated with the ocean surface, are shown in Figs. 8 and 10 with the corresponding surface analyses of air-sea temperature difference, wind and dewpoint depression shown in Figs. 9 and 11.

The typical winter cloud situation associated with a cold air outbreak over the Gulf of Mexico is characterized by stratiform clouds developing over the warm water areas changing from a solid overcast offshore to bands of clouds slightly downstream and finally to cells in the manner and sequence discussed in Section II. In Fig. 8a, it should be noted that relatively cold water exists off the western coast of Florida extending Gulfward for approximately 200 miles or approximately [illegible] hours flow time after the air

Fig. 8 (a) Temperature distribution in the Gulf of Mexico for the period of 26 February to 4 March 1967 (degrees Celsius).

(b) Photograph of the Gulf of Mexico taken by the ESSA III satellite at approximately local noon on 26 February 1967.



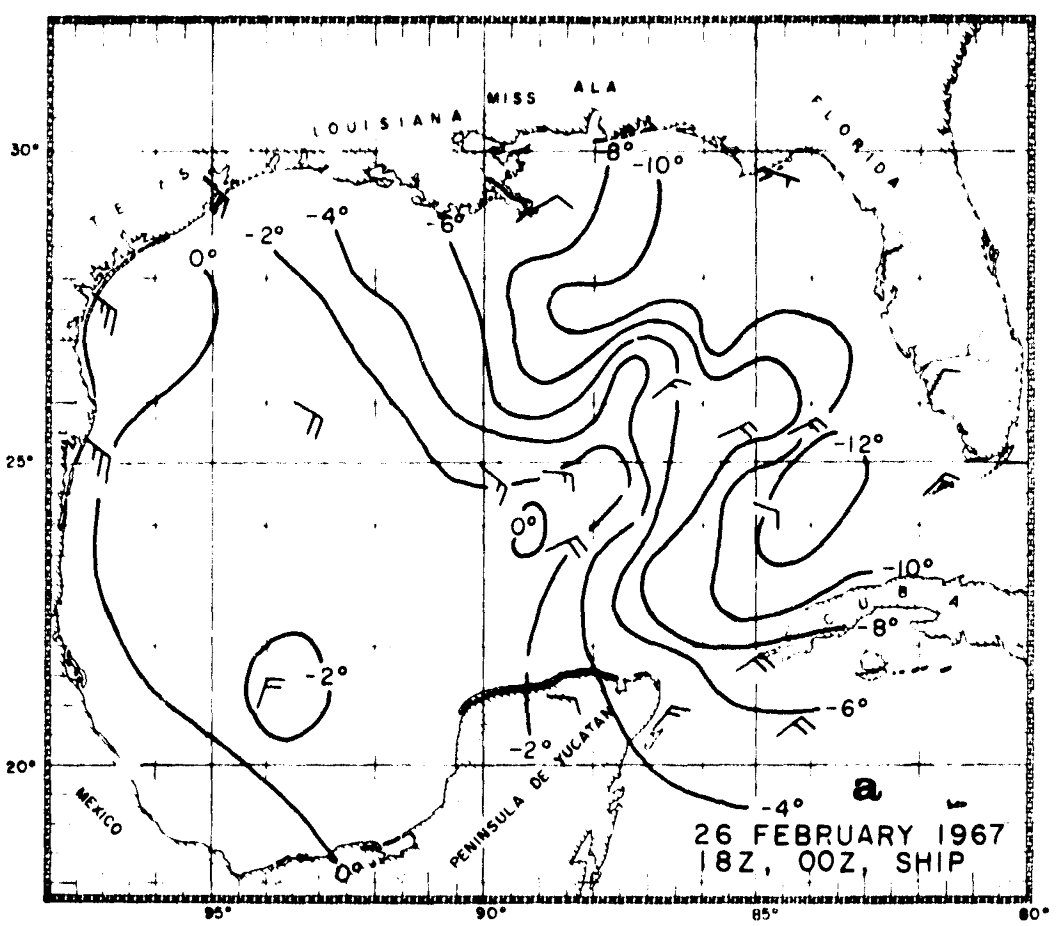


26 FEBRUARY 1967

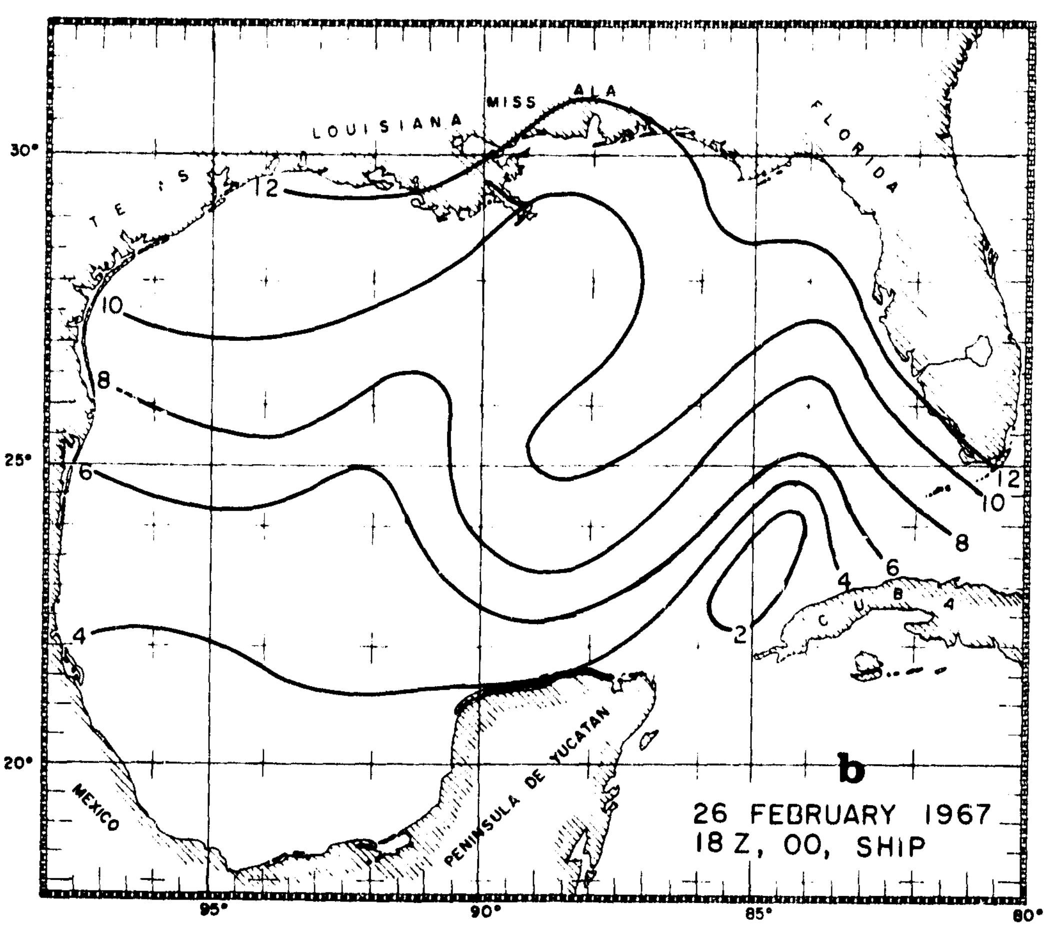
Fig. 9 (a) Temperature difference between the air and the sea on 26 February 1967. Sea-surface temperatures used were those for the week of 26 February to 4 March 1967. Air temperatures were taken from 1800 GMT ship reports and 0000 GMT 27 February ship reports. Land station reports of wind and temperature were for 1800 GMT, 26 February 1967.

(b) Air temperature minus dewpoint temperature over the Gulf of Mexico determined from 1800 GMT and 0000 GMT ship reports on 26 February 1967.

Note: Temperature differences are in degrees Celsius.



LOUISIANA
MISS
ALA
FLORIDA
TEXAS
MEXICO
PENINSULA DE YUCATAN
CUBA
30°
25°
20°
95°
90°
85°
80°
0°
-2°
-4°
-6°
-8°
-10°
-12°
-10°
-8°
-6°
-4°
-2°
0°
-2°
0°
a
26 FEBRUARY 1967
18Z, 00Z, SHIP



LOUISIANA
MISS
ALA
FLORIDA
TEXAS
MEXICO
PENINSULA DE YUCATAN
CUBA
30°
25°
20°
95°
90°
85°
80°
12
10
8
6
4
12
10
8
6
4
2
b
26 FEBRUARY 1967
18Z, 00, SHIP

leaves Florida. During this particular period, a strong cold water tongue is also present centered at approximately 24.5N, 88W. In the cloud field shown in Fig. 8b for 26 February 1967 (local noon), there is a total absence of clouds until the area of strong temperature gradient near the two warm areas in the eastern Gulf is reached. Also a noticeable decrease in cloud cover near the central Gulf cold water area at 24.5N, 89W is noted. There is a second small maximum of cloud activity at 22N, 94W corresponding to the western Gulf warm water region. Examination of the distribution of air-sea temperature difference and dewpoint depression in Figs. 9a and 9b shows that in the area of maximum cloud cover in the eastern Gulf the air-sea temperature differences are between 6 and 8 degrees (sea warmer than the air) decreasing to almost no difference in the region associated with the cloud minimum at 25N, 89W. In the coastal area off Florida, the air is very dry and contributes to the lack of clouds as can be seen in Fig. 9b. Over the regions of maximum cloud cover, the dewpoint depression spread is still relatively large, 6-8C. However, an increase in the spread is present over the areas where cloud cover tends to be less extensive, east of 90W. The proximity of the dry tongue and the cold water area in the central Gulf of Mexico reflects the decrease of moisture flux over the cold water portion of the air trajectory.

Examination of the satellite photographs through the period from February to August revealed that two time periods existed when there seemed to be the best correlation between the ocean surface temperature field, the associated air-sea temperature difference, and the instantaneous cloud field.

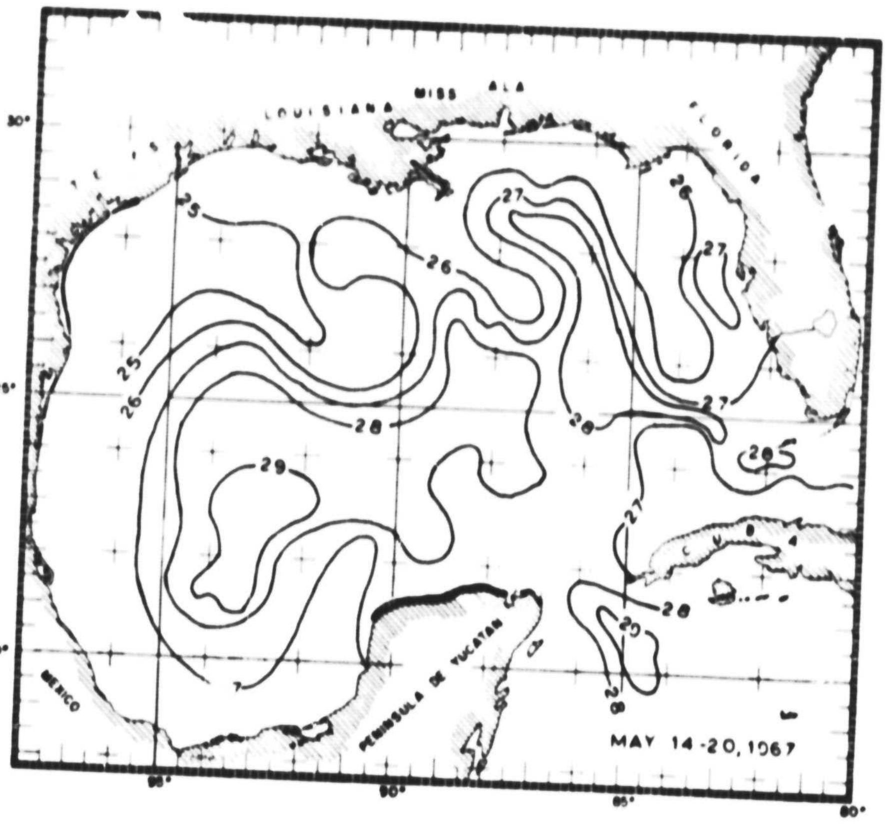
The first of these periods was in February and early March and is illustrated by the previous example. The second period extended from mid-May through mid-June and is illustrated in the next example.

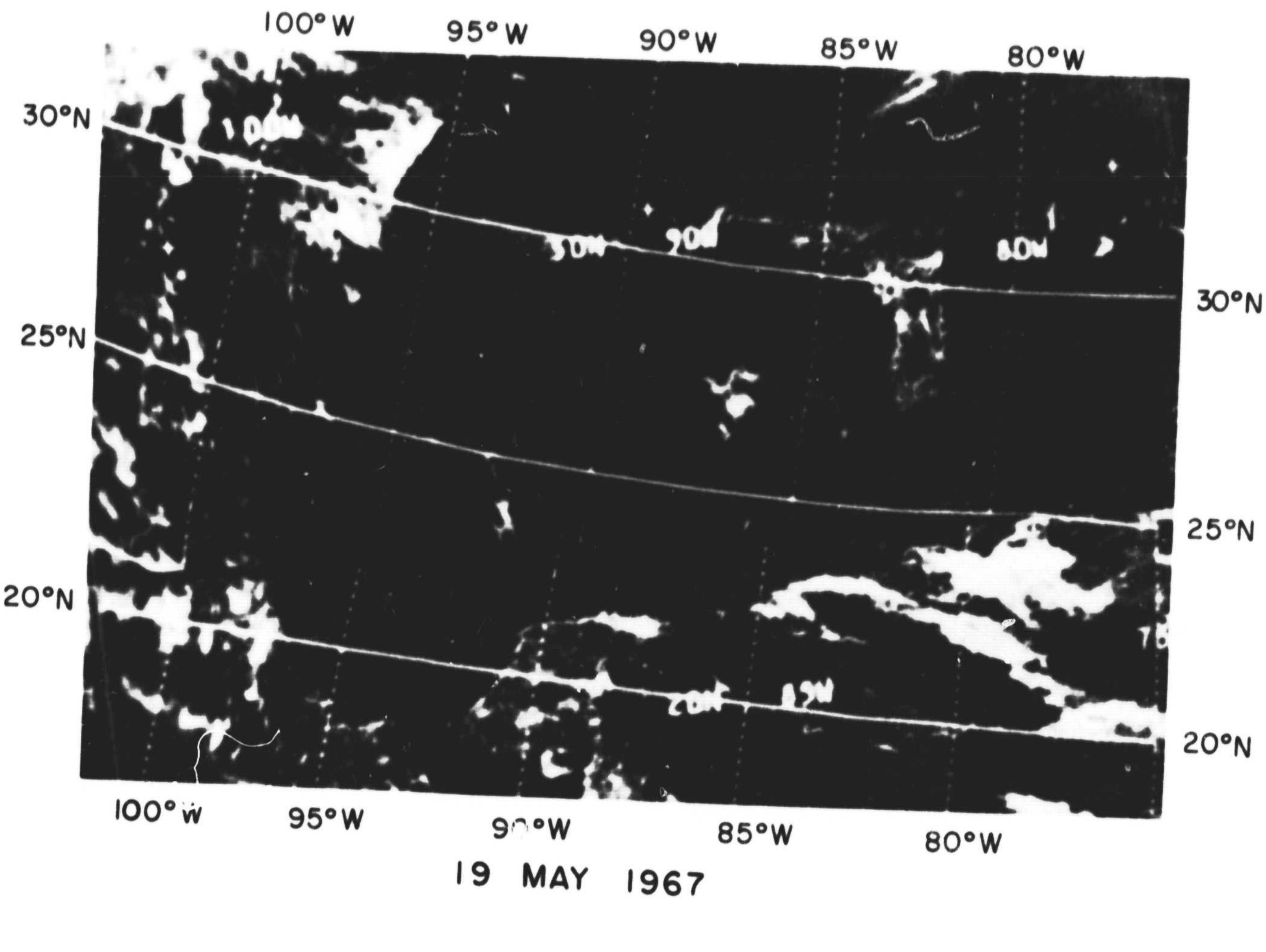
The satellite photograph of the cloud field shown in Fig. 10b was exposed at approximately local noon on 19 May 1967. The associated sea-surface temperature field, based on a one-week time period, is shown in Fig. 10a. The main points to note in Fig. 10a are the warm water areas centered at 26N, 86W and at 23N, 93W. Associated with the warm water areas are regions of maximum cloud activity with pronounced cloud cover near the warmest water areas and faint indications of additional cloud cover along the axis of both warm water regions. The air-sea temperature difference analysis presented in Fig. 11a supports the basic hypothesis advanced throughout this report that the cloud field is closely related to the air-sea temperature difference. In this particular example, the oceanic cloud cover is most pronounced when the air-sea temperature difference is 2C or greater (sea warmer than air). Areas within the region where the air-sea temperature difference exceeded 2C that had no appreciable cloud activity were also areas where the air was drier than the average as can be seen in Fig. 11b.

In view of the two examples presented, the low correlation coefficient between clouds and dewpoint depression spread determined from the weekly averages in section III does not seem particularly representative on an individual basis. The correlation between clouds and the air-sea temperature difference is clearly altered by the dewpoint depression when

Fig. 10. (a) Temperature distribution in the Gulf of Mexico for the period of 14-20 May 1967 (degrees Celsius).

(b) Photograph of the Gulf of Mexico taken by the ESSA III satellite at approximately local noon on 19 May 1967.


LOUISIANA
MISS
ALA
FLORIDA
MEXICO
PENINSULA DE YUCATAN
25
26
27
28
29
MAY 14-20, 1967

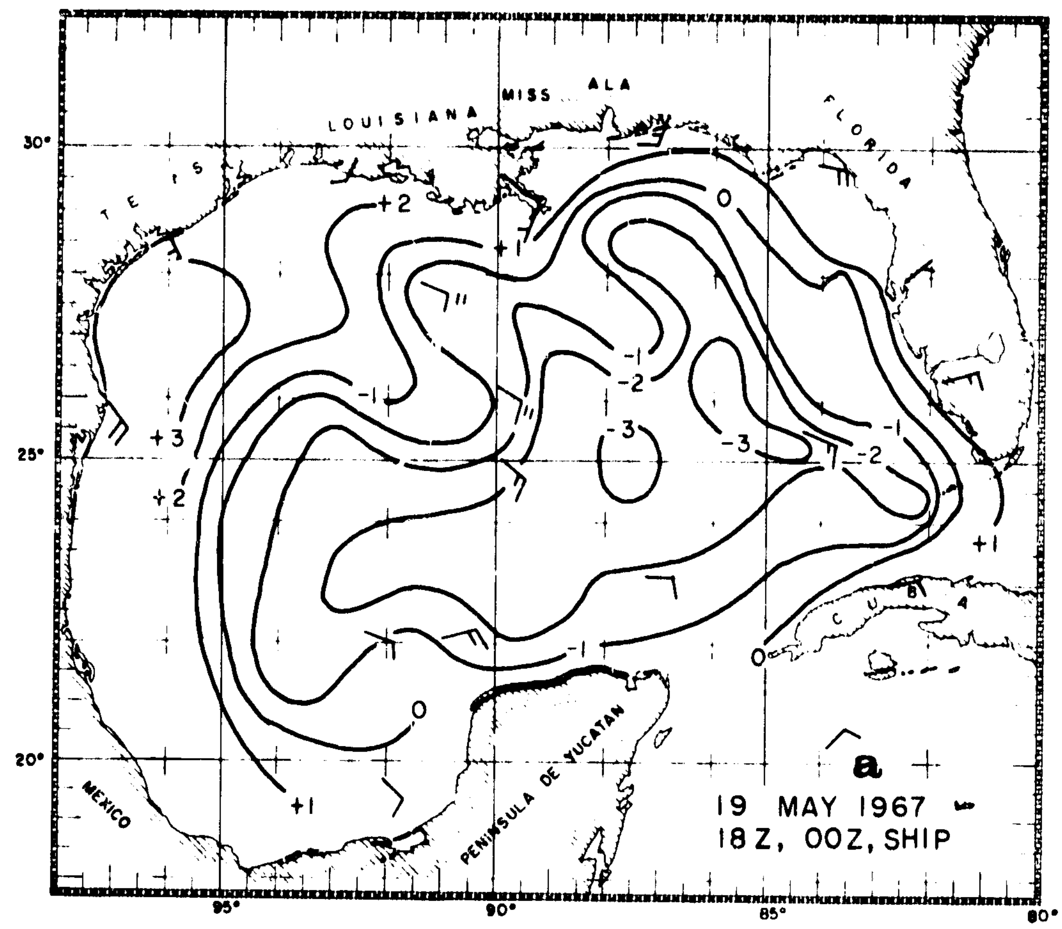

100°W
95°W
90°W
85°W
80°W
30°N
25°N
20°N

19 MAY 1967

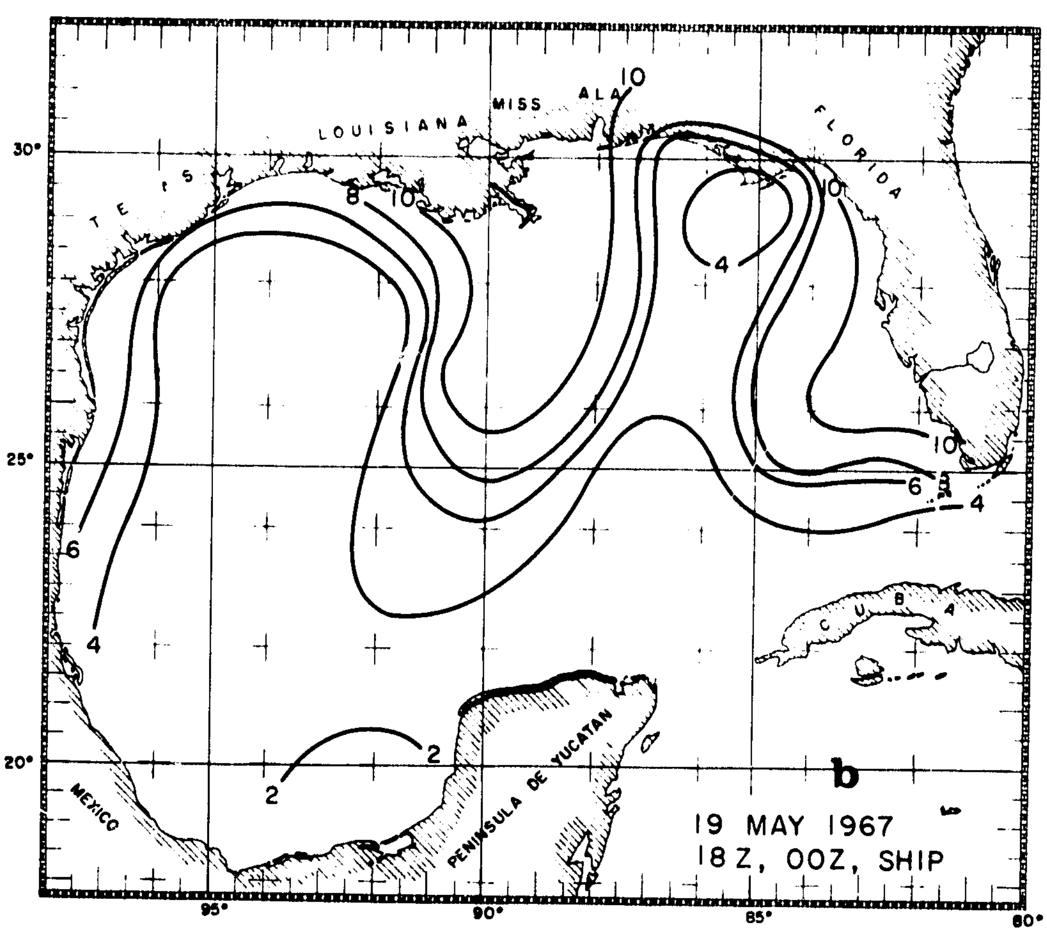
Fig. 11. (a) Temperature difference between the air and the sea on 19 May 1967. Sea surface temperatures used were those for the week of 14-20 May 1967. Air temperatures were taken from 1800 GMT ship reports and 0000 GMT 20 May ship reports. Land station reports of wind and temperature are for 1800 GMT 19 May 1967.

(b) Air temperature minus dewpoint temperature over the Gulf of Mexico determined from 1800 GMT and 0000 GMT ship reports on 19 May 1967.

Note: Temperature differences are in degrees Celsius.



LOUISIANA
MISS
ALA
FLORIDA
TEXAS
MEXICO
PENINSULA DE YUCATAN
CUBA
a
19 MAY 1967
18Z, 00Z, SHIP



LOUISIANA
MISS
ALA
FLORIDA
TEXAS
MEXICO
PENINSULA DE YUCATAN
CUBA
b
19 MAY 1967
18Z, 00Z, SHIP

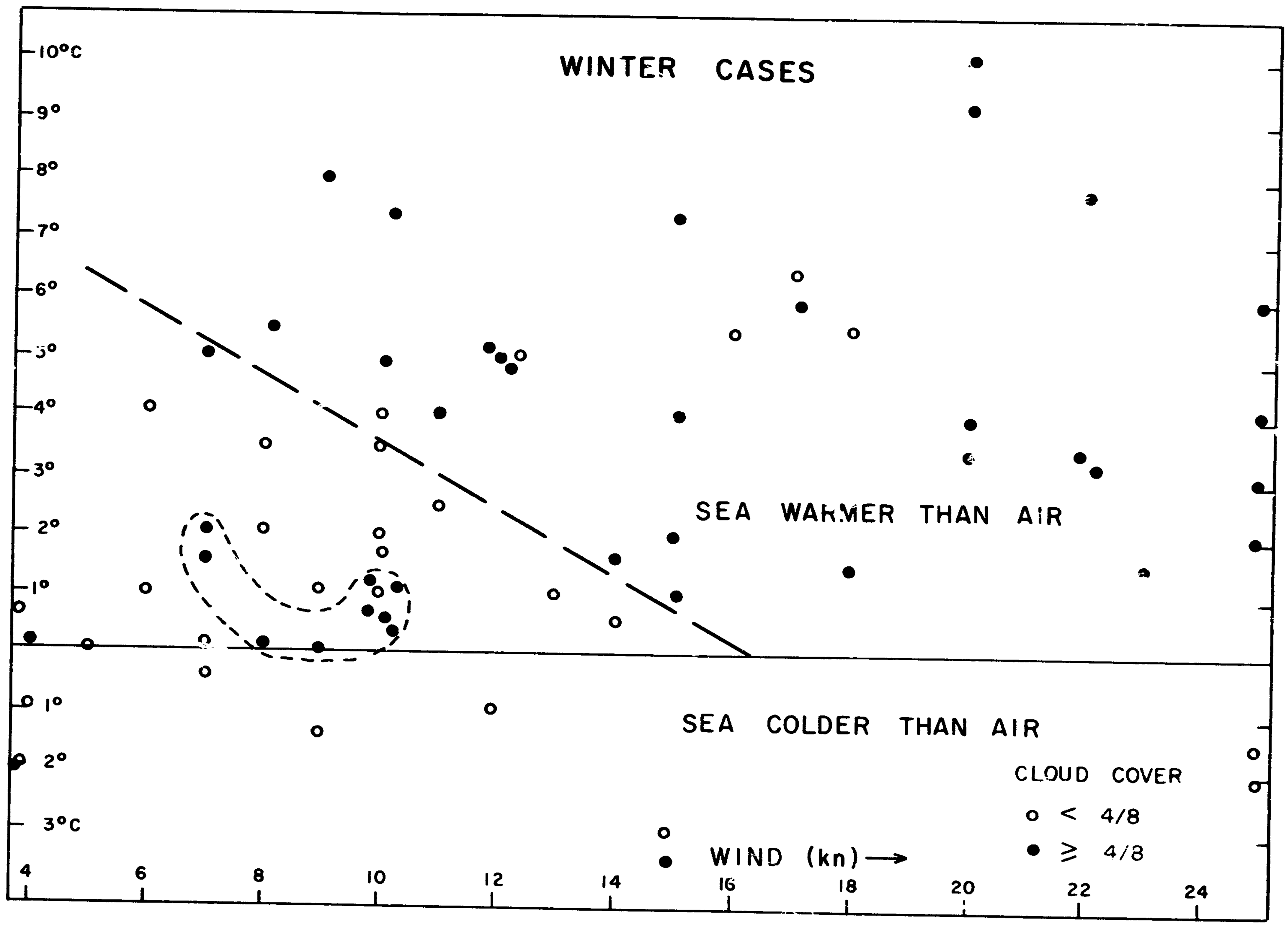
the lower atmosphere gets excessively dry. The relationship between wind velocity and the cloud field is difficult to determine when working with a specific case due to the sparsity of ship reports. In an attempt to determine how cloud cover responded to air-sea temperature differences and wind speed, individual ship reports were examined in the area of the Gulf of Mexico north of 25N and east of 90W. This area was chosen because of the large temperature gradients of the sea surface that usually exist in the area and the relatively large number of ship reports available. Data for two-week intervals were examined to eliminate trends and reports with excessively large dewpoint depression spreads and nearness to land. Examination of several periods throughout the time interval from February to August revealed two basic relationships between low cloud cover, air-sea temperature difference and wind, one for winter convection and one for summer convection. There was some indication of a slow transition between the two.

Data from two weeks in mid-February are shown in Fig. 12. Since the most frequently reported cloud cover was 3/8, cloud cover is plotted as being equal to or greater than 4/8, i.e., greater than average, or 3/8 or less representing average or below average coverage. As can be seen in Fig. 12, increasing wind speeds required progressively less air-sea temperature difference to maintain above average cloud cover. With the sea 4C warmer than the air, above average cloud cover was not exceeded until wind speeds in excess of 10 knots existed. At wind speeds in excess of approximately 15 knots very small values of air-sea temperature difference existed with above average cloud cover. The small area of above average cloud cover with light winds and small air-sea temperature differences occurred in the vicinity of frontal zones.

During the spring and summer periods, the temperature differences between the ocean and the atmosphere are considerably less than in the winter. In addition, wind speed and vertical wind shear are less than during the winter months. A change from a general state of subsidence in the lower troposphere in winter to one of convergence existing in the summer is also noted. The relationship between cloud cover, wind and air-sea temperature differences has also undergone an alteration. As can be seen in Fig. 13, beyond wind speeds of approximately 4 knots, an increasing air-sea temperature difference is required to maintain above average cloud conditions as the wind speed increases. Although there is considerable scatter in the data, there is a strong similarity between the trend shown in Fig. 13 and the pattern shown in Fig. 6. This mutual confirmation between averages and individual points over a short period indicates that the apparent trend is more than just chance. Application of the relationships illustrated in Figs. 12 and 13 to conditions presented in the two cloud field examples in Figs. 8 and 10 further confirms the hypothesis that changing heat fluxes at constant wind speed alters the cloud field. The data, of course, are not completely independent.

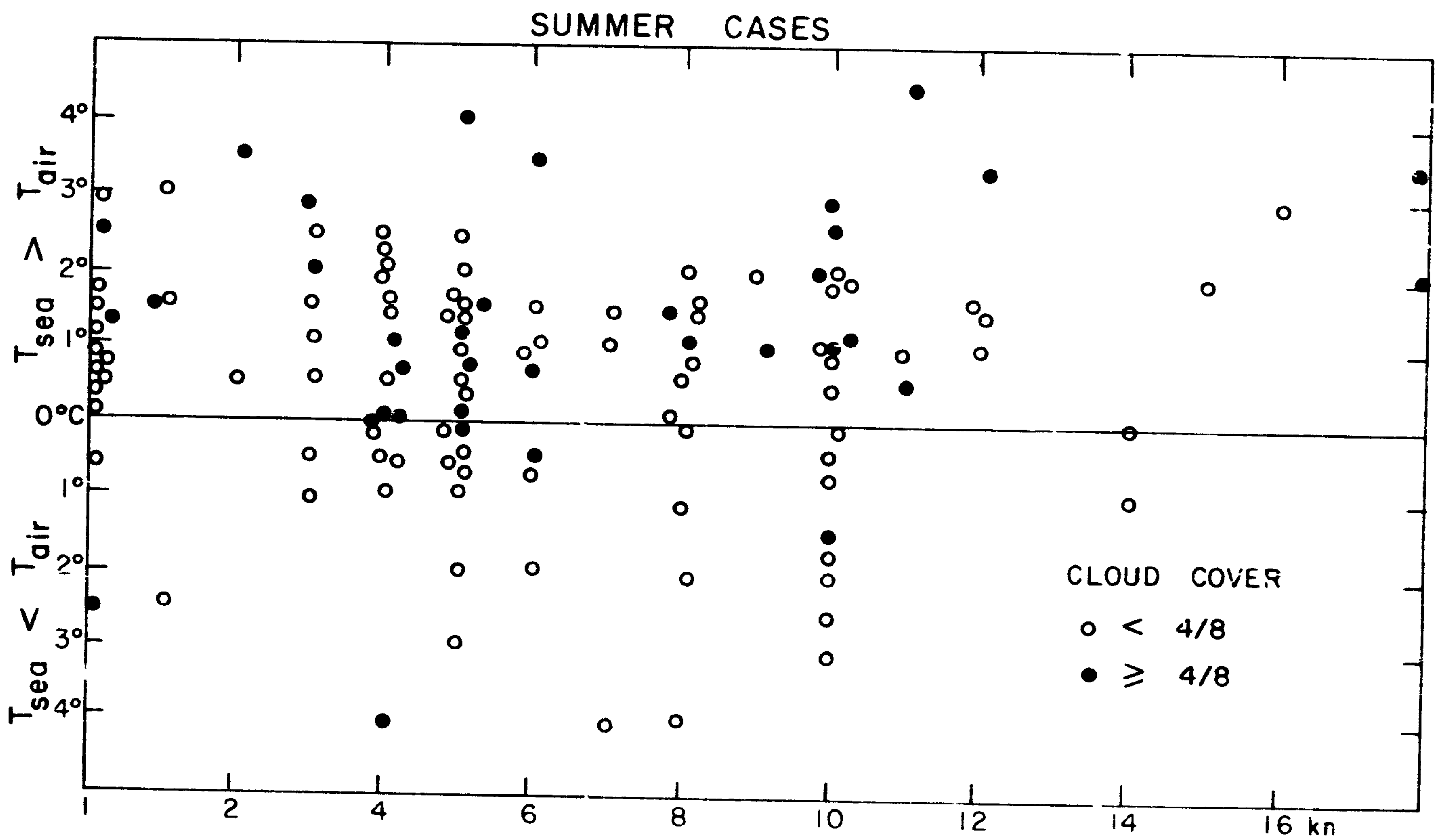
To illustrate the transitory nature of any particular cloud field or pattern as viewed from satellite altitudes, two four-day periods and one

Fig. 12. Low cloud cover (winter) plotted as a function of air-sea temperature difference and wind speed. Dots represent equal to or greater than 4/8 coverage, above average; circles less than 4/8 coverage, average or below average. Data are taken from individual ship reports for two weeks in February 1967 north of 25N and east of 90W. Reports near land or with excessively large dewpoint depressions were omitted. Dots within closed dashed line were associated with frontal activity.



WINTER CASES
10°C
9°
8°
7°
6°
5°
4°
3°
2°
1°
1°
2°
3°C
SEA WARMER THAN AIR
SEA COLDER THAN AIR
CLOUD COVER
< 4/8
≥ 4/8
WIND (kn) →
4
6
8
10
12
14
16
18
20
22
24

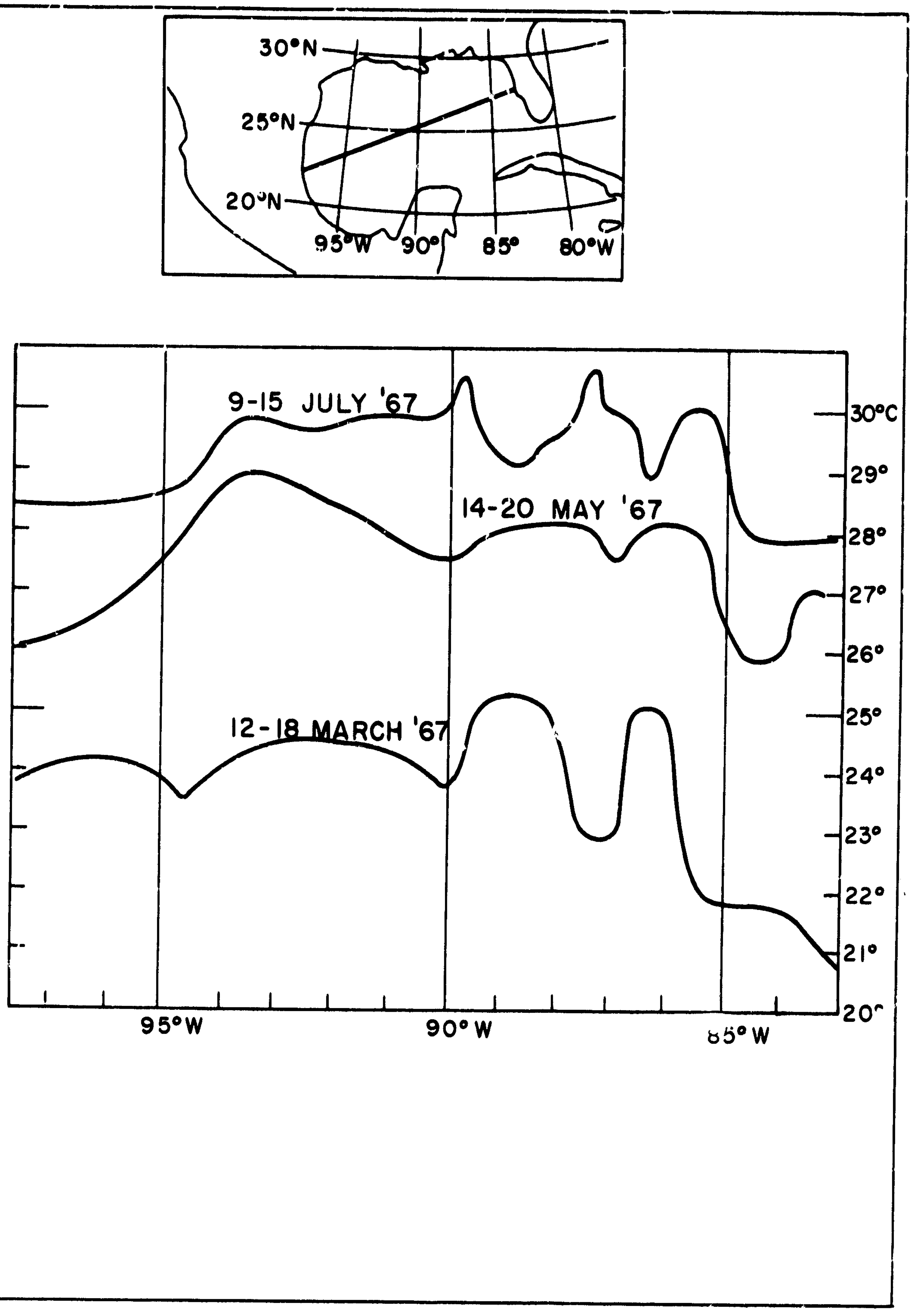
Fig. 13. Low cloud cover (summer) plotted as equal or to greater than 4/8 coverage, above average, in dots and less than or equal to 4/8 coverage, average or below average, in circles as a function of air-sea temperature difference and wind speed. Data are taken from individual ship reports for one week in late July and one week in early August north of 25N and east of 90W. Reports near land or with excessively large dewpoint depressions were omitted.


SUMMER CASES
$T_{sea} > T_{air}$
$T_{sea} < T_{air}$
0°C
1°
2°
3°
4°
2
4
6
8
10
12
14
16 kn
CLOUD COVER
< 4/8
≥ 4/8

five-day period will be presented. Meteorological data at the surface are given along the line from Tampa, Florida to Tampico, Mexico illustrated in Fig. 14. The sea-surface temperature gradient along this line for the periods examined is also illustrated in Fig. 14.

Photographs taken at local noon of the Gulf of Mexico for the period from 16 March through 19 March 1967 are shown in Fig. 15. During this period, a moderately well organized frontal system passes over the Gulf with the frontal cloud band best defined on 16 March, Fig. 15a. There is some indication that the cold water area centered at 27N and 87W to 88W, shown in Fig. 6, has contributed to the breaking up of the front in that region although no great local intensification due to the warm areas is visible at this time. By 17 March a pronounced region of cloud activity is apparent at 25N and 86W and appears to be associated with the development of a wave on the frontal zone in response to the warm water in approximately that area. The development of an open wave is also supported in the analysis of temperature and moisture, and to some extent pressure, reported by commercial ships in the area (not shown). From the photograph taken on 18 March, Fig. 15c, it appears that the developing wave has either moved out of the Gulf of Mexico area or dissipated. By 19 March, the entire Gulf seems to be under the influence of the same cool air mass. Comparison of the air-sea temperature differences, dewpoint depression spread and wind velocities, shown in Table II, along the data line for the four-day period reveals that cloud presence along the line is greatly influenced by the air-sea temperature difference and the dewpoint depression spread. The effect

Fig. 14. Horizontal variation of surface temperature along a line from Tampa, Florida to Tampico, Mexico for the periods of 12-18 March, 14-20 May, and 9-13 July 1967 (degrees Celsius).



30°N
25°N
20°N
95°W
90°
85°
80°W
9-15 JULY '67
14-20 MAY '67
12-18 MARCH '67
30°C
29°
28°
27°
26°
25°
24°
23°
22°
21°
20°
95°W
90° W
85° W

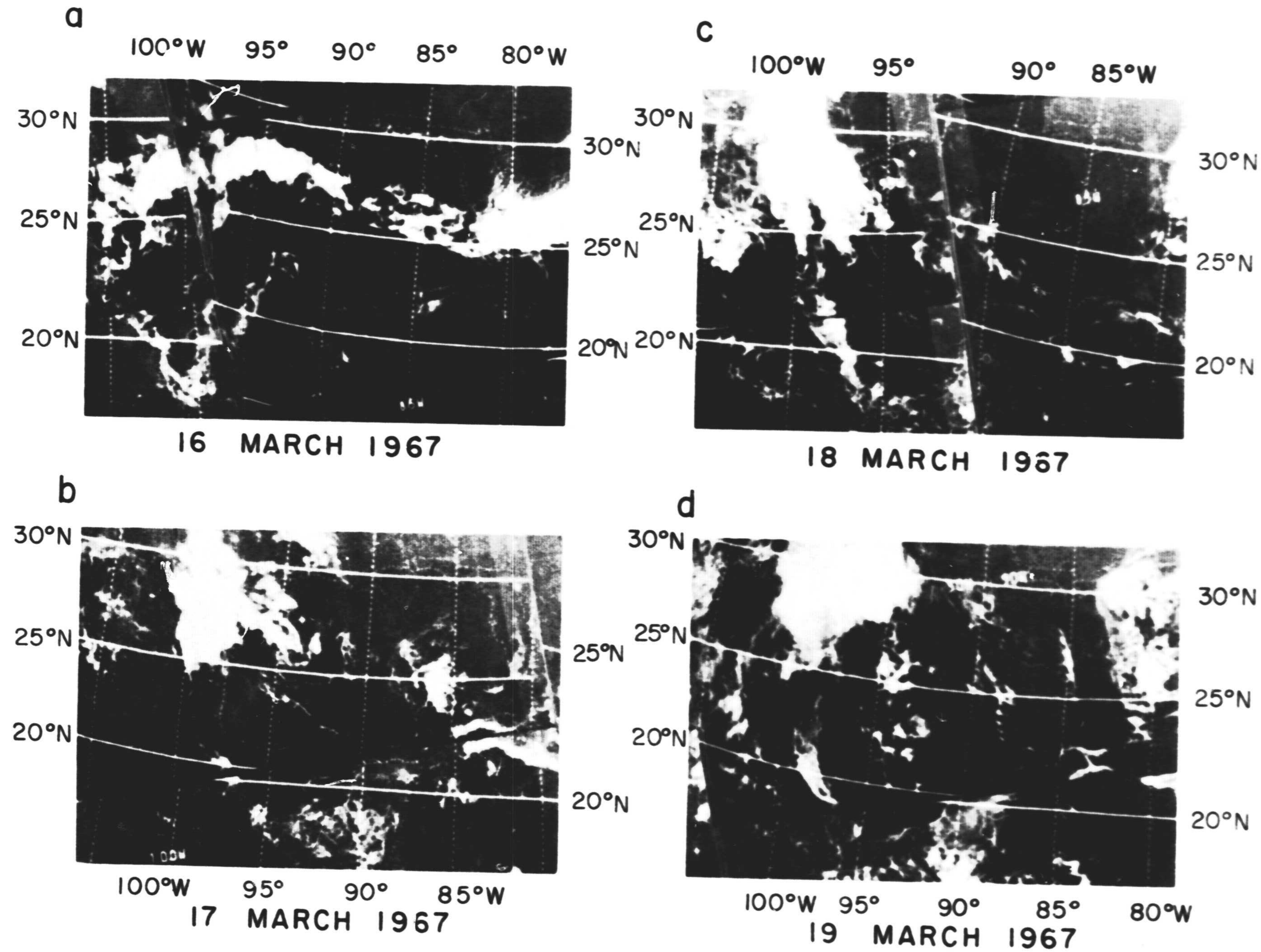
of wind is more difficult to determine as the values of wind speed are questionable. In general, it can be said that clouds persist or form over points along the line when the sea is significantly warmer than the air and the dewpoint depression is small. The long, roughly north-south cloud lines centered at 26N, 85W and 25N, 88W coincide, on 19 March (Fig. 15d), with regions of strong temperature gradients on the ocean surface as illustrated in Fig. 14. The cloud lines can be made more coincident with the zones of surface temperature gradient if the surface temperature pattern is allowed to depart slightly from its weekly average position used. The appearance of cloud lines along strong temperature gradients in this case, and in others not illustrated, indicates that the microscale convergence patterns can be enhanced due to changing buoyancy effects in the boundary layer as discussed in section II.

The series illustrated in Fig. 16 a-d, covering the period from 18 May to 21 May, shows the transitory nature of the sea-surface temperature associated cloud field described for 19 May 1967 and shown in Figs. 10 and 11. The meteorological data are presented at one degree longitude intervals along the line from Tampa, Florida to Tampico, Mexico in Table III. A comparison between the photograph series in Fig. 16 and the data in Table III reveals that in the eastern Gulf, east of 90W, days with little or no cloud activity correspond to days of greater dewpoint depression than do those with cloud activity. Through the four-day period, there was not great change in the air-sea temperature difference in the eastern Gulf.

Fig. 15. Photograph of the Gulf of Mexico taken by the ESSA III satellite at approximately local noon on:

(a) 16 March 1967
(b) 17 March 1967
(c) 18 March 1967
(d) 19 March 1967

Note: Discontinuities in latitude and longitude lines appearing in the picture are from joining photographs from successive orbits or successive frames to obtain complete coverage of the Gulf.



16 MARCH 1967

17 MARCH 1967

18 MARCH 1967

19 MARCH 1967

Table II. Air temperature minus sea temperature, dewpoint depression and estimated wind speed taken along the line from Tampa, Florida to Tampico, Mexico (16-19 March 1967).

Air temperature minus sea temperature

(Week 7)

March		95W					90W					85W			
16	-2	-2	-2	-2	-2	-3	-2	0	0	0	+1	-2	+1	0	+1
17	-2	-2	-1	-1	-1	-2	-2	-2	-3	-2	-1	-5	[illegible]	-2	+1
18	+1	0	0	-1	-1	-3	-2	-2	-4	-3	-3	-5	-1	-2	-1
19	-1	-1	-1	-1	-1	-3	-2	-2	-4	-4	-5	-8	[illegible]	-3	0

Dewpoint depression

March		95W					90W					85W			
16	1	1	2	2	2	2	1	3	4	3	4	3	4	5	8
17	2	2	3	3	3	3	3	4	5	4	4	5	9	10	12
18	5	6	7	7	7	5	6	10	11	9	6	6	6	8	10
19	3	5	5	6	6	6	6	7	7	8	7	6	6	6	9

Wind speed

March		95W					90W					85W			
16	05	05	05	05	05	05	10	15	10	10	10	10	10	15	20
17	10	10	10	10	05	05	08	08	10	12	10	12	10	[illegible]	08
18	05	20	10	08	10	13	17	20	18	15	15	12	12	10	10
19	15	10	10	10	10	15	20	19	20	20	15	10	10	10	10

Note: Values are given at each one degree longitude crossing point for the period from 16-19 March 1967.

Fig. 16. Photograph of the Gulf of Mexico taken by the ESSA III satellite at approximately local noon on:

(a) 18 May 1967
(b) 19 May 1967
(c) 20 May 1967
(d) 21 May 1967

Note: Discontinuities in latitude and longitude lines appear- in the picture are from joining photographs from successive orbits or successive frames to obtain complete coverage of the Gulf.

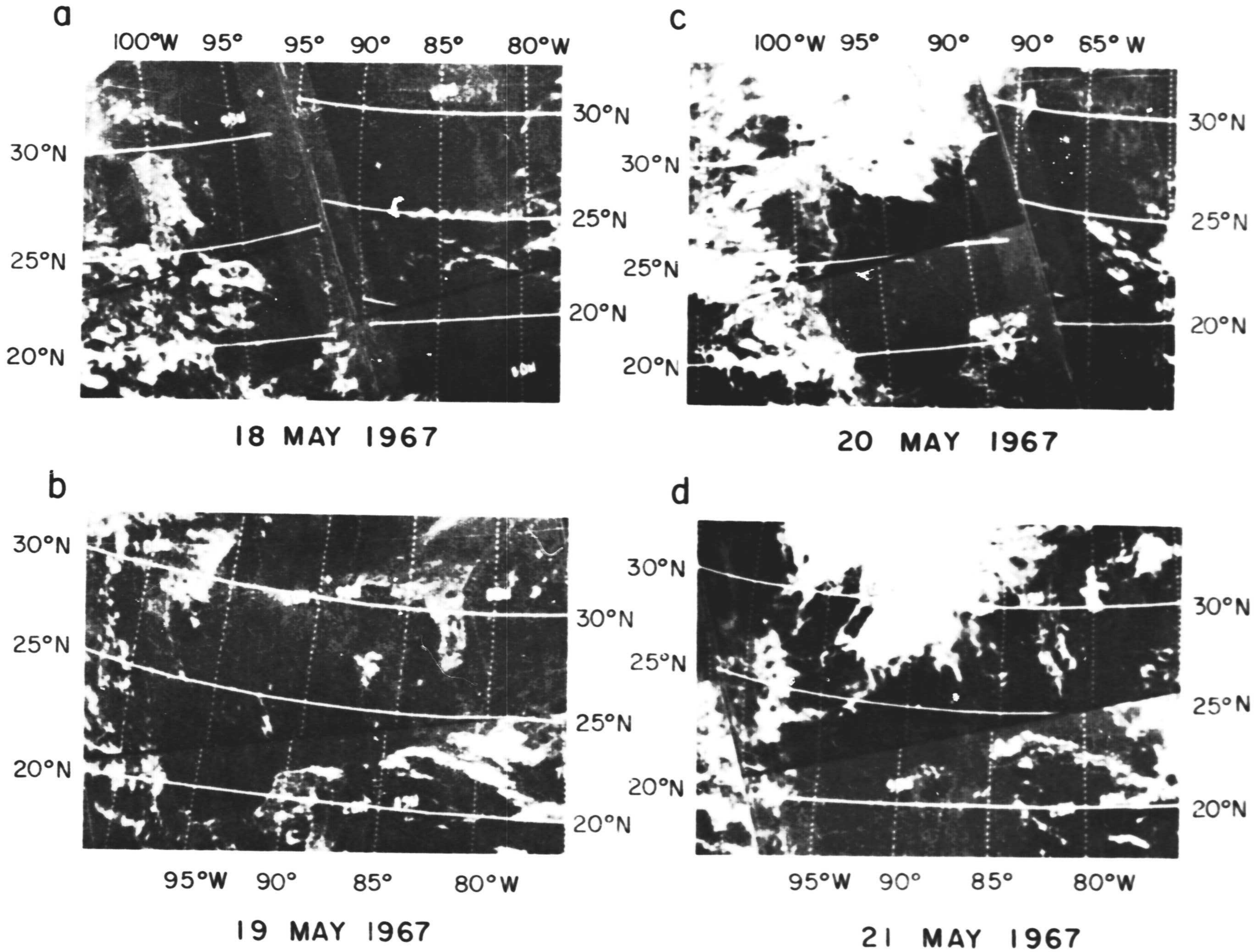

a
100°W 95° 95° 90° 85° 80°W
30°N
25°N
20°N
30°N
25°N
20°N
18 MAY 1967
b
30°N
25°N
20°N
30°N
25°N
20°N
95°W 90° 85° 80°W
19 MAY 1967
c
100°W 95° 90° 90° 65° W
30°N
25°N
20°N
30°N
25°N
20°N
20 MAY 1967
d
30°N
25°N
20°N
30°N
25°N
20°N
95°W 90° 85° 80°W
21 MAY 1967

Table III. Air temperature minus sea temperature, dewpoint depression and estimated wind speed taken along the line from Tampa, Florida to Tampico, Mexico (18-21 May 1967).

Air temperature minus sea temperature (°C)

(Week 16)

May			95W				90W				85W				
18	X	-1	-2	-4	-4	-3	-3	-2	-2	-2	-3	-3	-2	-1	X
19	+2	+2	0	-1	-1	-1	-1	0	-2	-3	-2	-3	-1	0	X
20	X	-1	-2	-3	-3	-3	-1	+2	0	-2	-2	-3	-1	0	X
21	X	0	-2	-3	-3	-3	-1	-1	-1	-2	-2	-2	-1	0	X

Dewpoint depression (°C)

May			95W				90W				85W				
18	8	7	8	7	7	9	9	10	10	10	10	10	10	10	X
19	4	4	4	3	3	5	6	9	9	8	5	5	6	9	10
20	X	2	2	3	3	4	6	9	7	6	7	7	8	8	X
21	4	3	2	2	3	3	4	5	5	4	4	4	6	7	11

Wind speed (knots)

May			95W				90W				85W				
18	10	10	15	15	15	15	15	15	15	10	10	10	10	10	10
19	X	17	17	17	17	17	16	16	11	10	10	10	12	10	05
20	10	20	10	10	15	15	15	15	15	10	10	15	15	15	20
21	10	10	10	10	10	10	10	05	10	15	15	15	15	10	10

Note: Values are given at each one degree longitude crossing point for the period from 18-21 May 1967.

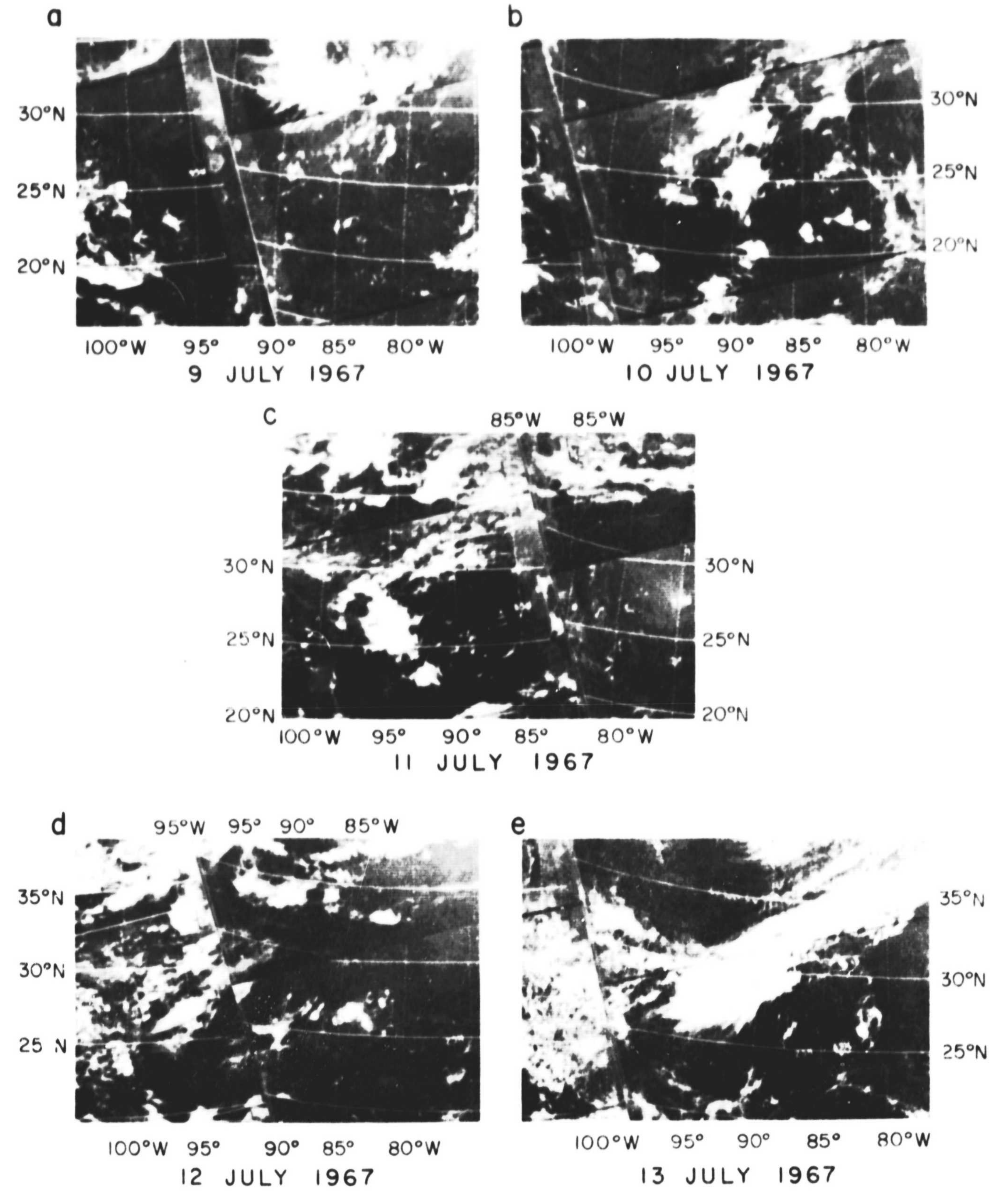
The cloud field over the western portion of the line is most pronounced when the air-sea temperature difference exceeds one degree (negative) and the air is relatively moist. On both 18 and 21 May there are weak fronts over the Gulf causing an ambiguity as to altitude of cloud activity in the western Gulf area.

The Gulf of Mexico cloud field for the period from 9 July to 13 July 1967 is shown in Fig. 17 to illustrate the large amount of scattered convection present during the summer period. During all except the last day, no fronts were in the Gulf area and the wind direction ranged from east to east-southest over the entire area. Association of individual cloud groups with the meteorological data along the line from Tampa, Florida to Tampico, Mexico (Table IV) while still possible is much more ambiguous than in the previous cases. During the period from 9 July to 13 July, there seems to be a clearer correspondence between the air-sea temperature differences and the estimated wind speeds conforming reasonably well with conditions specified in Figs. 6 and 13. This is not entirely surprising considering the uniformity of the dewpoint depression present throughout the period. A comparison between the actual sea-surface temperature chart representative of the time period (Appendix B) and the convection patterns in Fig. 17 a-c indicated that much of the convective activity is enhanced over the warm water areas. Since the air temperature reported by ships is relatively uniform over the entire Gulf, the departures from average water temperature probably represent actual changes in the air-sea temperature differences. Several of the more negative air-sea temperature

Fig. 17. Photograph of the Gulf of Mexico taken by the ESSA III satellite at approximately local noon on:

(a) 9 July 1967
(b) 10 July 1967
(c) 11 July 1967
(d) 12 July 1967
(e) 13 July 1967

Note: Discontinuities in latitude and longitude lines appearing in the picture are from joining photographs from successive orbits or successive frames to obtain complete coverage of the Gulf.


a
30°N
25°N
20°N
100°W 95° 90° 85° 80°W
9 JULY 1967
b
30°N
25°N
20°N
100°W 95° 90° 85° 80°W
10 JULY 1967
c
85°W 85°W
30°N
25°N
20°N
30°N
25°N
20°N
100°W 95° 90° 85° 80°W
11 JULY 1967
d
95°W 95° 90° 85°W
35°N
30°N
25 N
100°W 95° 90° 85° 80°W
12 JULY 1967
e
35°N
30°N
25°N
100°W 95° 90° 85° 80°W
13 JULY 1967

differences shown in Table IV result from cooler than average air temperatures reported in the vicinity of rain showers.

From the three time series presented, the short duration of the cloud field believed to be associated with processes occurring in the marine atmosphere have been emphasized. Considering the large number of factors determining the presence or absence of clouds in response to the surface temperature of the ocean, the intermittent appearance of such cloud fields is not surprising.

Table IV. Air temperature minus sea temperature, dewpoint depression and estimated wind speed taken along the line from Tampa, Florida to Tampico, Mexico (9-13 July 1967).

Air temperature minus sea temperature (°C)

(Week 24)

July			95W					90W				85W			
9	0	0	0	0	-1	0	-1	0	+1	-1	0	+1	-1	+1	+1
10	0	0	0	+1	0	+1	0	-1	+1	-2	-2	0	0	+2	+2
11	-1	-1	-1	0	-1	0	0	-1	+1	0	+2	+3	-1	+1	+1
12	-1	0	+1	+1	0	0	-1	-1	-1	-3	-2	+1	+1	+2	+3
13	+2	+2	+2	+2	+1	+2	+1	+1	+3	+2	0	0	-1	-2	+3

Dewpoint depression (°C)

July			95W					90W				85W			
9	5	5	5	5	5	5	5	6	6	5	6	6	5	6	7
10	4	4	5	5	6	6	6	5	6	4	5	6	8	8	8
11	3	3	3	5	5	5	6	5	6	7	8	7	6	6	6
12	4	5	5	5	5	4	4	5	4	4	4	6	7	7	8
13	5	5	5	6	6	6	6	7	9	8	6	5	5	7	9

Wind speed (knots)

July			95W					90W				85W			
9	08	08	08	07	07	07	08	08	10	10	10	10	05	05	05
10	XX	05	10	10	10	10	10	10	12	15	14	12	10	05	05
11	10	10	10	10	10	10	10	10	08	13	15	13	05	05	05
12	10	10	12	12	10	08	08	05	05	10	10	05	08	03	08
13	10	10	10	10	10	10	08	05	05	05	05	03	03	04	10

Note: Values are given at each one degree longitude crossing point for the period from 9-13 July 1967.

CONCLUSIONS AND RECOMMENDATIONS

The association of the marine cloud field with the sea-surface temperature and its distribution was examined through the use of weekly averages of commercial ship data, individual ship reports of various parameters and satellite photographs. Simple correlations between low cloud cover, air-sea temperature difference and dewpoint depression were exceptionally low. The correlation between low cloud cover and wind speed proved to be the most significant of the correlations examined but had a maximum value of only 0.57.

Division of the ship data into three periods provided what were felt to be logical seasonal subdivisions of the 6-month period examined during 1967. The first period from 6 February 1967 to 1 April 1967 was characterized by large air-sea temperature differences (sea warmer than the air) and a corresponding maximum in cloud amounts over most of the Gulf. The second period, from 2 April 1967 to 3 June 1967 was characterized by a noticeable cloud minimum over most of the Gulf, believed to be brought about by a general state of atmospheric subsidence due to the large scale circulation patterns over the region in question. During this period, the sea was just slightly warmer than the air. The low instability created at the ocean surface and the unfavorable conditions in the lower troposphere led to a high percentage of clear days. The number of clear days was more pronounced in the satellite photographs than in the commercial ship data. The third period, from 4 June 1967 to 29 July 1967, was characterized by an increase of cloud activity over the Gulf of Mexico to a level almost equal to that found during the winter period. It is felt that the large increase in cloud activity in the latter period was the result of overall convergence in the lower troposphere combined with localized instability created in the marine boundary layer due to air-sea temperature differences and low wind velocities.

Scatter diagrams of both average low-cloud amount versus average air-sea temperature difference and average low-cloud amount versus average air-sea temperature difference and average wind velocity indicated that some correlation was present in both cases. The scatter diagram between average low-cloud amount and average air-sea temperature difference was constructed from weekly averages of the two parameters for four of the most populated quadrilaterals examined in the Gulf of Mexico. For cases where the sea was warmer than the air, it was found that the average low-cloud amount increased-decreased by approximately 1/8 coverage for increases-decreases in average air-sea temperature difference of approximately 1C. For average air-sea temperature differences between -1C and +1C, no correlation appeared to be present between average cloud amount and average air-sea temperature difference. Isopleths of average low-cloud amount present in the four most populated quadrilaterals from 2 April to 29 July 1967 as a function of average air-sea temperature difference and average wind speed, indicated that there are definite areas of maximum and minimum low-cloud cover. In the data, an increase in the excess of the sea temperature over the air temperature was observed as wind speeds increased and the low cloud cover remained the same as at some lower speed. There was an indication that a maximum low-cloud cover also occurred in cases where the sea was colder than the air due to forced convection. A similar relationship appeared when individual reports of low cloud cover versus air-sea temperature difference and wind speed were examined for summer cases.

The wind speed at which maximum low cloudiness occurred with only slightly negative air-sea temperature differences shifted from approximately 10 knots in the average data to approximately 4 knots in the individual reports. A similar examination of low cloud amounts versus wind speed and air-sea temperature differences for winter cases alone revealed that increased wind speed existed with less air-sea temperature difference in the presence of above average low-cloud amounts. At a wind speed of approximately 16 knots, little or no air-sea temperature difference occurred with above average cloud amounts.

Changes in average low-cloud amounts from week to week for the various quadrilaterals in the Gulf of Mexico showed little response to the air-sea temperature difference changes over the same time span. Similarly, changes in average low-cloud amounts from area to area did not appreciably reflect changes in average air-sea temperature differences between the same areas. In both cases, it is felt that the lack of correlation between clouds and air-sea temperature difference in the average data was due to the small variations observed in both parameters. There seemed to be better correlations between low clouds and air-sea temperature differences when longer periods were examined and the consequent averages differed by larger amounts.

It was also found that diurnal variation of average low cloud amount did not appreciably reflect the diurnal variation of average air-sea temperature difference. Considering the small diurnal range, usually less than 1C, this is not unexpected.

Examination of photographs of the cloud field over the Gulf of Mexico revealed that on a specific day and time the cloud field frequently did reflect the sea-surface temperature and the consequent air-sea temperature difference. As the range of air-sea temperature difference usually amounted to several degrees at any one time over the Gulf, such an instantaneous reflection of the air-sea temperatures in the cloud field would be expected from relationships discussed previously. The inclusion of wind velocity and available moisture in the atmosphere improved the degree of correlation between the expected cloud field and the cloud field observed.

The presence of a cloud field over a warm water area, and the resultant negative air-sea temperature difference, occurred frequently in the mid-winter and with some degree of regularity in the months of May and June. During the months of July and August, it was more difficult to determine if cloud activity favored areas of warm water and negative air-sea temperature differences because of the wide spread convection induced by the atmosphere's vertical motion field. In all cases, however, presence of an individual cloud feature over an area with significant air-sea temperature differences seldom lasted more than one day. For time intervals longer than a one or two day period, meteorological features such as wind and moisture changed sufficiently to alter the cloud field. The vertical motion field of the atmosphere in the general area in which clouds are imbedded also undergoes appreciable changes from day to day.

Although no organized convection cells could be found that fit the models of uniform heating from below, with the exception of a few winter cases, the importance of this basic mode of convection in producing oceanic cloud fields in the Gulf of Mexico should be examined further. It was impossible to determine if only a portion of the cell's circulation was reflected in the cloud field or if the basic geometry of the cell was greatly distorted. There was some evidence that the thermal mountain concept was reflected in the cloud field during the summer period.

Utilization of the cloud field to determine the sea-surface temperature, in view of the dependence of the former on several parameters in addition to the sea-surface temperature, is impractical. On the other hand, the generation of the cloud field as a result of the sea-surface temperature gradients and various meteorological features presents a serious problem in remote sensing of the ocean surface by infrared methods. In the presence of favorable meteorological conditions cloud activity is enhanced over warm water due to negative air-sea temperature differences. The presence of the cloud field prohibits sensing the surface. In this respect, it is important to better understand the process of cloud generation over oceanic areas.

The probability of clouds present over the ocean surface, in response to the surface, that go undetected in the ESSA satellite photography has not been examined in this study. There is a good possibility that cloud fields of this scale do exist and reflect more closely the ocean surface temperature field. Their existence, however, should be governed by the same parameters as discussed for the larger cloud elements.

In regard to additional investigation along aspects discussed in this study the following points should be examined more thoroughly.

1. The mechanism which leads to the production of the cumulus cloud field at low levels should be investigated utilizing aircraft observations combined with data taken on specific research cruises. Data obtained at the surface should consist of, at the minimum, cloud photography, ocean surface temperature measurements from both infrared and bucket measurements. Continuous surface wind measurements should be recorded and the vertical variation of wind sampled. The latter could be accomplished utilizing balloon soundings or through photographing smoke plumes released from a simple rocket device. Measurements of the air temperature and moisture should also be recorded continuously. Measurements should be taken in areas which are well removed from any appreciable surface temperature gradients as well as in the vicinity of large gradients of sea-surface temperature. The effect of alterations of low level stability, due either to thermal instability or changes in the vertical wind structure, should be examined in relation to the existing cloud field. From measurements of this type the validity of the data presented in Figs. 5 and 13 could be determined.
2. An extension of the time period examined, to cover at least one

year if not more, should be undertaken to better describe the cloud field and additional meteorological parameters existing in the Gulf of Mexico. The areas examined should be subdivided into two-degree-latitude quadrilaterals to obtain more localized effects. It is felt that a reduction to one degree quadrilaterals would severely limit the amount of data in most of the quadrilaterals necessitating several years of data or longer averaging times than one-week periods utilized in this study. Either would severely limit any application to reality, introducing the unknown parameter of the ocean surface thermal structure in the vertical and its changes from year to year. Multiple correlation coefficients should be determined between the various oceanic and meteorological parameters and the cloud field in addition to including sensible and latent heat fluxes.

This study has not been meant as a statistical approach to the phenomena of oceanic clouds and associated oceanic and atmospheric features. Its intent has been primarily to investigate possible mechanisms leading to cloud development in the marine atmosphere. Results in this study are to be combined with results in a previous study undertaken by the author on the question of oceanic cloud development in relation to the temperature distribution of the sea surface.

REFERENCES

Arnold, J.E., 1967: Reflections of the sea surface temperature field in low level cloud development: an observational air-sea interaction study from space. Preliminary Report, Texas A&M University, College Station, Texas, Ref 67-4T, 53 pp.

Avsec, P., 1939: Thermoconvective eddies in air. Application to Meteorology. Scientific and Tech. Pub. of Air Ministry Works of Inst. of Fluid Mech. of Fac. of Sci., Paris, No. 155. Published (in French) at Ed. Blondel la Rougely 7, Rue St., Lazare, Paris.

____________, 1964: Some factors influencing the skin-temperature of the sea and its measurement by infrared thermometer. In Techniques for Infrared Survey of Sea Temperature, U.S.D.I., Bureau of Sport Fisheries and Wildlife, Cir. No. 202, Washington, D.C., 94-113.

Garstang, M., 1964: The distribution and mechanism of energy exchange between the tropical ocean and atmosphere. Ph.D. Dissertation, Dept. of Meteor., The Florida State University, Tallahassee, Florida, 177 pp.

____________, 1967: Sensible and latent heat exchange in low latitude synoptic scale systems. Tellus, XIX, 492-508.

Hastenrath, Stefan L., 1968: A contribution to the wind conditions over the Caribbean Sea and Gulf of Mexico. Tellus, XX, 163-178.

Hubert, Lester F., 1966: Mesoscale cellular convection. Meteorological Satellite Laboratory Report No. 37, Manuscript of the Environmental Science Services Administration, National Environmental Satellite Center, Washington, D.C., 68 pp.

Jeffreys, H., 1928: Some cases of instability in fluid motion. Proc. Roy. Soc., A, 118, 195-172.

Malkus, J.S., and M.E. Stern, 1953: The flow of a stable atmosphere over a heated island. Part I., J. Meteor., 10, 30-41.

____________, 1957: Trade cumulus cloud groups: Some observations suggesting a mechanism of their origin. Tellus, IX, 33-44.

____________, 1958: On the structure of the trade wind moist layer. Papers Phys. Oceanog. Meteor., 13, No. 2.

Monin, A.S., and A.M. Obukhov, 1954: Basic regularity in turbulent mixing in the surface layer of the atmosphere. USSR, Acad. Sci. Geophys. Inst. No. 24.

Priestly, C.H.B., 1959: Turbulent transfer in the lower atmosphere. Chicago, Ill., University of Chicago Press, 125 pp.

Riehl, H., and J.S. Malkus, 1965: Cloud structure and distribution over the Tropical Pacific Ocean. Berkeley, Calif., University of California Press, 229 pp.

Roll, H.U., 1965: Physics of the Marine Atmosphere. New York, N.Y., Academic Press, 426 pp.

Saltzman, B., ed., 1962: Theory of thermal convection. New York, N.Y., Dover Publications, 459 pp.

Scorer, R.S., 1951: Billow clouds. Quart. J.R. Meteor. Soc., 76, 235-241.

____________, 1958: Natural Aerodynamics. New York, N.Y., Pergamon Press, 300 pp.

Stern, M.E. and J.S. Malkus, 1953: The flow of a stable atmosphere over a heated island. Part II. J. Meteor., 10, 105-120.

Tsuchiya, K., and T. Fujita, 1967: A satellite meteorological study of evaporation and cloud formation over the western Pacific under the influence of the winter monsoon. J. Meteor. Soc. Japan, 45, 232-250.

Appendix A

Week	Date
2	5-11 February 1967
3	12-18 February 1967
4	19-25 February 1967
5	26 February - 4 March 1967
6	5-11 March 1967
7	12-18 March 1967
8	19-25 March 1967
9	26 March - 1 April 1967
10	2-8 April 1967
11	9-15 April 1967
12	16-22 April 1967
13	23-29 April 1967
14	30 April - 6 May 1967
15	7-13 May 1967
16	14-20 May 1967
17	21-27 May 1967
18	28 May - 3 June 1967
19	4-10 June 1967
20	11-17 June 1967
21	18-24 June 1967
22	25 June - 1 July 1967

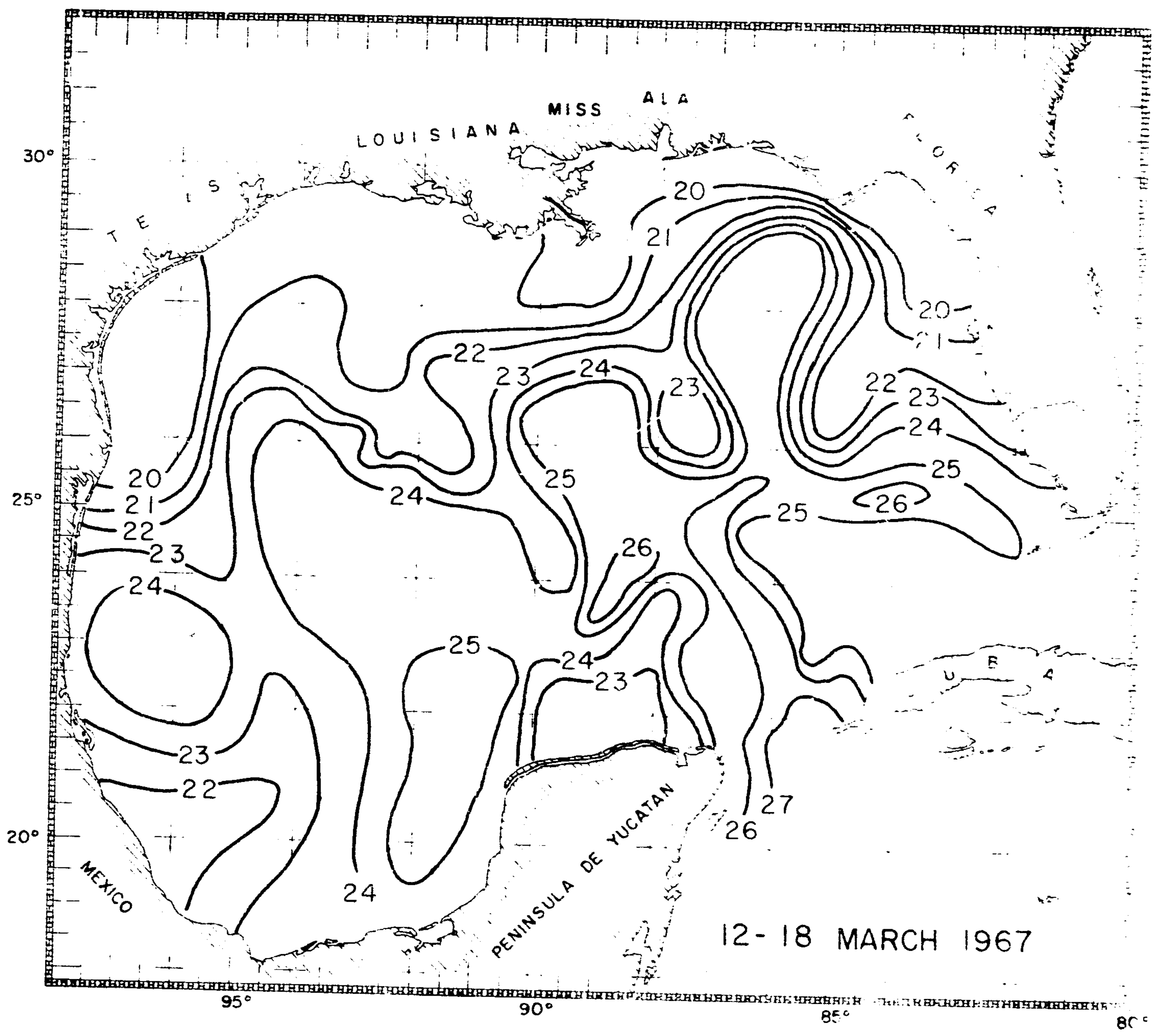
Appendix A (Continued)

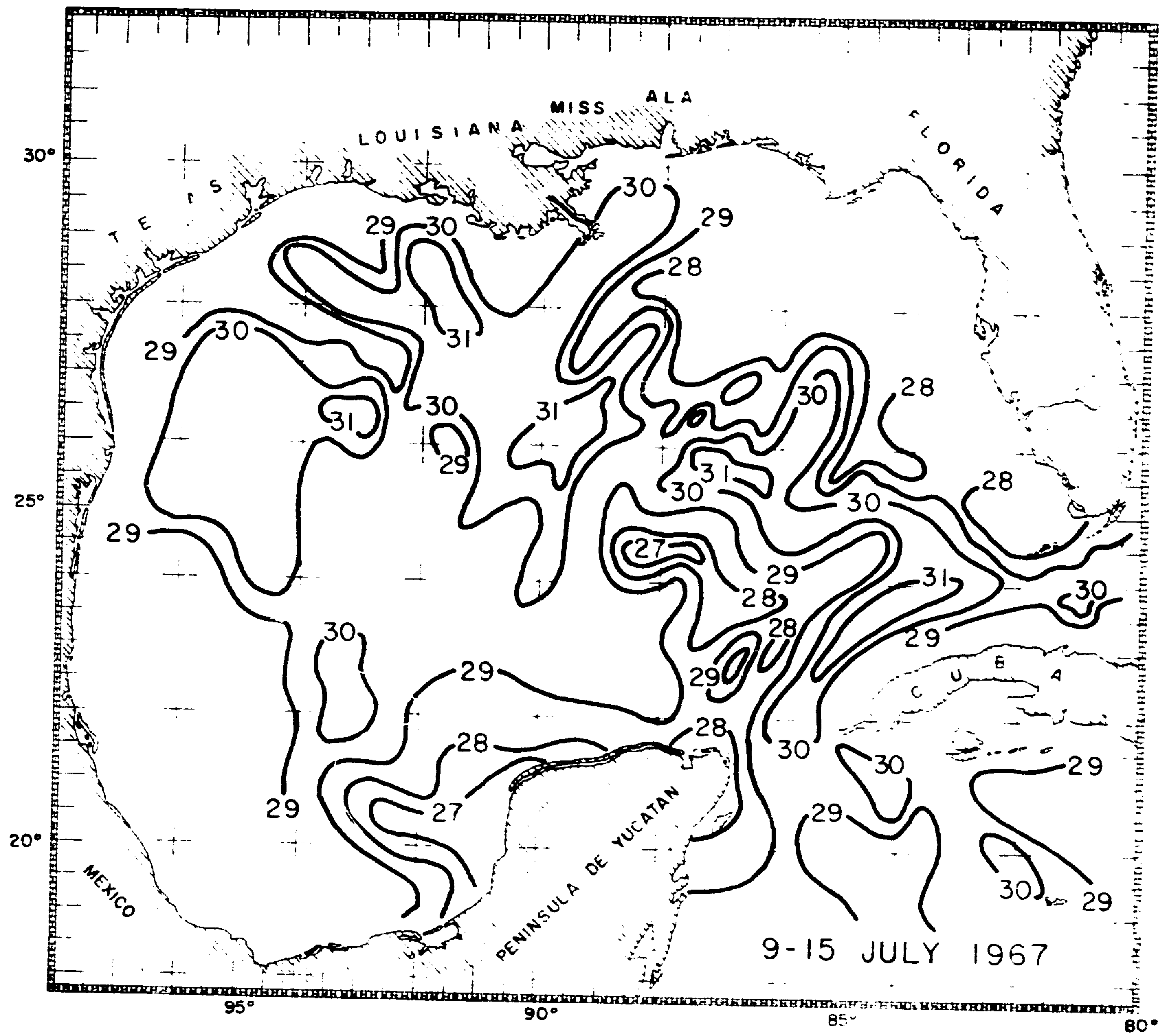
Week	Date
23	2-8 July 1967
24	9-15 July 1967
25	16-22 July 1967
26	23-29 July 1967

Appendix B

Distribution of surface temperature (degrees Celsius) in the Gulf of Mexico for the period of 12-18 March 1967 from commercial ship data.

Distribution of surface temperature (degrees Celsius) in the Gulf of Mexico for the period of 9-15 July 1967 from commercial ship data.


LOUISIANA
MISS
ALA
FLORIDA
TEXAS
MEXICO
PENINSULA DE YUCATAN
30°
25°
20°
95°
90°
85°
80°
20
21
22
23
24
25
26
27
12- 18 MARCH 1967


LOUISIANA
MISS
ALA
FLORIDA
TEXAS
MEXICO
CUBA
PENINSULA DE YUCATAN
30°
25°
20°
95°
90°
85°
80°
9-15 JULY 1967