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ABSTRACT

By compositing time-latitude sections of infrared photographs from the Synchronous Meteorological Satellite (SMS) and latitudinal cross sections of observations from several GATE ships and island stations lined meridionally along 23.5 °W longitude during the period September 8 through 16, 1974, inclusive, a three-dimensional structure of a section of an easterly wave is presented. Observations covering one wave length of the wave train are analyzed for temperature and wind distribution from the surface to higher levels, including that on surface pressures.

It is observed that, in particular, the wave perturbation in the wind field is most prominent on the

700-mb surface, the horizontal axis of the wave is oriented northeast-southwest and with a thickness of about 4500 meters. There are measurable horizontal gradients of temperature at each level of analysis and the vertical thermal structure of the system appears to indicate cooler air at low levels and warmer air at high levels within the trough than in the neighboring areas. From the SMS infrared photograph composite, the period of this wave train is estimated to be about 5 days and the wave length is approximately 35 degrees of longitude, which amounts to a phase speed of roughly 9 meters per second.

INTRODUCTION

It has not been possible to carry out a complete synoptic analysis, in the ordinary sense, of the easterly wave structure because of the inadequate distribution or absence of observing stations in the areas where such analysis is vital. Additionally, due to the absence of an all-embracing theoretical principle for understanding the wave phenomena, deduction of a complete picture of the wave structure from theoretical studies have, so far, not been satisfactorily obtained. Various techniques (e.g., vertical time-cross sections from single stations by Riehl (1954), a combination of time cross sections and satellite photographs by Arnold (1966), Carlson (1969), and Frank (1969)) have been employed in the analyses of these easterly wave disturbances and some limited but quite useful results have been obtained from such efforts. However, single vertical cross sections do not sufficiently describe the horizontal profile of the disturbance; even composited synoptic maps are too gross to yield a reliable horizontal picture of the wave at all levels. Some of the observations on synoptic charts are also on the borderline of accuracy. Local convection vitiates the use of satellite photographs of clouds over continental West Africa in studying the cloud forms associated with the waves as they move towards the Atlantic.

Time-longitude sections of satellite photographs have been used by Chang (1969) in the study of disturbances in the tropical Pacific. The cloud forms associated with the disturbances appear as parallel lines in the composited photographs.

In this paper, time-latitude sections of infrared photographs over the GARP Atlantic Tropical Experiment (GATE) area taken by the Synchronous Meteorological Satellite (SMS) have been utilized in conjunction with analyses of observations from ships and land stations on temperature and wind from the surface to higher levels including surface pressure.

It was noted by Frank (1969), among others, that the structure of easterly wave disturbances becomes prominent at about 25-30 °W longitude as they emerge from the African continent. The deployment of GATE ships in that general location by the GATE planners is most appropriate. The mode of presentation used in this paper has allowed an opportunity for studying the cloud distribution associated with an easterly wave or wave disturbance at an area where the cloudiness associated with such phenomena is most prominent and also, in this particular case, over an area where adequate surface and upper-air observations have been set up. This approach to the utilization of GATE data for the study of tropical waves is an attempt to bring a new order of comprehension into the structure of the easterly waves; to determine more accurately the base and depth of the perturbation, the orientation of the horizontal axis and the three-dimensional structure of its temperature field.

An easterly wave, as defined herein, is a westward propagating wave of short wave length (1500-4000 km) in the lower troposphere.

GENERAL PROCEDURE

Satellite pictures from geostationary platforms provide a convenient tool in visually recognizing, identifying and following weather systems or patterns. Examination of cloud structures from SMS photographs in full disc has indicated successive passages of two easterly wave disturbances as they move west of the African continent about the second week of September, 1974, during the third phase of GATE. Although they are not readily detectable in the visible range, yet they appear to persist and move consistently westward in the infrared range. Consequently, a time-latitude section for the period September 8 through 16, 1974, is prepared. This is achieved in Fig. 1 by compositing narrow rectangular strips of successive six-hour intervals of infrared photographs, each with a width of roughly

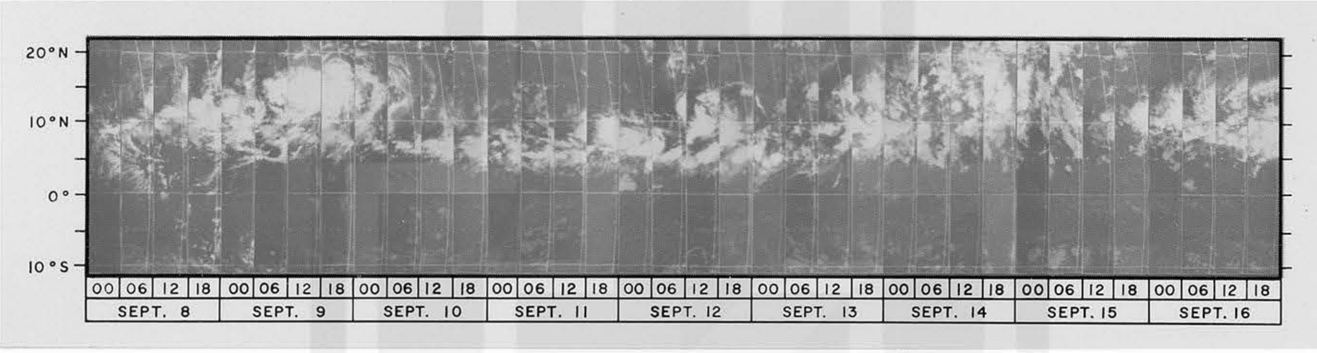

Fig. 1. Time-latitude section of SMS infrared pictures at six-hour intervals from September 8-16, 1974. This is composed of longitudinal rectangular strips, five degrees wide and centered at 23.5°W near 10°N, extending from 10°S to 20°N. Time is in GMT.

5 degrees centered at about 23.5 °W near 10 °N and with a length extending from 10 °S to 20 °N. The preparation of surface and upper-level charts is achieved by plotting the six GATE ship stations and the two Cape Verde Islands land stations (shown in Fig. 2) which provided the surface and upper-level observations. It is impressing to note their north-south alignment; obviously, such orientation could easily detect zonal motions of weather systems passing over this line. Ship locations appear as almost stationary during the period of analysis. One ship, UHGZ, provided additional observations while it travelled northward from about 4 °S to 15 °N during September 10-16. Table I shows the list of the participating ship and land stations.

Table I. GATE Ship and Land Station Locations

Name	Call Letters/ Station No.	Lat. (N)		Long. (W)	
Akad. Kurchatov	UBLF	00°	00'	23°	30'
Prof. Zubov	UMFW	05	00	23	30
Researcher	WTER	07	00	23	30
Prof. Vize	UPUI	08	30	23	30
Vanguard	MVAN	10	00	23	30
Akad. Korolov	UHQS	12	00	23	30
Praia (Cape Verde Is.)	589	14	54	23	31
Sal (Cape Verde Is.)	594	16	44	22	57

Synoptic-time observations for wind and temperature are plotted every six hours for each of the five levels: surface, 850-mb, 700-mb, 500-mb, and 200-mb. Sea surface temperature and sea level pressure also are plotted on separate charts. It must be noted that the data herein used are taken from the GATE set of preliminary data and may not be representative of all

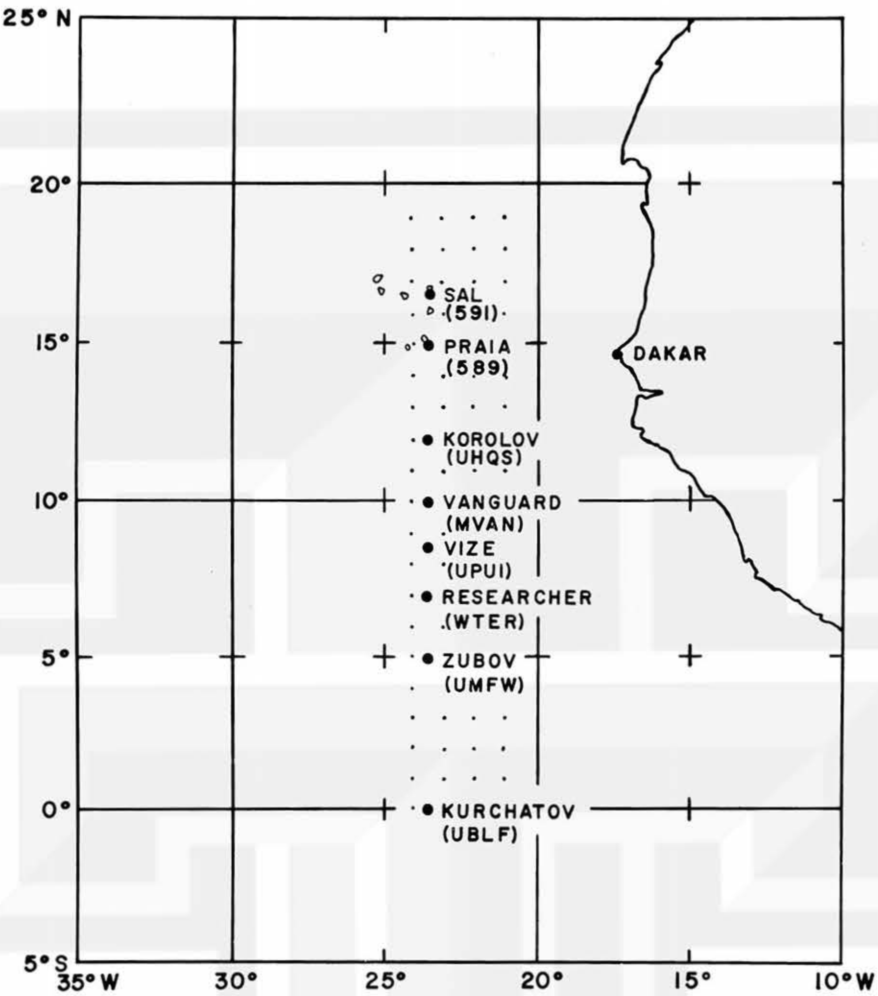

Fig. 2. Positions of the selected GATE ships and land stations where synoptic-time observations for surface and upper-air were utilized. The land stations have index numbers and the ship stations bear call letters.

measurements made during GATE. The data are yet unvalidated but, because of time considerations, they are presently used. This set of preliminary data is obtained from World Data Center-A in Asheville, N. C. Mention should be made that although the wind speeds were observed in either kt or m/sec in the original observations, they are all converted, where applicable, to kt in this paper. A distinction is made between sea surface and surface observations. Surface observations are those made on ships, whereas, sea surface observations are those made on the surface of the sea. Streamlines, isotachs and isotherms are drawn on the charts from observations along 23.5°W. The charts are a series of time sections on which latitude and time are the coordinates.

CLOUD DISTRIBUTION

It is noted earlier from a series of satellite photographs that cloudiness associated with the wave structure diminishes as the wave moves westward on the Atlantic. Therefore, for most wave trains, the associated cloudiness is not uniform in space as shown on such photographs. In the present approach to the utilization of the SMS photographs, the cloud mosaic that appears in the previous figure not only shows a continuous wave-like cloud pattern but also displays clearly the latitudinal extent of the cloud forms, indicating a sinusoidal pattern with troughs on September 9 and September 14. The "inverted V" pattern referred to by Simpson *et al*. (1968) and Frank (1969) is discernible at both times. The distance from the axis of one "inverted V" structure to the other constitutes one wave length. From the cloud mosaic the period of the wave train is observed to be 5 days (see also Gruber and Replane (1975)). With a wave length determined to be about 35 degrees of longitude, the phase speed of the wave is estimated to be approximately 9 meters per second. One striking feature of the cloud distribution is its remarkable alignment with the winds at 700-mb level as shown in Fig. 3. While such alignment has been suspected from earlier studies, it has not been properly backed by observational data. The distribution of clouds about the axis of the wave trough is at variance with that of the classical model of the easterly wave trough as given by Riehl (1954).

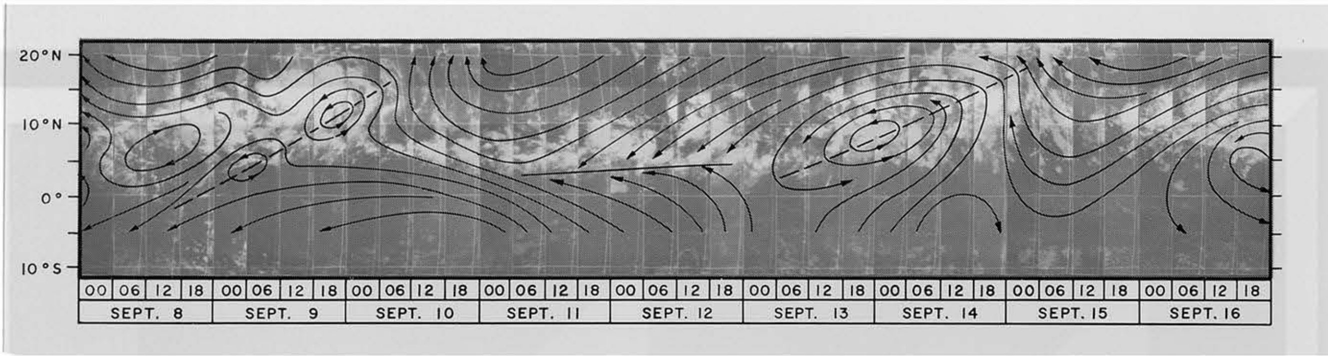

Fig. 3. 700-mb wind analysis of observations along 23.5°W superimposed on the SMS cloud mosaic shown in Fig. 1. The heavy solid line indicates the trade confluence zone. The trough axis appears as a heavy dashed line.

WEATHER DISTRIBUTION

Figure 4 shows the time-latitude section of the weather reported by the GATE ships and island stations under study. Although shower activity is reported throughout the period, more pronounced shower activity took place in the trough region. There appears to be no preferred sector of weather activity with respect to the trough axis. There is less precipitation associated with the trough that passed earlier than with the later passage. It is remarkable also that only showers are mostly reported, which could suggest that only weakly- or moderately-enhanced convection is associated with

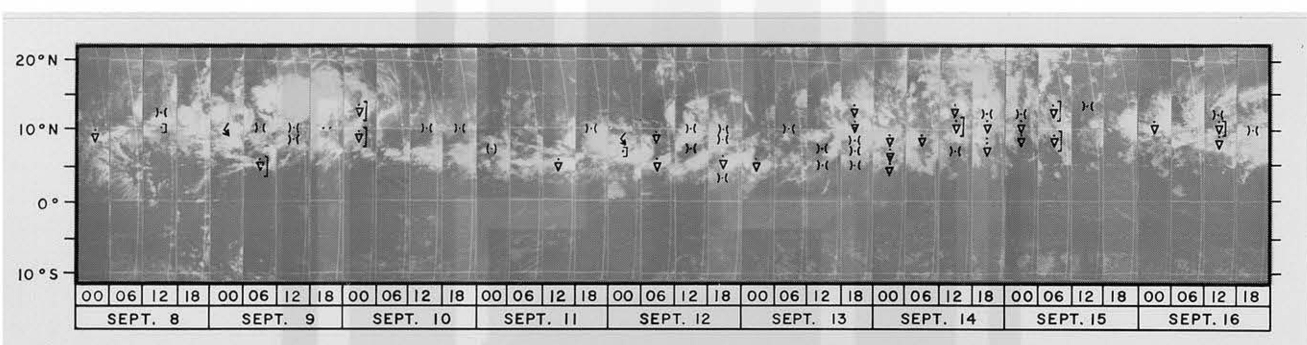

Fig. 4. Synoptic-time surface weather observations along 23.5°W superimposed on the SMS cloud mosaic.

the wave structure at that stage. Figure 5 shows the superposition over the SMS cloud mosaic of the 700-mb wind analysis and the surface weather reports.

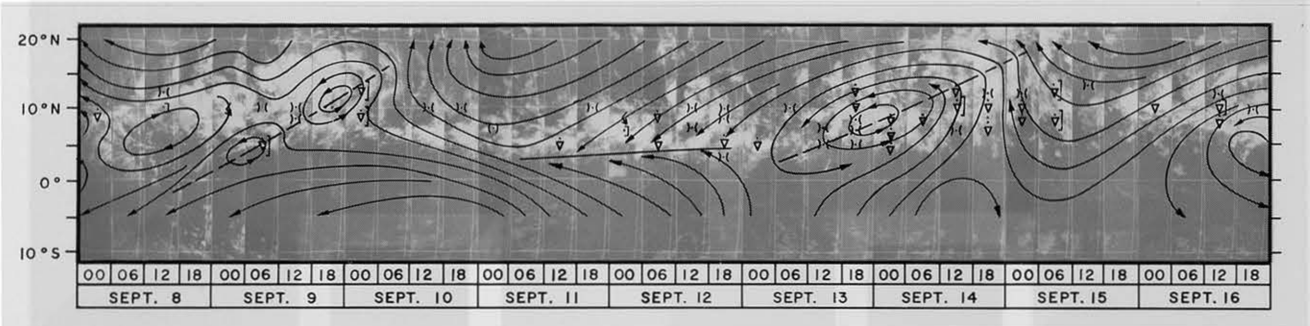

Fig. 5. Synoptic-time surface weather observations and 700-mb wind analysis along 23.5°W superimposed on the SMS cloud mosaic.

WIND DISTRIBUTION

Figure 6 shows the streamline-isotach analysis of the winds at various levels on a time-latitude coordinate system. The ordinate consists of the observations by selected GATE ships and land stations along 23.5°W located from the equator northward, while the abscissa is a continuous time span covering six-hour synoptic-time intervals from September 8 through 16, 1974. Wind speeds are in knots. The heavy solid lines in the lowest 3 levels mark the trade confluence zone.

(i) Surface

There is no evidence of easterly wave activity in the surface wind analysis. This observation also has been confirmed by earlier studies (Aspliden *et al.* (1965) and Frank (1969)). However, the surface flow is characterized by anticyclonic eddies. The characteristics of these eddies have been studied by Fujita *et al.* (1969).

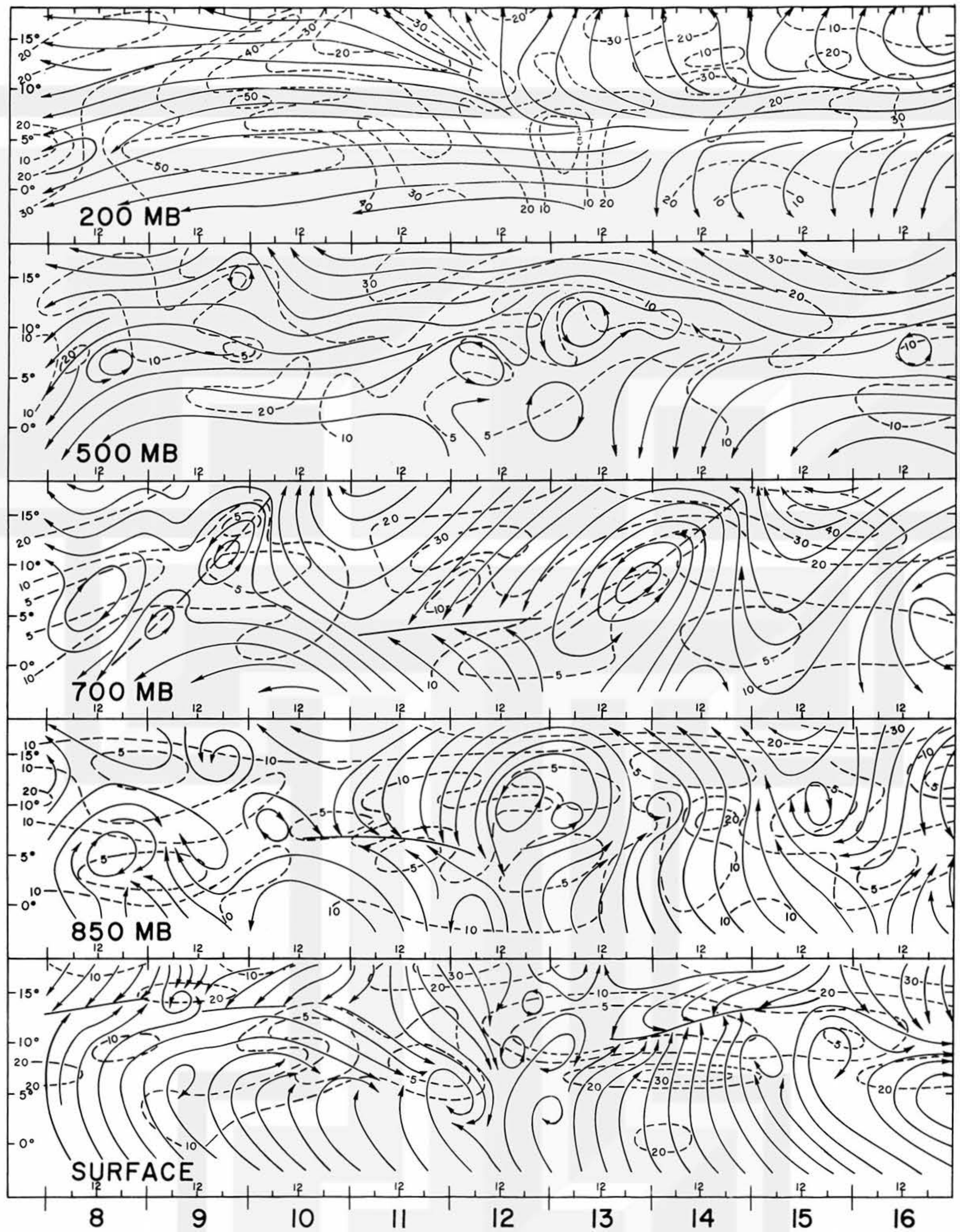

Fig. 6. Streamline-isotach analysis at various levels on time (abscissa)-latitude (ordinate) charts from observations along 23.5°W. Heavy solid lines at the lowest three levels indicate trade confluence areas. Slanted heavy dashed lines in the cyclonic circulation at 700-mb level are wave-associated trough lines. Wind speeds are in knots.

(ii) 850-mb Level

The flow on this surface is characterized by both cyclonic and anticyclonic eddies. Cross-equatorial flow is still in evidence but not as pronounced as on the surface chart. The small agitation in the wind field around September 9 and 14 suggests that this level may be the base of the disturbance.

(iii) 700-mb Level

The correspondence between the wind field and the cloud distribution at this level is quite striking (see Fig. 3). The orientation of the axis of the trough is well delineated in the flow field. This is shown as a heavy dashed line along the trough. Further analysis of the GATE data should show clearly the characteristics of the wave axis. Results from theoretical models of the easterly waves show that these waves attain maximum intensity at the 700-mb level. The axis of the trough is oriented in a northeast-southwest direction and the flow is characterized by cyclonic shear.

(iv) 500-mb Level

Relatively light winds prevail in the trough area of the wave structure at this level. This height probably marks the top of the disturbance. The cross equatorial flow, this time from the northern to the southern hemisphere, becomes more evident. Also evident is the emergence of the base of the anticyclonic cells that characterize the upper-level motion at this time of the year over that part of the Atlantic Ocean. Earlier in the period of the chart analysis (September 8 through 14) the wind is essentially easterly but at the later time, the flow at this level is characterized by large anticyclonic cells. Winds at this level are generally light.

(v) 200-mb Level

This level shows a more pronounced anticyclonic circulation between September 13 and the end of the period of analysis. Before then, winds are mostly easterly with jet speeds between 3°N and 8°N. The wave structure prominent at the lower level is no longer evident here.

Many earlier papers have placed the core of the strong easterly winds, which sometimes attain jet speeds, at about 14°N latitude over West Africa in the summer months of the Northern Hemisphere. The analysis here indicates that the core of the strong easterly winds at this level is further south than believed earlier. Further analysis of GATE data may help place the structure of the latitudinal extent of these jets in proper perspective.

THERMAL STRUCTURE OF THE WAVE DISTURBANCE

It was generally believed that the circulation in the easterly wave was indirect; that is, more rising motion occurs at the lower potential temperature than descending motion. With this view, the easterly wave would be an energy sink; however, this has been modified. Riehl's (1965) observation tends to show that the rising air in the system gained heat from the heat of condensation and the cold descending air has had heat subtracted from it by evaporation. This theory tentatively explains the fact that the colder air is usually at the lower levels of these wave structures rather than at the higher levels and thus portray the system as an energy generating system. This explanation, however, still has to be backed by sufficient data to warrant its acceptance in principle.

Figure 7 shows isotherms in °C at various levels on a time-latitude coordinate system similar to that in Fig. 6. The shaded portions indicate regions of colder air temperature than the mean temperature of the tropical atmosphere at that level.

(i) Sea Surface

One striking feature of the sea-surface temperature chart is the fact that the temperature in the area of the wave activity is 1-3 °C higher than the sea-surface temperature in the neighboring areas. There is very little temperature gradient over the area of wave activity. The mean annual temperature over the area of the wave activity is about 25 °C. The sea-surface temperature over such area during the period is observed to be over 27 °C. No shading is attempted for this chart.

(ii) Surface

Except for the tongues of relatively colder air at about September 13 to 14, there is no indication of the wave at this level. Between the trough regions, the temperature field is flat.

(iii) 850-mb Level

Regions of colder air are clearly shown on the chart for this level. It is obvious that the lower levels of the wave structure is cold. The area of the cold air is aligned roughly with the cloud areas. Observations from the chart also suggest that this level could well be the base of the easterly wave.

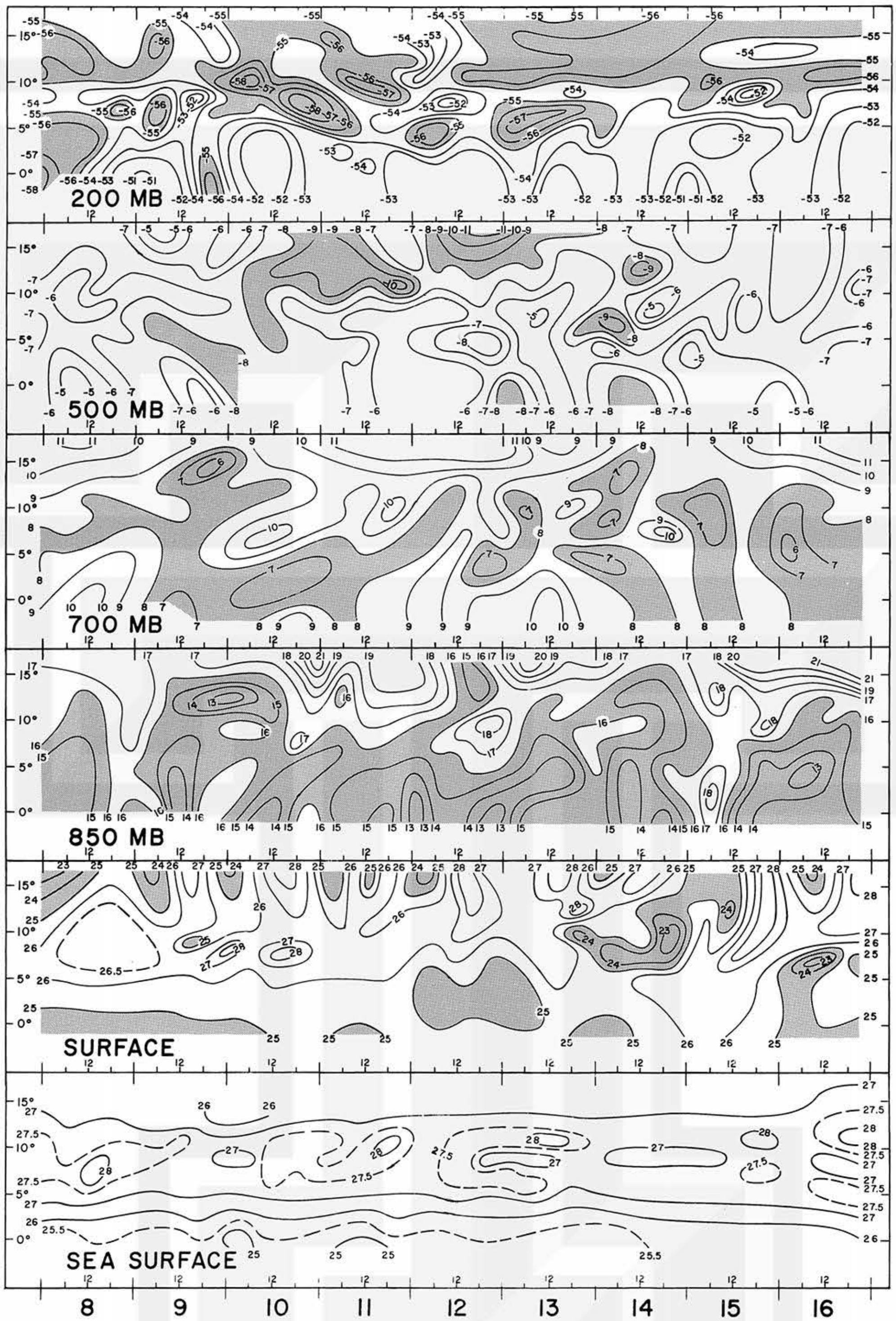

Fig. 7. Isotherms in °C at various levels on time-latitude charts similar to that in Fig. 6. Shaded portions indicate regions of colder air temperature than the mean temperature in the tropical atmosphere at that level.

(iv) 700-mb Level

There are relatively fewer colder areas on this chart than on the 850-mb chart. However, it could be noted that the trough areas are still relatively cold.

(v) 500-mb Level

At this level, relatively colder areas at lower regions have given way to relatively warmer areas. However, cold pockets are still detectable at the trough areas. This level marks the top of the wave phenomena.

(vi) 200-mb Level

The trough areas are relatively warmer compared with the neighboring areas. The temperature field at this level and on the 500-mb level seems to confirm the belief that in these wave systems, the net heating from condensation takes place at the upper levels of the system.

24-HOUR SURFACE PRESSURE DISTRIBUTION

The pattern of the 24-hour surface pressure change in millibars is shown in Fig. 8. Positive (negative) pressure changes indicate an increase (decrease) in pressure during the preceding 24-hour period. There are positive pressure changes in the trough areas (shaded) which can be attributed to precipitation. Negative pressure changes show up between the trough areas. There is a general pressure fall ahead of the trough system and a gradual pressure rise as the trough approaches. Pressure changes are of the same sign on either side of the axis of the trough.

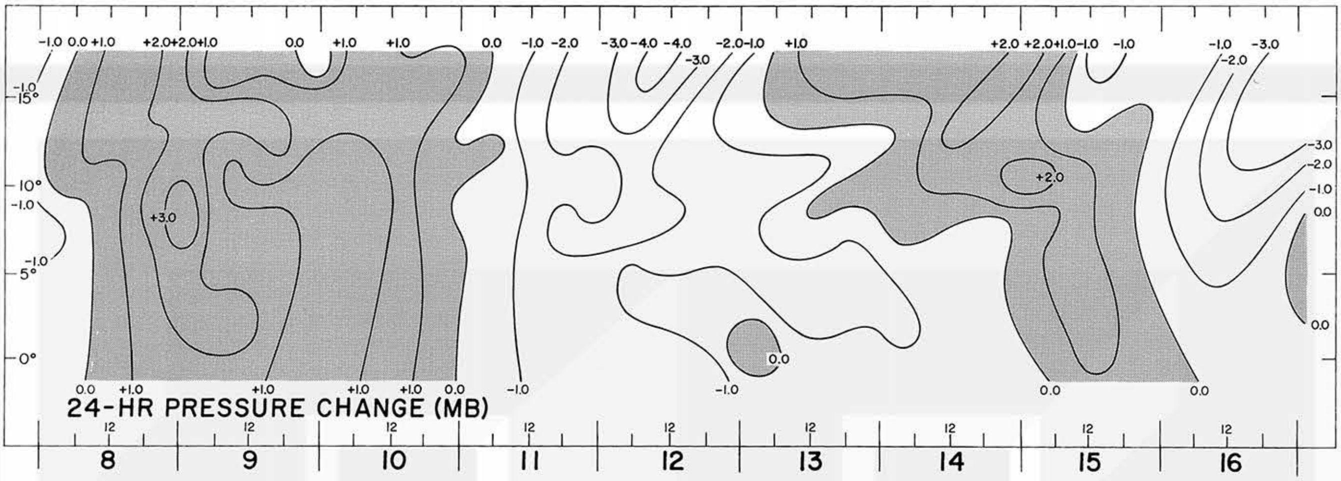

Fig. 8. 24-hour surface isallobars in mb on time-latitude chart similar to that in Fig. 6. Positive (negative) isopleths indicate increased (decreased) pressure during the preceding 24 hours. Positive values are observed during the periods of passage of the wave disturbance.

CONCLUDING REMARKS

This analysis is an attempt to present a three-dimensional picture of an easterly wave over the Atlantic through the combined use of high-quality infrared photographs from the geostationary satellite SMS and observations from selected GATE ships and land stations mostly in the A/B Scale area during the period September 8 through 16, 1974, inclusive.

One of the salient points observed in this analysis is the striking correspondence between the 700-mb wind and the cloud composite. The wave perturbation in the wind field is most prominent in the 700-mb surface. The surface wind gives no indication of the presence of waves and is characterized, in fact, by anticyclonic eddies. The thermal structure of the system appears to show the cooler air at the low levels and warmer air at the high levels over the trough areas, similar to that observed by Carlson (1969). The physical aspect of the wave appears to extend from 850 mb to 500 mb, a thickness of about 4500 meters. The horizontal axis of the wave as delineated in the cloud composite and the 700-mb level analysis is oriented northeast-southwest. The SMS cloud mosaic displays a sinusoidal wave pattern with wave troughs on September 9 and 14. Considering this as a period of 5 days and, with a wave length determined to be about 35 degrees longitude, the phase speed is approximately 9 meters per second. The 24-hour pressure change pattern shows positive values in the trough areas while negative pressure changes exist outside these regions.

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