PROGRESS REPORT #1
ON CID CONTRACT #CSU-SA-KAU-02

AN INVESTIGATION OF THE RADIATIVE BOUNDARY CONDITIONS DURING THE DEVELOPMENT OF THE SOUTHWEST MONSOON SAUDI ARABIAN HEAT LOW

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DEPARTMENT
OF
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KING ABDULAZIZ UNIVERSITY
FACULTY OF METEOROLOGY AND
ENVIRONMENTAL STUDIES

AN INVESTIGATION OF THE RADIATIVE BOUNDARY CONDITIONS DURING THE DEVELOPMENT OF THE SOUTHWEST MONSOON SAUDI ARABIAN HEAT LOW

Progress Report No. 1

On the Cooperative Research Project
between the Department of Atmospheric Science
at Colorado State University and the Faculty of Meteorology
and Environmental Science at King Abdul-Aziz University
in Accordance with the CID-ARMETED Project
of the University of Arizona

"An Investigation of the Radiative Boundary Conditions during the Development of the Southwest Monsoon Saudi Arabian Heat Low"

Period Covered

(February 15 - August 15, 1981)

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I. Introduction

In a continuing effort to support the Southwest Summer Monsoon Experiment - Summer MONEX (see WMO-ICSU Joint Organizing Committee (1976) and MONEX Panel (1977)), we have implemented an investigation of the desert boundary layer within the confines of the Saudi Arabian Kingdom. This research program has been designed to augment our knowledge of the energetics of the Arabian Peninsula prior to the onset of the Southwest Summer Monsoon. The research project itself was enabled via the recent cooperative arrangement between the Department of Atmospheric Science (ATS) at Colorado State University (CSU), and the Faculty of Meteorology and Environmental Science (FMES) at King-Abdul-Aziz University (KAAU), in accordance with the CID-ARMETED project, administered at the University of Arizona at Tuscon.

The Southwest Summer Monsoon is an annual meteorological feature which affects the lives of over a billion people in Southern Asia, and dictates the summertime weather pattern throughout much of the Middle East and Eastern Africa (see Ramage, 1971). The Summer MONEX experiment was designed as a component part of the First GARP Global Experiment (FGGE) in order to understand the mechanisms leading to the onset, intensity, surges and breaks in the Southwest Monsoon, particularly in terms of the mechanisms controlling monsoon rainfall. In an experiment of this sort, a definition of the energetics of the atmosphere and a physical description of the external controls and boundary conditions is essential. The preliminary scientific results of Summer MONEX offered in FGGE Operations Report Volume 9, edited by Grossman (1980a, 1980b), reveal for the first time some of the key meteorological elements of the Indian Monsoon. Their new results represent a dramatic improvement in quantifying the physics of a monsoon, over the more qualitative, large scale examination carried out during the 1963-1964 Indian Ocean Expedition (See Ramage and Raman (1972), and Ramage et al (1972)).

The atmosphere over the Arabian Peninsula serves as a vast energy sink during the transformation of the south-easterly trade wind to the monsoonal southwesterly flow. Some of the essential radiative features of this particular monsoon region are briefly examined in Ackerman et al (1981). As a result of the radiative exchange, a substantial atmospheric heat low develops, driven by sensible heating from the desert surface. This effect, in turn, leads to a pressure anomaly which aids in triggering the recurvature of the Southern Hemispheric trade winds to their characteristic spring-summer time southwesterly flow pattern (See Figure 1 from Krishnamurti et al, 1976). A detailed graphical depiction of the onset flow has been given by Young et al (1980) based on a computer model developed by Smith and Phillips (1972).

DECEMBER 1976 T. N. KRISHNAMURTI, J. MOLINARI AND H. L. PAN

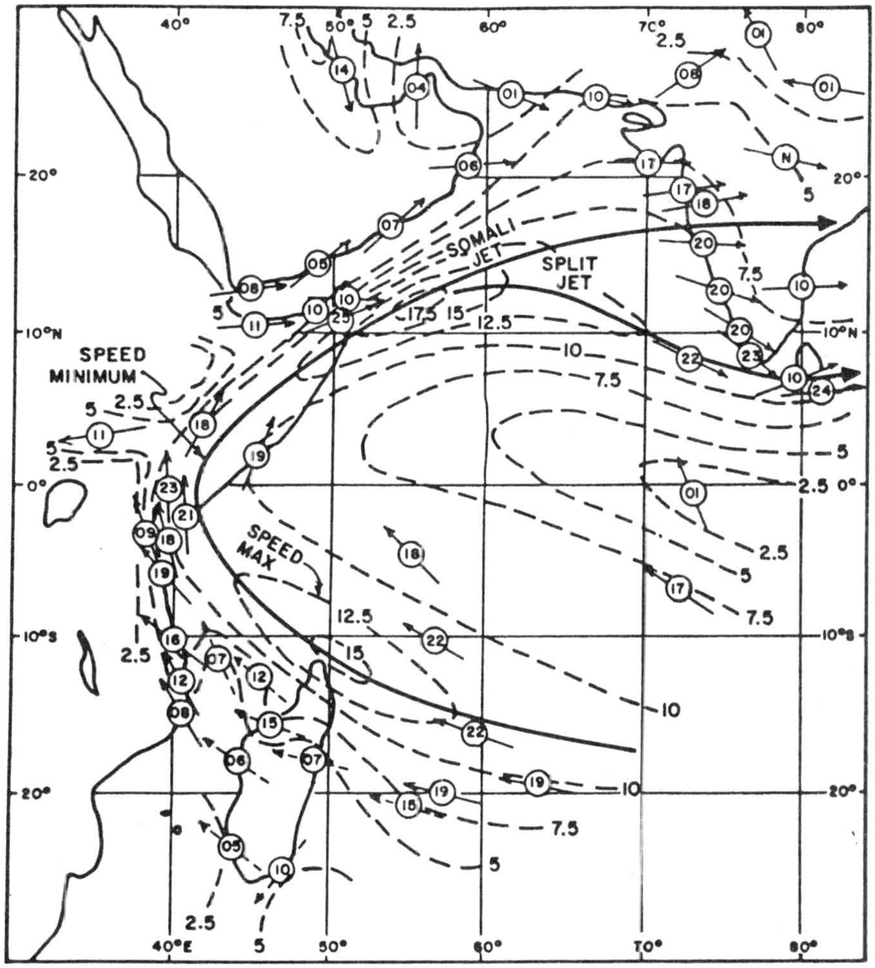


FIG. 1. Findlater's (1971) analysis of 1 km streamlines (solid lines) and isotachs (dashed lines, m s⁻¹) for August. The dark heavy line illustrates the axis of the low-level jet. The locations of observational sites are shown by circles. The enclosed numbers within the circle are the observed monthly mean speed in knots.

Figure 1: Southwest Monsoon Low Level Flow (From Krishnamurti et al (1976)).

During the 1979 MONEX the development of the Arabian Peninsula Heat Low was examined in detail by the NASA CV-990 experimental jet aircraft with the cooperation of the Saudi Arabian Government and its offices within the Ministry of Defense and Aviation. The CV-990 data includes detailed radiative measurements in the verticle for both solar and terrestrial wavelengths, as well as profiles of conventional meteorological parameters of wind, temperature, and moisture (see Smith et al, 1980). Atmopsheric particulates were also sampled during the Saudi Arabian Flights. This data along with satellite measurements from the GOES-1, TIROS-N, and Nimbus 7 satellites are now being used at CSU to develop the radiative energy budgets of the Heat Low Phenomenon (see Smith and Vonder Haar, 1980).

During the preliminary analysis of the 1979 data, a group of radiation experts at CSU noted a serious gap in the Arabian Peninsula data sets, i.e., a detailed account of the surface boundary term which includes the radiative and sensible heat fluxes as well as the effect of soil heat storage (in this case and sand-pebble mixture which dominates the Arabian Peninsula terrain). In addition, the CSU group noted the presence of an abnormally deep mixed layer over the expansive southern desert (Rub Al Khali or Empty Quarter) along with apparent total radiative heating throughout much of the low and middle layers

(See Cox and Ackerman, 1981). Considering the presumed compensating subsidence that caps the thermal low and suppresses convection over most of the southern peninsula, in summer we are still unsure how the lower layers balance the continuous radiative, thermodynamic, and convective energy input. The present results are not well understood at this time, due in particular to our lack of quantitative information concerning the surface energy budget.

In response to this problem, we proposed and are now carrying out a series of field experiments designed to monitor the radiative and thermodynamic aspects of the Arabian Peninsula boundary layer. We are especially interested in the desert boundary layer within the Rub Al Kahli desert (Empty Quarter) to which the thermal low locks itself during the onset and course of the Southwest Monsoon. The proposed measurement program will establish the basis for a more thorough, long-term study of the pre-monsoon environment and hopefully one of the first thorough examinations of the structure of a pure desert boundary layer.

II. Cooperation of Scientific and Governmental Agencies

In order to carry out our proposed measurement and research program we have required the cooperation of personnel and agencies within King Abdul-Aziz University and various Ministries and Agencies of the Saudi Arabian and American governments. The assistance and advice of a number of key individuals have been essential to the success of our program. To date, the research project has necessitated the assistance of administrative and scientific staff at The Faculty of Meteorology and Environmental Science including CID project personnel and key officials within the Ministry of Defense and Aviation, particularly within the General Directorate of Meteorology and the Saudi Arabian Air Force and Army. The tacit support of the National Science Foundation through its MONEX project office has also been essential. We point these matters out with some emphasis so as not to diminish the importance and contributions that the respective individuals and agencies have provided. We recognize and fully acknowledge that the future of our research program will continue to depend on the cooperative relationships that have been established, and that the importance of these relationships should not be under-estimated.

III. The Radiative Boundary Layer Station

The research project was initiated, for all practical purposes, upon delivery of a prototype radiative boundary layer station to the FMES in late April 1981. The station had been fabricated and checked out at CSU-ATS during the spring of 1981 under the guidance of one of the PI's of this project, Professor Stephen Cox. The equipment components had been purchased on a very timely basis by the ARMETED project at the University of Arizona, under the directorship of Professor Martin Fogle.

The station was designed to make measurements of shortwave and longwave radiative parameters into and out of the surface, to monitor the storage and losses of heat within the surface, and to monitor the conventional atmospheric parameters of wind temperature and mixing ratio near the surface. Rainfall monitoring was not included since, for the initial experiments, we intended to deploy the station in dry environments.

The measurements are collected automatically by a pair of micro-processor controlled data logging systems developed by Campbell Scientific Inc. (Model CR-21 - see Figure 2). The individual sensors are interfaced to a data logger via transducers which are compatible to any of 7 analog input channels available on either micrologger. Two additional digital inputs are available on each micrologger for monitoring pulse-counting instruments - in our case a horizontal wind anemometer.

CR21 MICROLOGGER

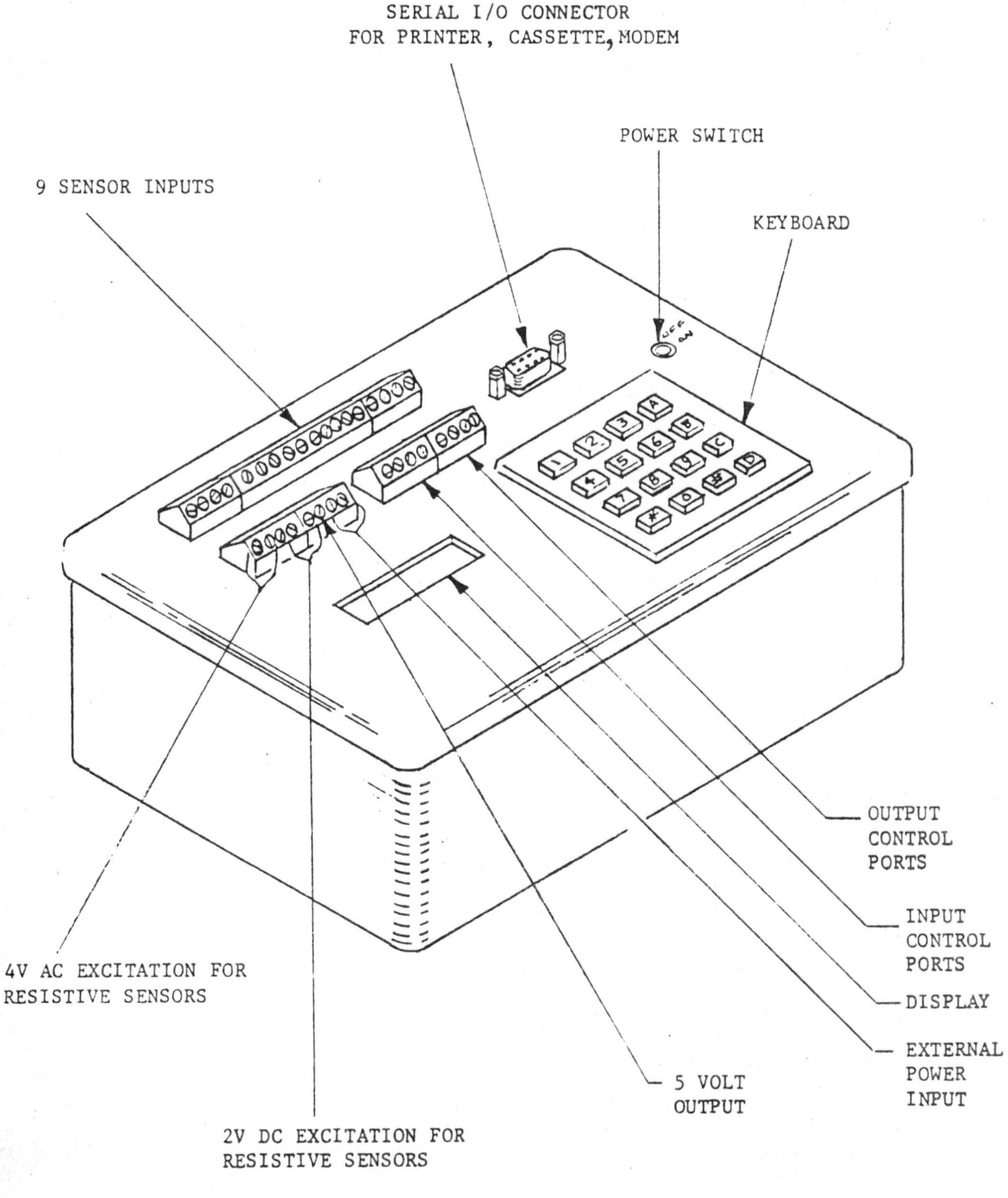


Figure 2: Campbell Scientific CR-21 Micro-Data Logger.

The radiation sensors consisted of pairs of total solar, near-infrared, and total longwave flux radiometers, all of which were manufactured by the Eppley Laboratories (PSP Pyranometers and PIR Pyrgeometers). One of each pair of radiometers was configured to view upward so as to measure downwelling radiative flux - the other of each pair was configured downward to measure upwelling reflected or emitted radiation. By differencing the total solar and near-infrared channels, the UV-visible radiation band is determined. By differencing the respective downwelling and upwelling fluxes, the net radiative divergance at the surface is determined. This sensor configuration duplicated that used during the MONEX so as to facilitate date intercomparison and integration. In fact, the thermopiles used in the infrared pyrogeometers were the same thermopiles flown on the CV-990 during MONEX. This was done so as to maintain a consistent data record for the IR flux measurement which is highly instrument sensitive. The solar wavelengths are divided into UV-visible and near-infrared regions so as to facilitate intercomparisons with weather satellite data.

The soil heating cycle was monitored with a set of 3 Fenwal Electronics Thermistors located at 3 different depth settings (normally 2, 20, and 35 cm). These depth settings were selected, based upon various trial runs, so as to best retrieve the amplitude and phase of the sub-surface thermal wave which in turn is needed to determine the characteristics of the sub-surface thermal storage cycle.

The sensors used to gather the conventional parameters consisted of a thermistor-hygristor probe (Fenwal UVT-51J and Phys-Chemical Research PCRC-N) used to retrieve air temperature and mixing ratio, and a Met-One Corporation Wind Vane-Anemometer system used to retrieve the horizontal wind vector. A schematic illustration of the monitoring system is given in Figure 3. A summary of the individual measurements available from this system are given in the following table.

1. Downwelling Total Solar Radiative Flux
2. Downwelling UV-Visible Radiative Flux
3. Downwelling Near-Infrared Radiative Flux
4. Downwelling Total Infrared Radiative Flux
5. Total Downward Radiative Flux
6. Upwelling Total Solar Radiative Flux
7. Upwelling UV-Visible Radiative Flux
8. Upwelling Near-Infrared Radiative Flux
9. Upwelling Total Infrared Radiative Flux
10. Total Upward Radiative Flux
11. Net Radiative Flux Divergence
12. Surface Albedo
13. Equivalent Black Body Surface Temperature
14. 2 cm. Depth Thermal Wave
15. 20 cm. Depth Thermal Wave
16. 35 cm. Depth Thermal Wave
17. Near Surface Air Temperature
18. Near Surface Relative Humidity (or mixing ratio/specific humidity)
19. Dew Point Temperature
20. Horizontal Wind Vector (u, v, speed, direction).

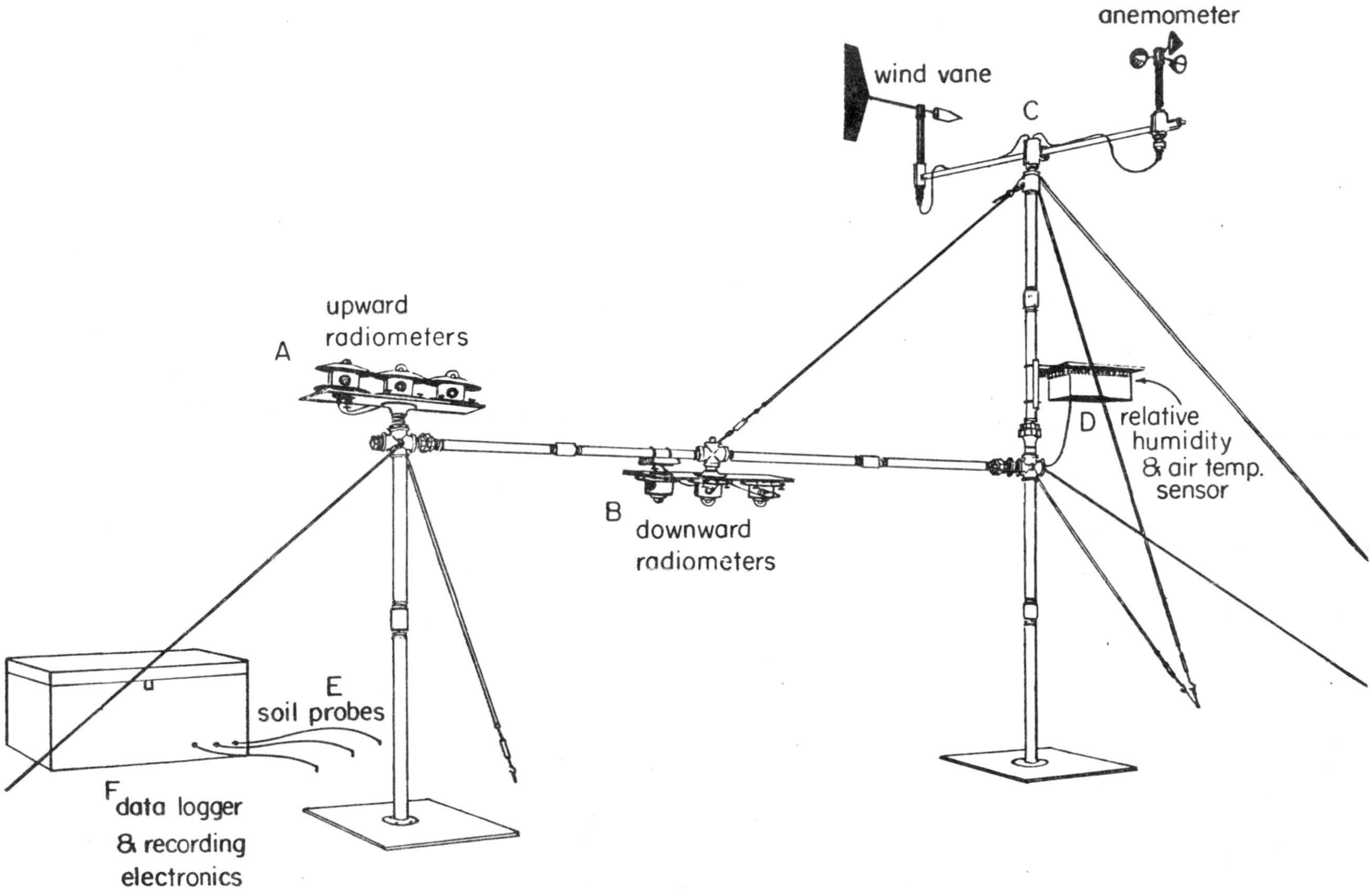


Figure 3: Schematic diagram of the Radiation Boundary Layer Station.

The measurements are used to diagnose the surface radiation budget and the sensible heat flux transported from the desert surface into the atmosphere by convective processes. The latter term results as a residual parameter if the net radiative conditions are well determined and the sub-surface thermal storage is properly monitored for diurnal variations and seasonal trends. The system described above is specifically designed to meet those requirements as it is equipped with soil probes and a complete set of radiation flux devices. It should be noted, in addition, that the system has general applications as a surface weather observation system because it is also equipped with conventional temperature, moisture, and wind sensors.

The major features of the system are its sensors and its automated recording capability. Each of the sensors, whether it provides an analog (such as a soil thermistor or radiometer) or a digital (such as the anemometer) signal, is digitized via a Campbell Scientific CR-21 micro-processor controlled data logger and then routed to a conventional cassette tape recorder for later analysis. The tape cassettes may be played back to a portable hard copy printer (strip chart variety) or more conveniently to a standardized RS-232 computer interface for quantitative computer processing. The system is rather inexpensive, fairly easy to assemble and operate, and requires minimal maintenance. Since the system uses battery power for the logging and recording systems, absolutely no external power or communication sources are required.

The prototype system was delivered to KAAU by Mr. Chris Pasqua and Mr. Charles Wilkins, both of whom hold engineering appointments at the CSU Department of Atmospheric Science. The equipment was assembled and debugged at the JECOR* compound in Jeddah before initiating the field tests. The lead PI of this project and Mr. Pasqua are shown in Figure 4, alongside the station when it was first assembled at the compound. Mr. Smith and Dr. Sakkal were instructed in detail how to assemble, dismantle, program, and maintain the system while it was at the JECOR compound.

The system was then taken to FMES and reassembled in a training mode for various personnel in the Department of Meteorology including; Mr. Salah Abdul-Halim, the departmental technician; Mr. James Vergin, a department staff member; and Mr. Abdullah Khayatt, one of the senior meteorology students. Figure 5 is a photograph of Mr. Pasqua, instructing members of the Institute in the wiring procedures from the sensors to the data logging devices. After these preliminary tests, checkouts, and training periods, the station was ready for its initial field tests.

* The JECOR Compound is a living and office facility for CID personnel.

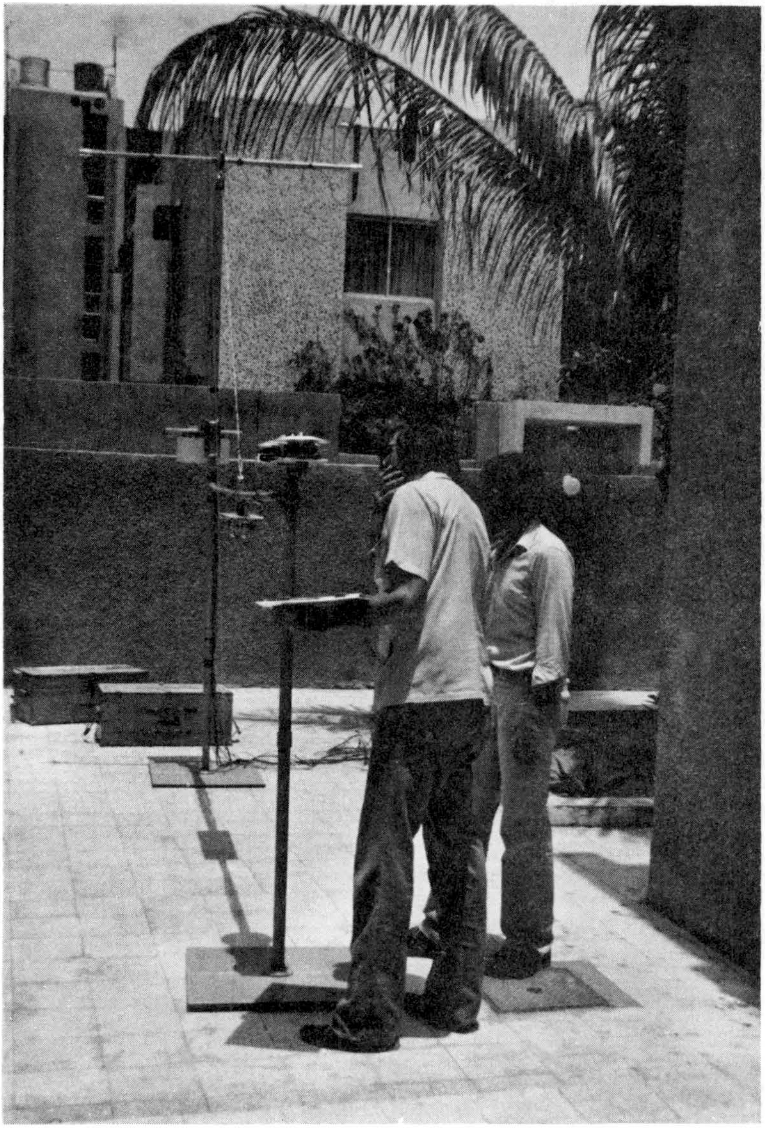


Figure 4: Mr. Smith and Mr. Pasqua are shown examining the measurement system at the JECOR Compound.

Figure 5: Mr. Pasqua is shown instructing various members of the Department of Meteorology at the FMES in proper wiring procedures.

(From left to right: Mr. Khayatt, Mr. Sabbagh, Mr. Vergin, Mr. Salah.)

IV. Field Tests

Three sites were selected for the initial field tests. The locations of these sites are indicated in Figure 6. The first tests were carried out at the old Jeddah airport (site 1 in figure 6) within the secured grounds of the Jeddah upper air weather station facility. Authorization to use this site facility was arranged with the General Directorate of Meteorology (GDM; now MEPA) through the office of Mr. Abdul-Karim Heneidy who is director of field operations for GDM operated weather stations.

This first test was an important trial run because we wanted to intercompare our measurements with the airport station measurements to verify proper operations. We also required a shake down analysis to determine the optimal depths to set the soil probes. We accomplished this task by deploying six probes at uniform intervals, finally selecting 3 depths which best characterized the sub-surface thermal profile. Only 3 probes are enabled in the normal system configuration.

The preliminary results showed that the amplitude of the diurnal wave damped out at 40 cm; depths of 2, 20, and 35 centimeters were later selected to characterize the amplitude and phase shift of the sub-surface thermal wave profile. Data was taken for 3.5 days at the Jeddah airport site. Figure 7 provides preliminary plots of the soil probe data along with the conventional parameters (temperature, wind speed, dew point).

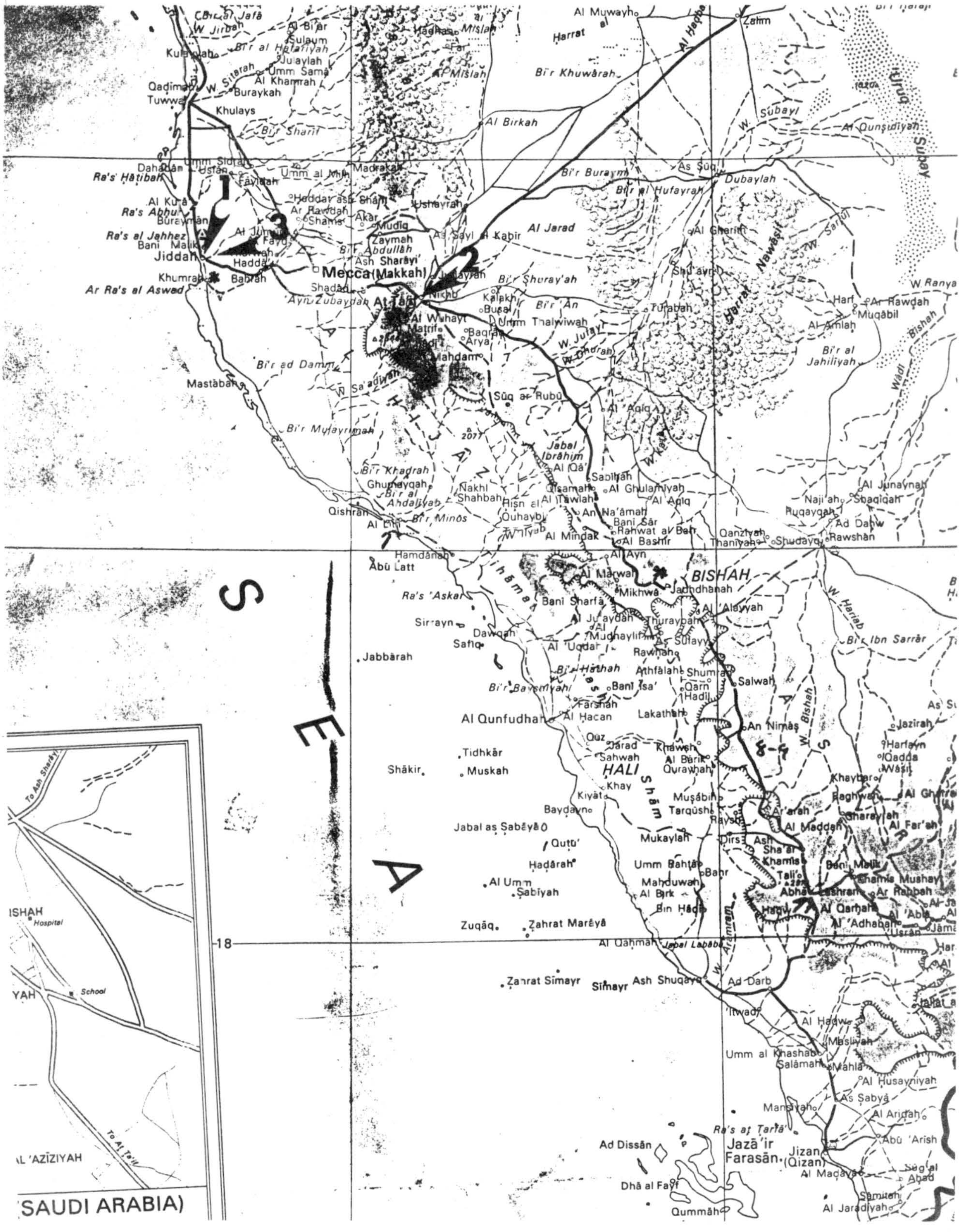


Figure 6: Map illustration indicating the 3 field test site locations.

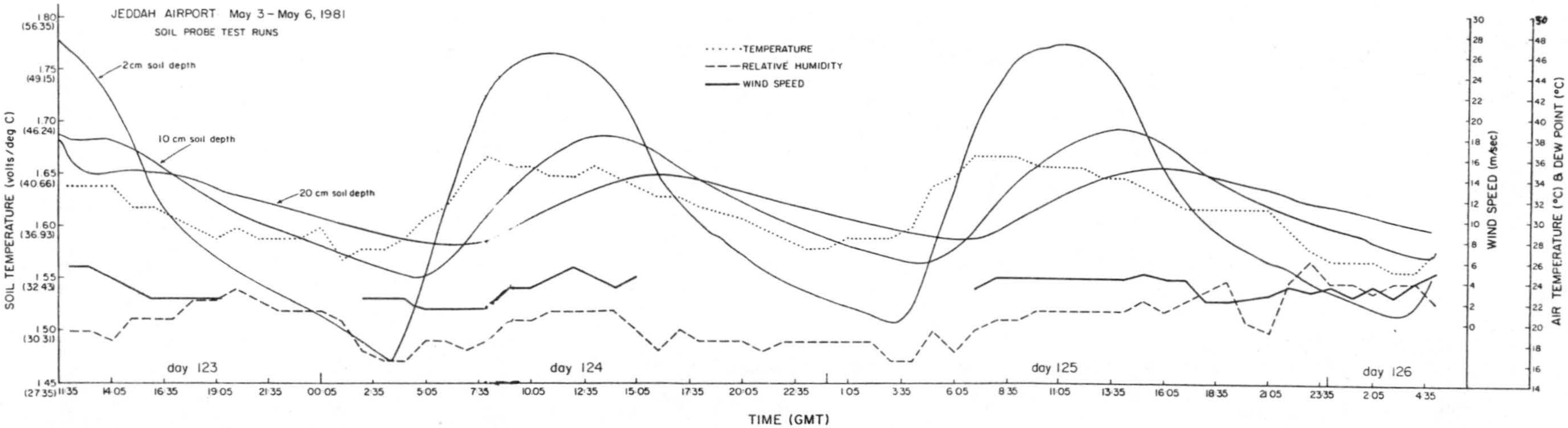


Figure 7a: Results of the Jeddah Airport Field tests (2, 10, 20 cm. soil temperatures, air temperature, dew point, wind speed).

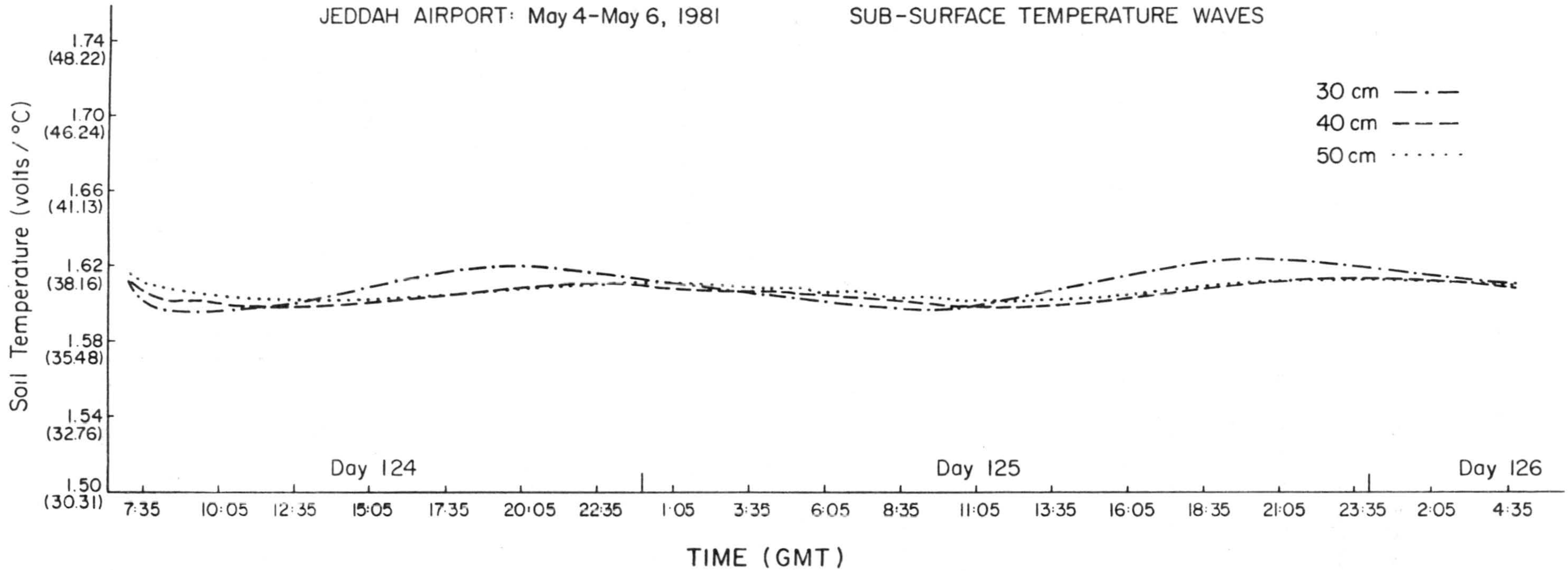


Figure 7b: Results of Jeddah Airport Field Tests (30, 40 and 50 cm. soil temperatures).

It was noted from this first data set, and confirmed in later tests, that the shape or wave form of the thermal wave can be well described by a modified gamma function (steep rise on the left with a varying tail length to the right). The selection of this function form to describe the sub-surface thermal process is discussed in Section VI. Another factor we noted immediately was the very smooth and stable performance of the sensors. This was a very important result in terms of the tolerable errors the later analysis will require.

An important feature we noted from these tests was the very smooth decrease of the amplitude of the thermal wave with depth. This result is shown in Figure 8. The corresponding graph of phase shift is given in Figure 9. Note that by 40 cm. the wave has almost damped out so that any phase shift of the wave peak is no longer easily detectable. This is the reason for the discontinuity shown in Figure 9 on the right hand part of the phase shift plot.

Our second field test site was the mountainous escarpment to the east of Jeddah, at the Taif airport (site 2 in Figure 6). Again Mr. Heneidy made arrangements to use the grounds near the weather station. The selection of a mountain station for field testing was based on our future plans to collect a long term record at the orographic western boundry of the Empty Quarter. The site we were assigned by Mr. Heneidy turned out to be an ideal location for a semi-permanent station that we envision in the second year plan.

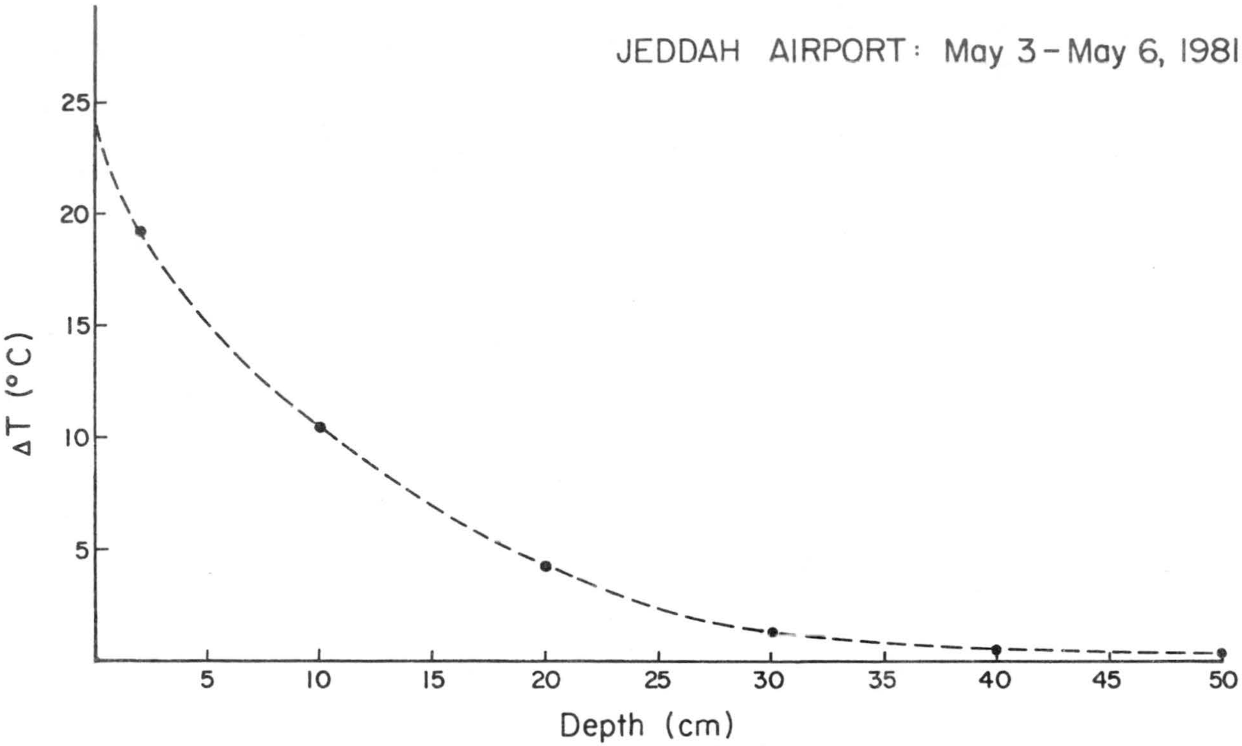


Figure 8: Amplitude of Sub-Surface Temperature Wave.

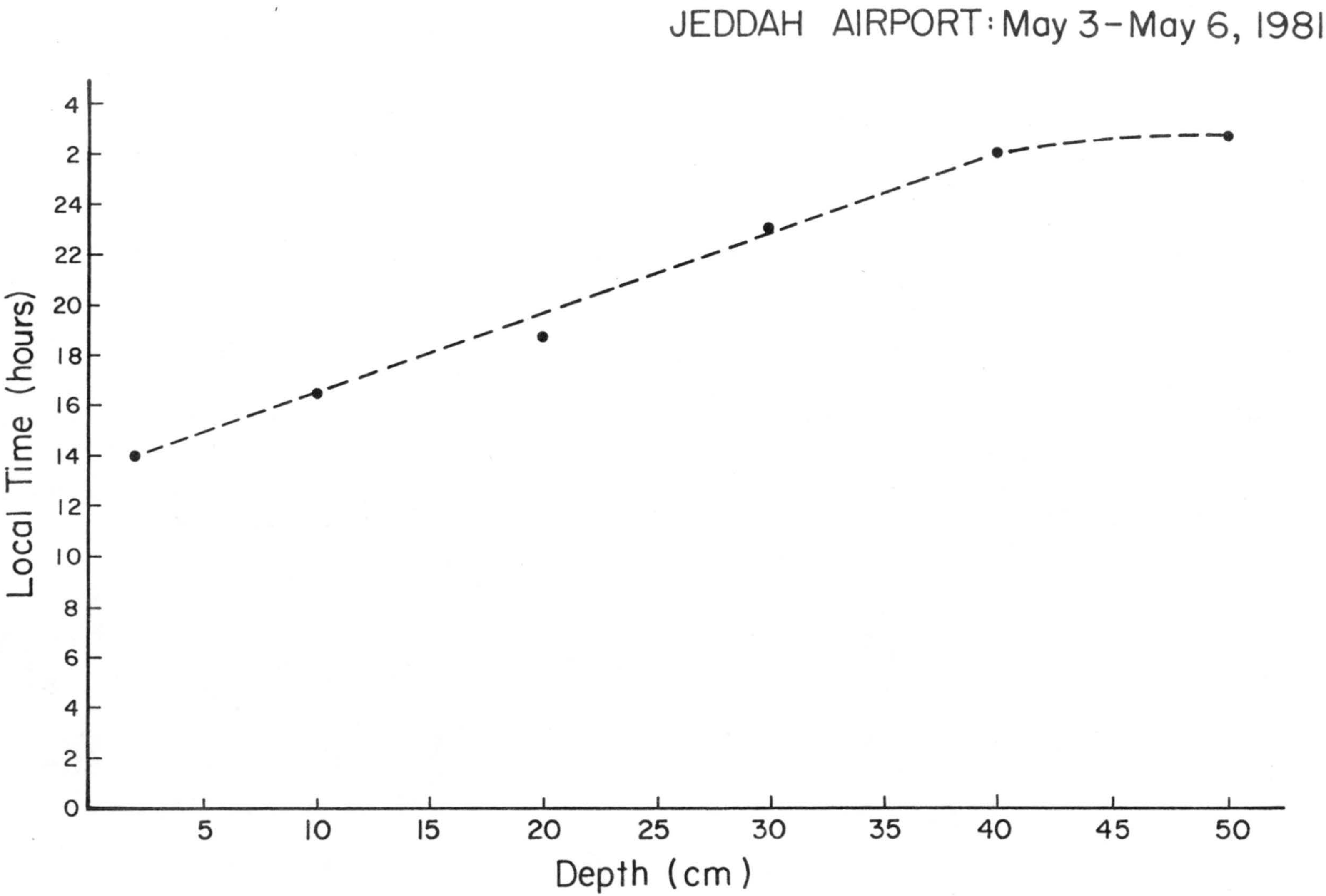


Figure 9: Phase Shift of Sub-Surface Temperature Wave.

The station was deployed at the Taif site for four days, again resulting in a very interesting, and in many ways, unique data set. Figure 10a illustrates the results for the 3 soil probes (2, 20, 35 cm) and the near surface meteorological parameters. The wind direction is plotted at the top of the graph. The amplitude - phase shift diagram of the sub-surface thermal wave is seen in Figure 10b. Note for these results the double peak seen each day in the 2cm. probe temperature. The explanation for this is found in the afternoon cloudiness cycle. The sea breeze, orography and an elevated heat source all lead to the development of an afternoon cloudiness maximum along the escarpment on afternoons of days without significant synoptic activity. As the cloudiness develops surface heating is cut off leading to the initial drop in the surface temperature. As surface heating is suppressed, boundry layer convection begins to diminish and the large scale subsidence dominating the peninsula during the summer thermal low period begins eroding the cloud field. As the cloud field breaks up surface heating is re-established, but by this point static stability has been restored and little new cloud development is observed. This second stage surface heating effect explains the second peak in the 2 cm. trace. Note that on Day 127 a minor peak occurs due to light shower activity on that particular afternoon. Note also the very structured diurnal variation in the surface air temperature and the corresponding variation in the relative

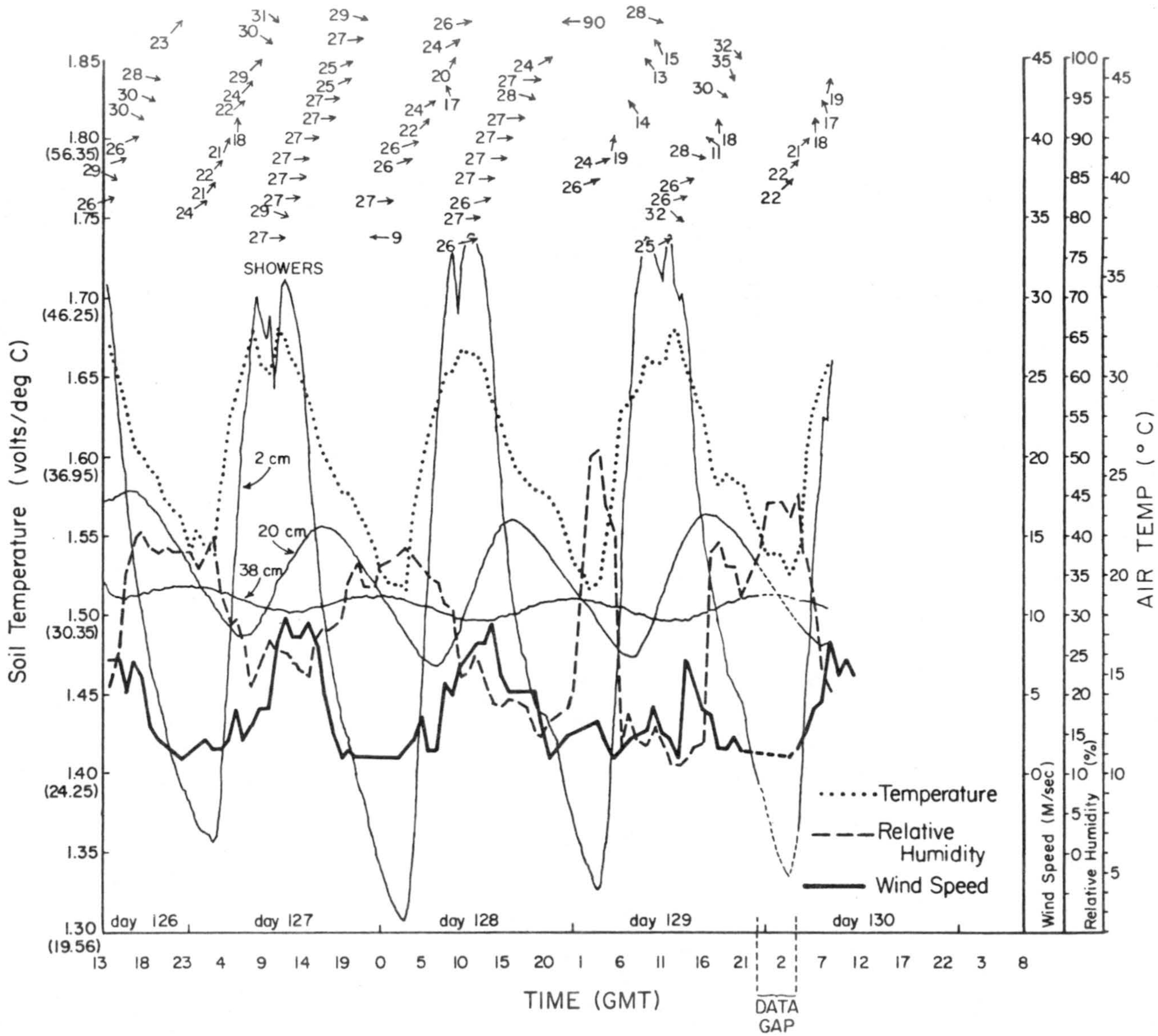


Figure 10a: Measurements taken during the Taif Airport Field Test.

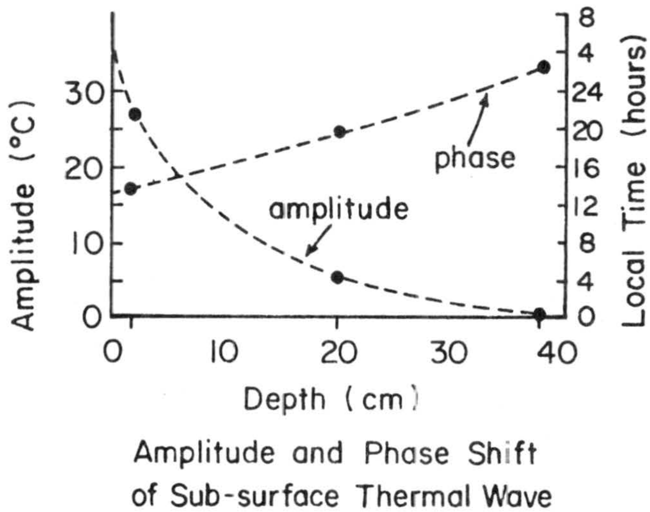


Figure 10b: Amplitude and Phase Shift of Sub-Surface Thermal Wave at Taif Airport.

humidity trace. The wind speed picks up during daylight hours due to differential heating across the mountain barrier.

Our third field test site (shown in Figure 6 as site 3) consisted of a pure sand dune area east of Jeddah. This was to be our only shakedown operation carried out in dune sand before deploying the station in the Empty Quarter. Therefore, it was essential that this test be carried out because we still had much to learn about the reliability and response of the equipment in a sand environment, particularly during high wind and hard blown sand periods. We were especially interested in the effect of wind on the placement of the near surface soil probe. Over the course of this final trial run we learned how to position the 2 cm. probe so that it did not act as a barrier to the wind and thus undergo depth variation. We again experimented with 6 soil probes to verify that our 3 optimal depth selections were appropriate in this type of terrain. Figure 11 provides a photograph of the system as it was deployed in the dune area. Also seen in the photograph are the two lead scientists and their junior assistant, Makmud Sakkal.

Results for the soil probes are given in Figure 12. The discontinuities seen in the 2 cm. probe signal result from the probe being readjusted due to the wind disturbing its orientation. By the end of this 11 day trial, we found a way to insert the probe so that the wind no longer disturbed it (tilting it forward in line with the prevailing wind). These results, which were taken in a pure dune sand terrain, as opposed

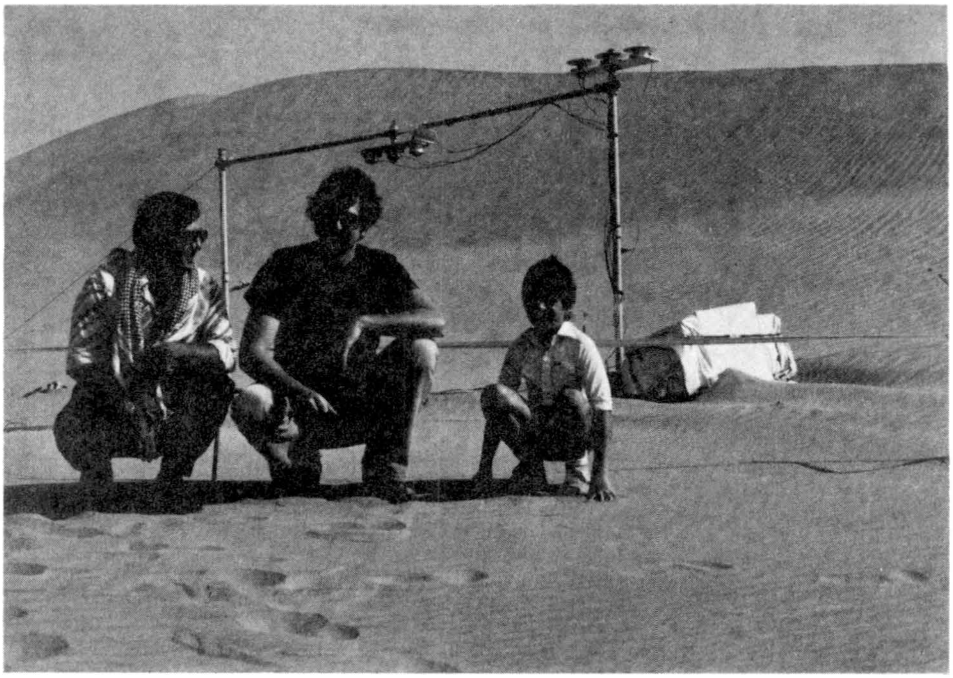


Figure 11: Dune Sand Field Test Site
(East of Jeddah).

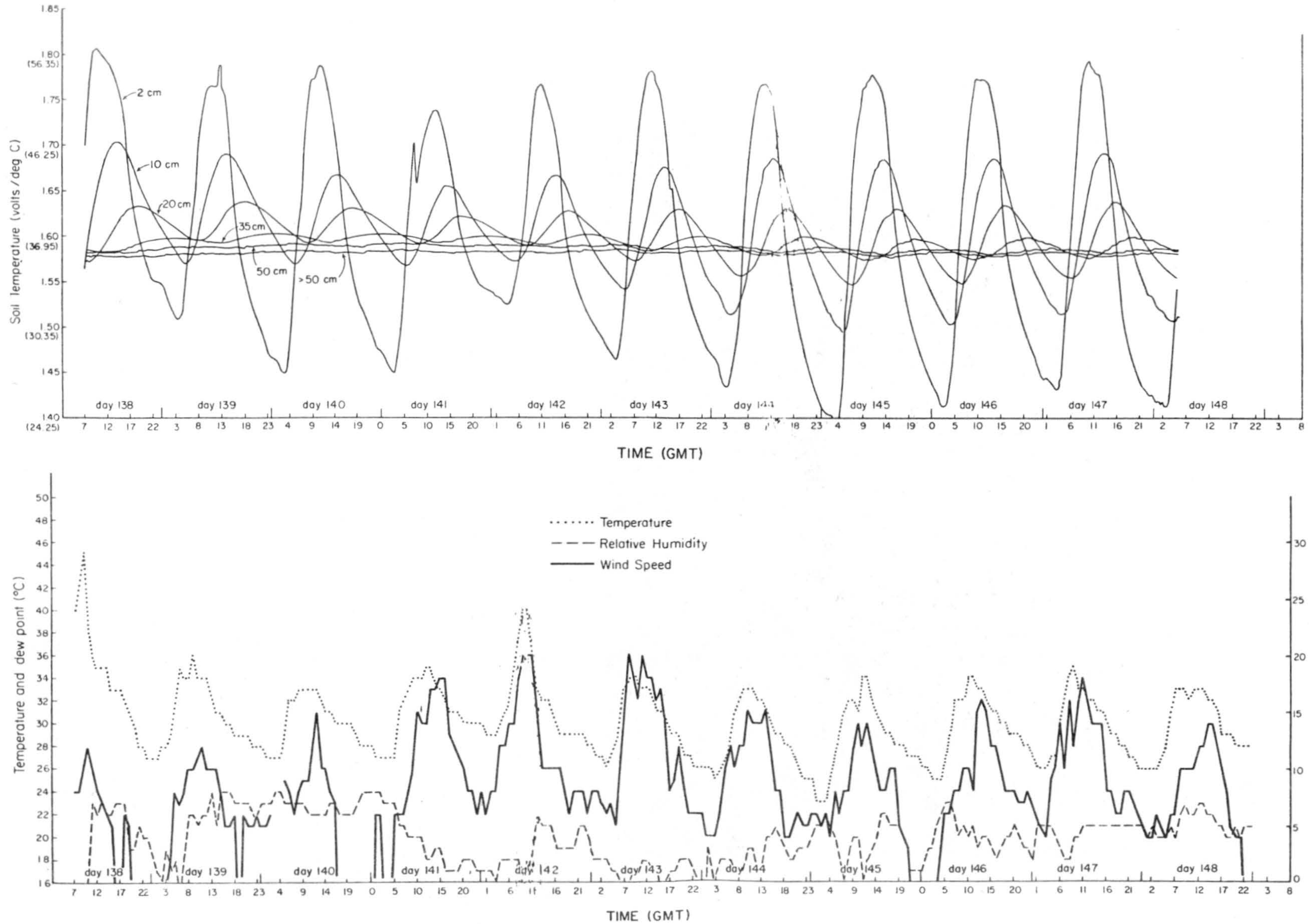


Figure 12: Results of the East Jeddah Dune Sand Tests

to the gravel-sand terrain we experienced at the Jeddah and Taif Airports, again show the characteristic modified gamma function form in the sub-surface thermal wave. The nighttime "shelf" seen in the 2 cm. temperature trace is most likely due to a diurnal wind effect on the heat diffusion process. We did not have our own wind instruments deployed for this test so it is difficult to verify this speculation.

The wind speed data plotted in Figure 12 were taken at the Jeddah Airport. The dune sand test concluded the field test phase, and after careful analysis of the preliminary results, we made the decision to carry out the initial Empty Quarter experiment.

V. The Empty Quarter Experiment

After the preliminary field tests were carried out, a decision was made to attempt a brief measurement period in the Empty Quarter. During the 1979 Summer MONEX, the CV-990 flights over the Arabian Peninsula took place in May, during the pre-monsoon period. Our plan was to obtain a few days of data during the corresponding time period in 1981, in order that the two data sets would be seasonally compatible. The final outcome of our efforts were far more than we originally expected as we were able to obtain a continuous four week data record in The Empty Quarter, from June 1 until June 28. That is, we were able to obtain data during the pre-monsoon period, the monsoon onset period, and the active monsoon period. Thus, one of our first conclusions is that the first experiment has been a major success based on the location of measurements, the duration of the data collection, and the overall quality of the data.

We recognized that in order to deploy the station in the Empty Quarter, we were moving into a far more severe and potentially hostile environment than that which we had previously been exposed. For this reason, we had to select a location near a village that we could travel to conveniently. The area chosen for this purpose was Sharouwrah, approximately 1,000 km. southest of Jeddah near the southern boundry of the Rub-Al-Khali Desert (The Sands) and only about 40 km. north of the northern border of the Democratic Republic of Yemen. Due to the fact that this is a politically sensitive region, Sharouwrah is governed as a secured military zone. Figure 13 provides a map indicating the Sharouwrah location.

The administrative preparation for carrying out this expedition was initiated by an April meeting with Sheikh Nasser Assaf, the Director General of the Saudi Arabian Civil Aviation Authority, in which we requested authorization for the use of civil aviation aircraft for use on our project. This first meeting was very successful in that he was fully aware and supportive of the MONEX and 1979 CV-990 Missions, and thus promised full cooperation from the Directorate to continue the research to the limits of his authority and the resources he has available. He suggested that it would be appropriate for us to take the matter concerning the use of Saudi Government Aircraft to the Deputy Minister of Defense and Aviation, Sheikh Kamel Sindi.

Although we intend to follow these procedures for the long term experiement, this channel seemed too lengthy, as our more immediate plans were to obtain measurements during the May-June period. Accordingly, we decided to pursue a different channel involving a meeting with the Commander of the Jeddah Military Air Base, in which we requested transport for personnel and equipment to and from the Sharouwrah region. He expressed a willingness to approve this request upon our obtaining an authorization from the Minister of Defense and Aviation, Prince Sultan. This authorization was required because the

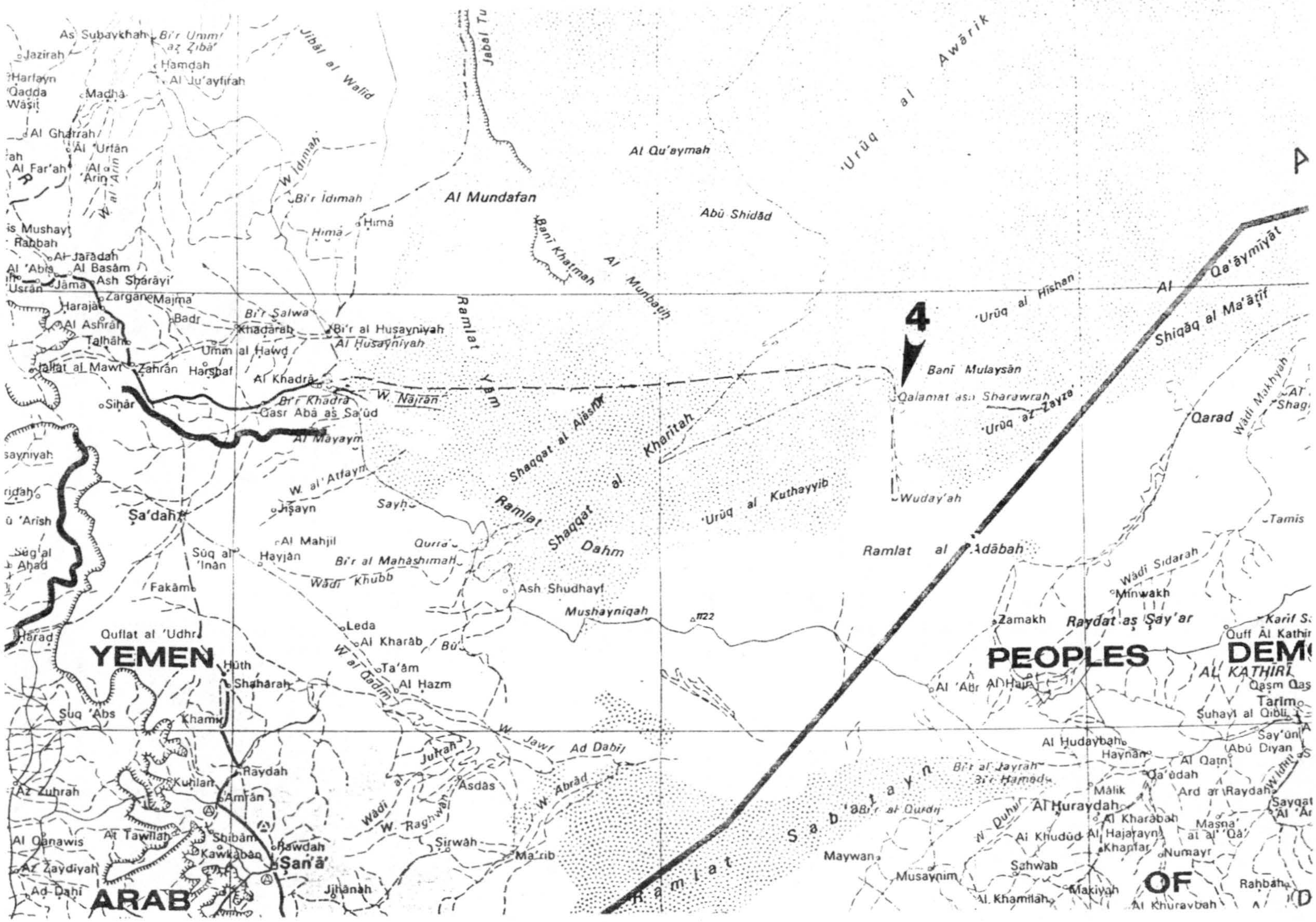


Figure 13: Map indicating the Sharouwrah (Empty Quarter) site.

Sharouwrah region is within a military zone. We recognized, of course, that this authorization could not be obtained quickly.

After considering our alternatives, we decided to simply go to Sharouwrah on a commercial flight, and try and obtain approval from either the Military Commander or the local Emir, to set up the station and begin collecting data. There were no guarantees with this approach, thus when we departed we did not take the bulky items of the station with us. These were left in the hands of The Meteorology Department technician, Mr. Salah Abdul-Halim, who was to bring them via a commercial flight, if and when we received approval from the local authorities.

After our arrival at the Sharouwrah air-strip, some of the local residents escorted us to meet with the Military Commander of the area, Major-Colonel Ali-Hasan El-Naimee. After a brief explanation of our mission and our anxiety associated with obtaining a useful period of 1981 data, and after presenting him with an official letter of recommendation from our Institute, and after his consultation with the Riyadh security officials, he extended us his full cooperation and hospitality. He also provided us with housing and meal facilities, transport, and an official host and driver. These ammenities, to a large degree, insured the success of our measurement program, for instead of being preoccupied with trying to get through the days and nights of a relatively severe environment, we were able to concentrate fully on the experimental apparatus and the data collection effort.

We cannot over-emphasize our appreciation to Major-Colonel El-Naimee in supporting, assisting, and when there was time, entertaining us during our stay in Sharouwrah.

After receiving this authorization, Mr. Salah was instructed by telephone to bring the remainder of the equipment the following day. Our agreement with the Commander, with respect to the measurement program, stipulated that we place the station in the Empty Quarter dune sands off the military base. We were allowed to go to and from the site and our quarters, as we deemed necessary, accompanied by the driver who was assigned a four wheel drive vehicle. We agreed to provide a report to the Commander concerning our activities and a brief description of the data, at the end of our one week stay.

The actual site we eventually selected was a very flat stretch of wind blown dune sand, to the north of Sharouwrah, about 300 yards off the Najrahn-Sharouwrah Highway, which is the only paved highway into the Empty Quarter Sands. The METEOSAT image shown in Figure 14 has the location of the site marked (location 3). Note the high albedoes in this region associated with the dune sands of the Rub-Al-Khali.

The dune sands in this area are fascinating. Quite often in the course of our stay, the winds were strong enough to raise a veil of sand off the desert floor, which would then meander in streaks and wisps across the dunes. At other times when the wind was quiescent, there was nothing but the stillness and the etched out sand patterns to contend with.

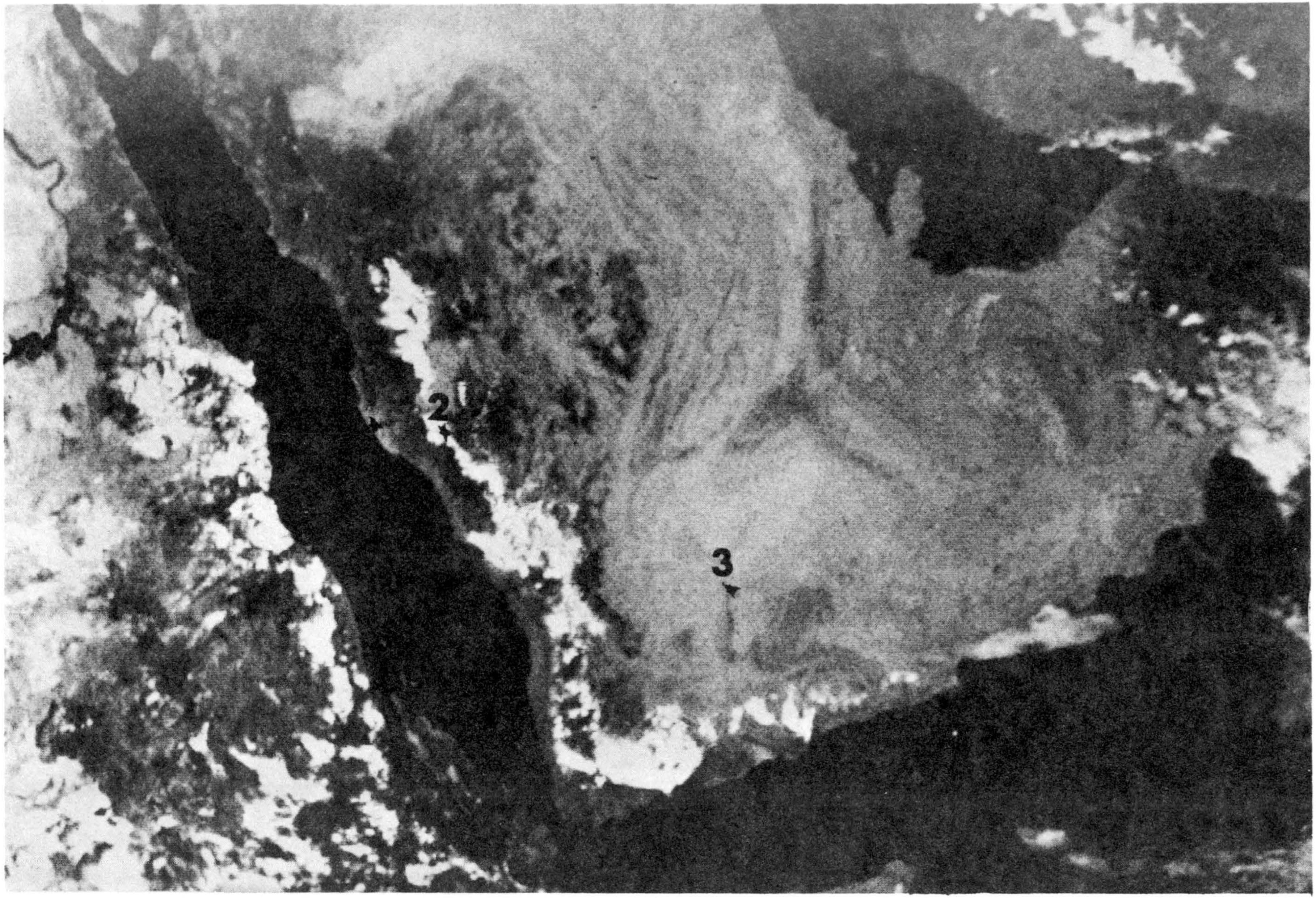
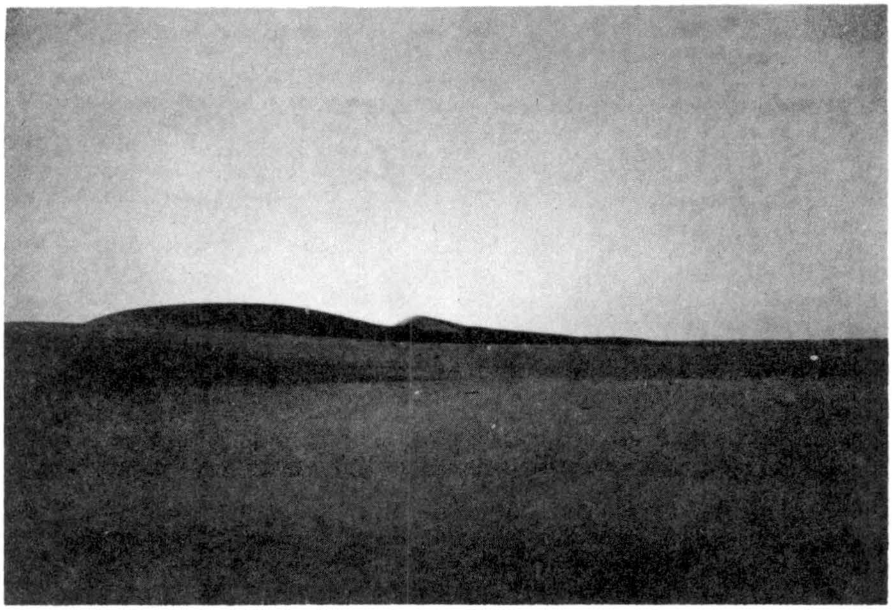


Figure 14: Visible image from METEOSAT indicating the date collection site (Mercator projection provided by Dr. Gary Hunt, Laboratory for Planetary Atmospheres, University College, London).

It is important to keep in mind that the Empty Quarter is an extensive desert, on the order of one million square kilometers. The photographs in Figure 15 are an attempt to portray the character of the desert area in which we were working. In the bottom photograph, Mr. Salah is seen walking toward the station on the sand flats we had selected for the site. The sand at this location has a distinctly reddish hue. This is due to the ferrous composition of the sand grains. This type of sand plays an interesting role in the radiation budget of this region, as it appears to have anomalous reflective characteristics in the near-infrared portion of the solar spectrum. This characteristic was noted by Smith and Vonder Haar (1980) based on the CV-990 flux radiometer data, and has now been verified by first hand measurements. The impact of these reflectance properties on the Arabian Peninsula energy budget will be addressed in later scientific publications.

The station was erected during a minor sand storm, at dusk on June 1. It was an arduous task requiring over twice the amount of time needed for assembly under normal circumstances. Four 4-wheel drive vehicles were immobilized in the sand (buried to their axels) in the course of this exercise. Although we were wrapped in the local Arab head-gear, our ears, eyes, noses and mouths were innundated with sand by the time we returned to our quarters. On the following day, the weather relented somewhat and we were able to obtain some photographs portraying the assembled system. These are shown in Figures 16 and 17.



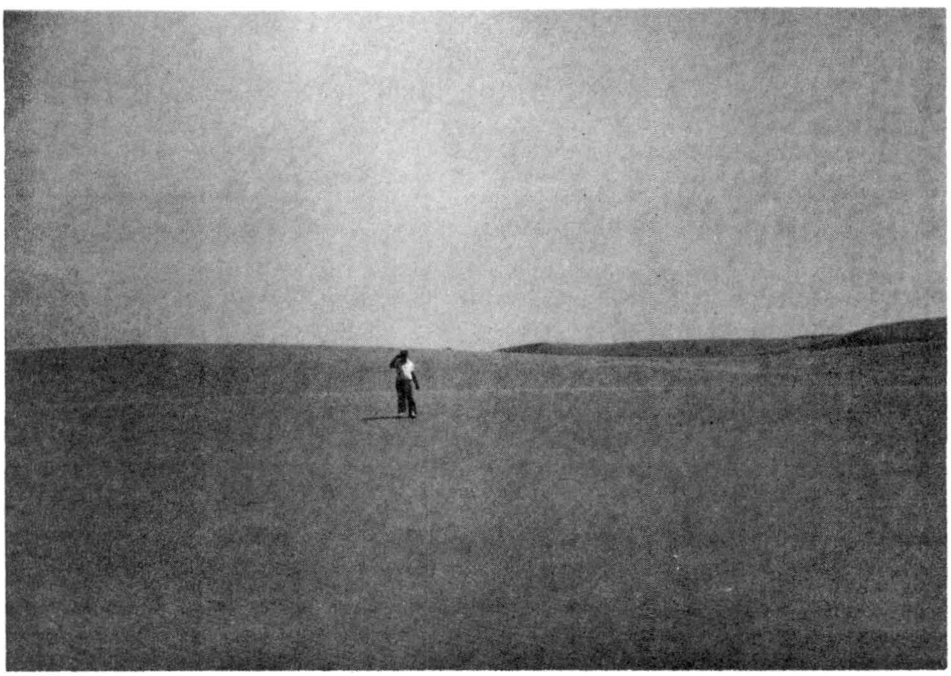
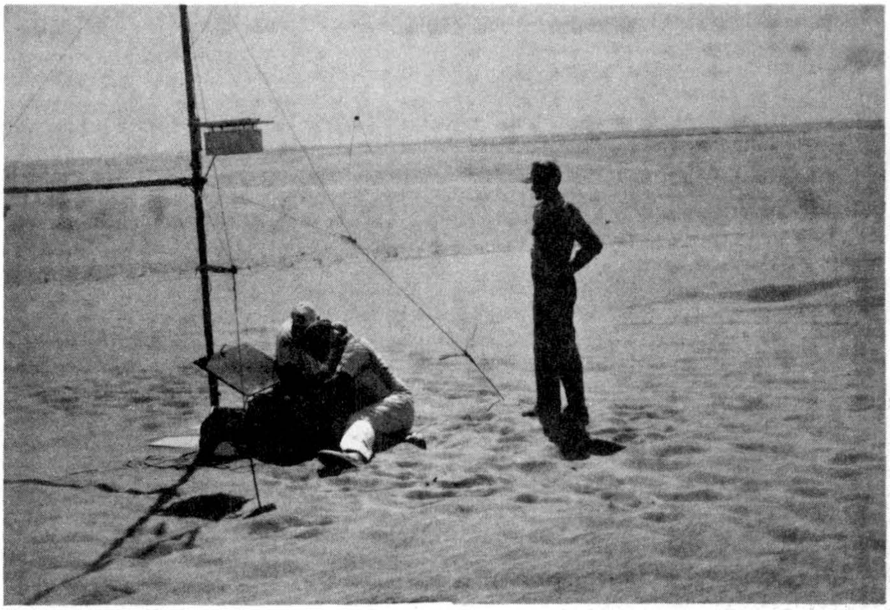


Figure 15: Dune scenes from the Empty Quarter (north of Sharouwrah). Mr. Salah is shown walking toward the measurement station in the lower photograph.



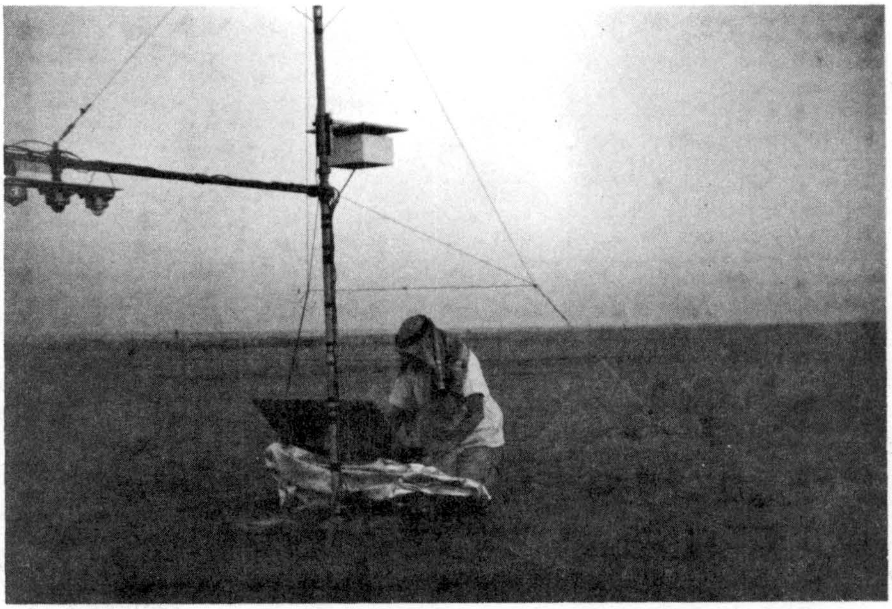


Figure 16: Installation of the Radiation Boundary Layer Station in the Empty Quarter.

Top - Dr. Sakkal and Mr. Salah are seen programming the microloggers while the driver observes.

Bottom - Mr. Smith is shown activating the microloggers and recording systems. A space blanket is used to shield the electronics from excessive solar heating.

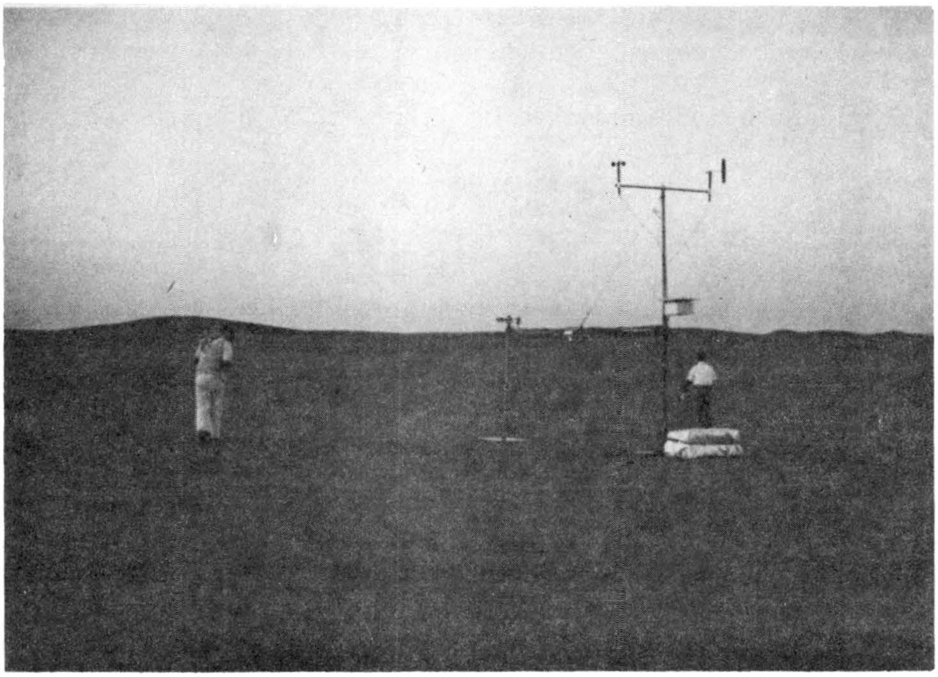


Figure 17: Scenes at the Sharouwrah site.

Top - View of the Najrhan-Sharouwrah highway (Mr. Smith is in foreground in desert garb for blowing sand protection).

Bottom - Photograph of the assembled station. (Dr. Sakkal (left) and Mr. Salah (right) are inspecting the soil probes and tie down cables).

The system was programmed for a ten minute time constant (all sensors sampled every 10 minutes) for the first few days. At the beginning we gave the system constant attention, because of our concern with dust and sand coating the radiometer domes. We were also unsure of how structurally stable the system would be in light of the constant sand storms. The foundational support for the system consisted of four sand filled paint cans, backed by one foot square plywood slabs, and buried in the sand with anchor pins exposed to tie down the guy wires. As it turned out we had no basis for our worries as the sand in this region is so dry and clean that it simply did not stick to the radiometer domes. Furthermore, within twelve hours, the buried cans had been packed so firmly that the station swayed very little in the higher winds.

After two days of data collection the cassette tapes were replaced and the first data examined for problems. There were none. All sensors had performed exceptionally well. The first four days of data are shown in Figures 18 and 19. The soil temperatures, air temperature, and relative humidity are given in Figure 18. In addition the average wind speed, average wind magnitude, and wind direction (top of graph) are given. The amplitude and phase of the sub-surface thermal wave, as a function of depth, is shown in the top right of the figure.

There are some remarkable features of the Empty Quarter environment illustrated in these plots. First note the very

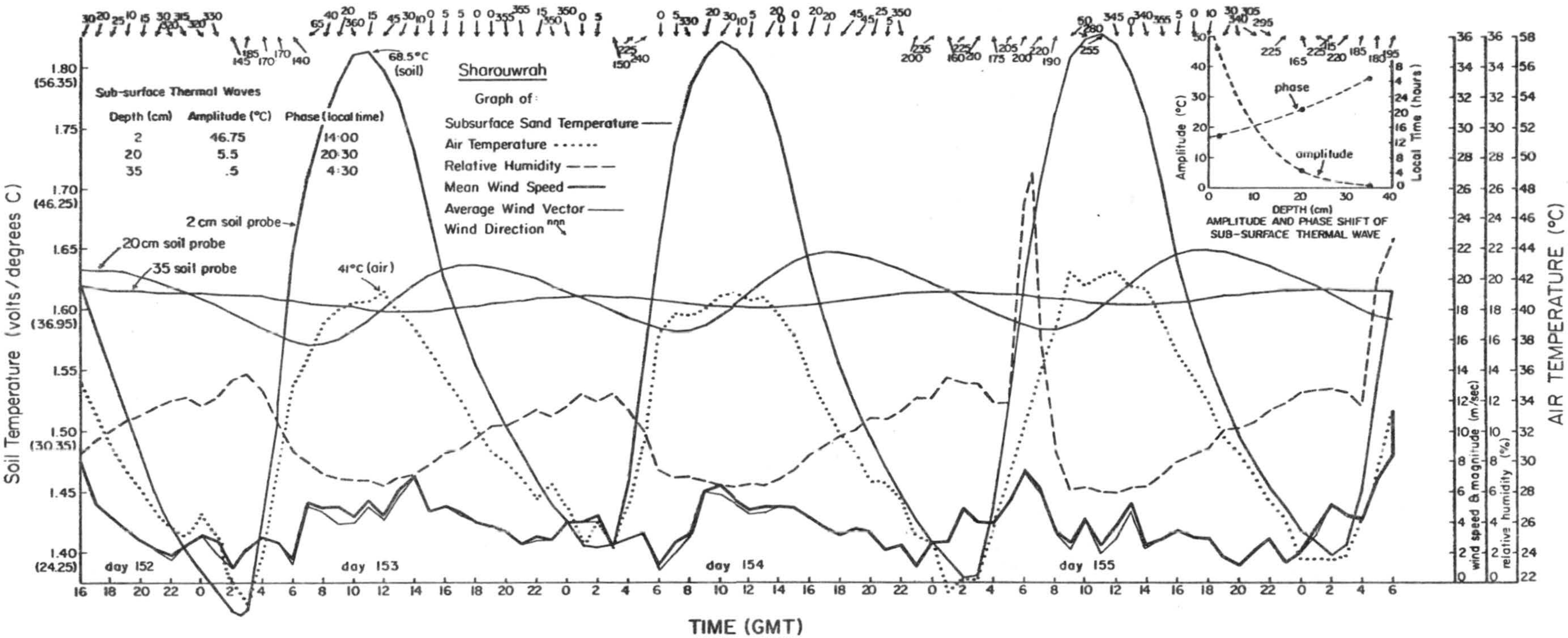


Figure 18: Soil temperature, air temperature, relative humidity, and wind measurements from Sharouwrah (June 1 - June 5).

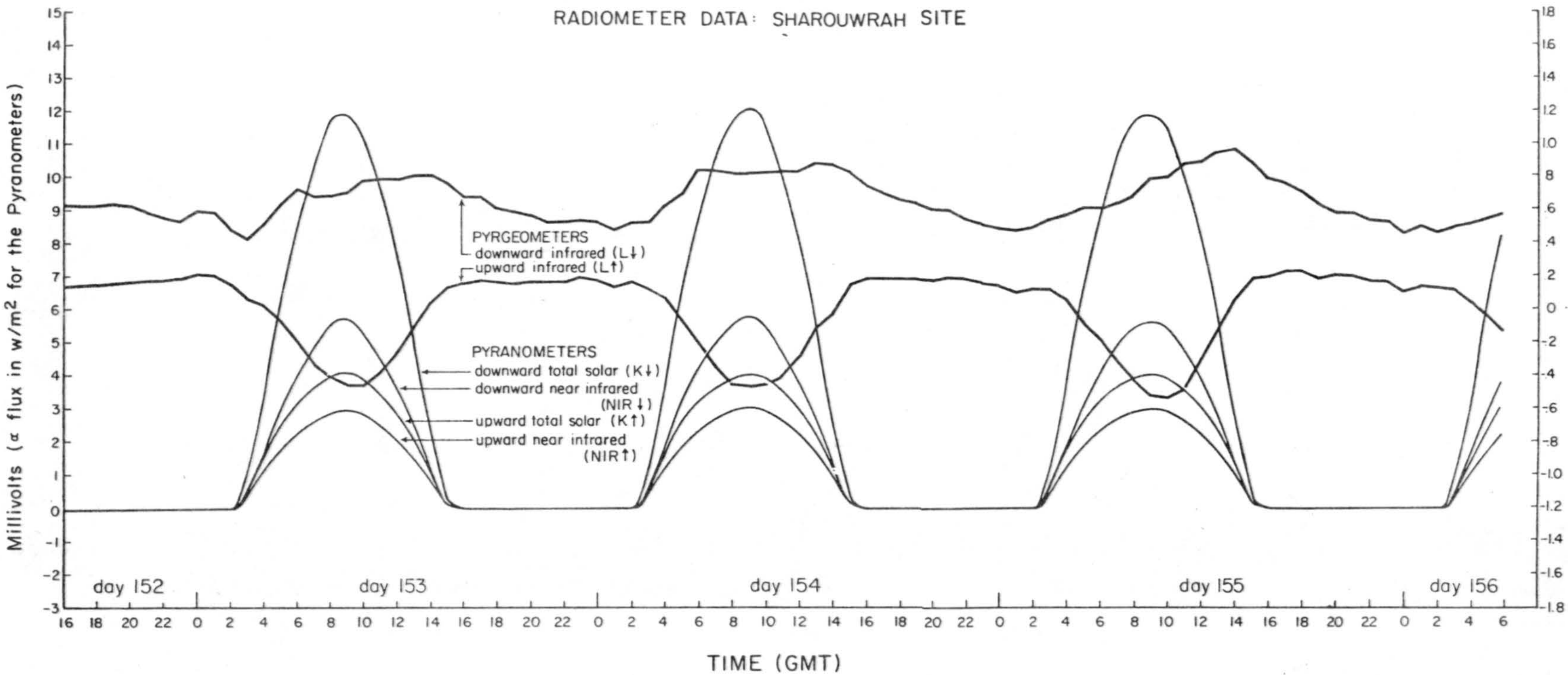


Figure 19: Radiation measurements from Sharouwrah (June 1 - June 5).

large peak to peak variation in the surface temperature (2 cm. probe), a variation of almost 50°C. Note, however, by 35 cm. the diurnal thermal wave has almost damped out. This indicates the virtual lack of heat capacity in a desert (in contrast to an ocean) but also the significant diurnal amplitude of the surface emission term. Note also the very periodic diurnal rhythm in the air temperature and the required corresponding variation in the relative humidity (assuming no new moisture sources). Just after 5 GMT on Day 155, the humidity term takes a dramatic rise. This appears to be associated with the duration of the daytime southerly wind, which apparently, if it sustains itself long enough throughout the day, can bring in moisture from the southern coastal region. On the two previous days, the southerly winds lasted only a few hours giving way to the primarily night time northerlies, probably representing the southwest flank of the cyclonic thermal low, which dominates the lower troposphere during this period.

The plots of average wind speed and average wind vector ($\sqrt{\bar{u}^2 + \bar{v}^2}$) illustrate the basic features of the boundary layer turbulance. The difference between the average speed and average magnitude is a measure of the steadiness of the wind. At night there is little difference, indicating the wind is steady and thus transports according to the mean speed. In the daytime, horizontal turbulent stresses develop resulting from variations in the surface heating and conversion of vertical momentum transfer into horizontal components. This is characteristic of a convectively active environment. Thus the difference in these two quantities illustrates the loss of efficiency in the wind for the horizontal flux of atmospheric quantities, such as water vapor or aerosols.

Figure 19 illustrates plots of the flux radiometer data for the first four days. The scale is given in terms of raw output voltage: for the pyranometers (solar radiation) voltage is directly proportional to radiative flux (through a constant sensitivity coefficient). The pyrgeometer (long wave radiation) voltages require a thermal adjustment based on the difference between the dome and sink temperatures of the pyrgeometer housings. Thus the pyrgeometer traces are difficult to interpret on this graph. The important result indicated here is the magnitude of the near infrared reflectance or albedo. The daily value is found by ratioing the integral of the upward near-infrared flux by the downward infrared flux. The values are very high, more so than the corresponding UV-visible reflectance. This is an abnormal condition for a natural earth surface with respect to top of atmosphere exchange. Given the dryness of the Arabian desert atmosphere, we can assume the integrated daily near infrared albedo measured at the surface is very close to that which would be determined at the top of the atmosphere. This excess loss helps explain why deserts appear to be such dramatic energy sinks when viewed from space. The anomolously large near-infrared term (the near-infrared spectrum contains nearly half the solar energy) gives an added boost to the reflectance loss term. This effect has been difficult to assess with low resolution broad band satellite radiation budget sensors and impossible to assess with high resolution weather satellite sensors which incorporate visible bandpass detectors.

Near the end of our intended stay in Sharouwrah we submitted our report to Commander El-Naimee. It was well received and as a result sent on to the office of the Defense Minister. It was at this juncture that we took the opportunity to extend the period of data collection. We requested approval to leave the station at the Sharouwrah site throughout the remainder of June. Commander El-Naimee not only approved our request, but made arrangements to have the station guarded in our absence. Dr. Sakkal made two further trips to Sharouwrah thereafter to replace and retrieve the cassette data tapes. The station was finally removed on June 28th after a very successful measuring program.

VI. Present Status and Future Planning

In order to utilize the 1981 data in energetics studies we require fairly precise final calibration and sensitivity coefficients for the thermistors and radiometers. We are presently preparing the calibration equations for the soil probes based on laboratory data. The calibration coefficients for the pyranometers and the pyrgeometers are known. Software required to adjust the measurements for thermal drift in the instruments is being prepared for the mini-computer system used to read the cassette data. Software for retrieving cassette data and preparing computer files has recently been completed.

In the near future we shall fabricate the apparatus necessary to measure the heat capacity of a dry soil-sand mixture. This will be necessary in order to calculate the absolute thermal storage term. We are also interested in examining differences in the thermal capacity of the various sand-rock mixtures collected at six different sites from the coast inward to the Empty Quarter Site.

Another immediate problem is to model and parameterize the soil storage term for application to the 1979 MONEX experimental data set. The problem is one of developing a wave equation which physically approximates the periodicity of a diurnal cycle, and a parameterization for scaling the amplitude of the wave. The parameterization must be based on the conventional surface weather parameters and possibly a radiative parameter. Preliminary analysis of the data indicate that the probable form of the model-paramaterization will be as follows:

$$t_{soil} = t_{ref}\ (JD) + A(\bar{T},\bar{V},\bar{q})\cdot \exp\ (-a\cdot z)\cdot$$

$$\{\ b \cdot t^{\alpha} \cdot \exp \left[\frac{-\alpha}{\gamma} \left(\frac{t}{t_m} \right)^{\gamma} \right] \}$$

Where JD = Julian day

t = Diurnal time variable

t_{ref} = Reference temperature

$A(\bar{T},\bar{V},\bar{q})$ = Parameterized amplitude scale coefficient based on measures of temperature ($\bar{T}$), wind ($\bar{V}$), and mixing ratio ($\bar{q}$).

$\exp(-a\cdot z)$ = Amplitude function (z is soil depth, a is an empirical coefficient).

$b \cdot t^{\alpha} \cdot \exp \left[\frac{\alpha}{\gamma} \left(\frac{t}{t_m} \right)^{\gamma} \right]$ = Wave form of thermal wave, i.e. modified gamma function (b, α, γ are empirical constants)

t_m = Phase shift time constant

= to + $c\cdot z$ (to is reference time, c is an empirical coefficient).

Since we were able to collect almost seven weeks of data through May and June, we believe it will be possible to construct enough profiles of radiation and heat exchange to quantify the surface energy budget during both the pre-monsoon and monsoon onset period. These results will go a long way in diagnosing some of the ambiguities discussed in the Introduction.

We plan to present our preliminary results in late October at the "International Conference of the Scientific Results of the Monsoon Experiment", to be held in Denpasar, Bali, Indonesia. Two papers will be presented. The first to be given by Sakkal, Alamy, and Smith will concentrate on the scientific objectives and the overall design of the experiment and the measurement system. The second paper, by Smith, Cox and Vonder Haar will consider the Empty Quarter results in the context of addressing some of the scientific questions raised during the planning of the MONEX, and will go into some detail on the residual approach used to diagnose the surface sensible heat exchange.

We are planning a substantive expansion of our measurement program based on the successes of the first year. These plans will be discussed in a supplementary proposal to be submitted for consideration at the Fall, 1981 CID-ARMETED Research Council Meeting. We shall obtain additional scientific support by way of the participation of Dr. Teizi Henmi, who shall spend the 1981-82 school year at KAAU-FMES as one of the two CID-FMES faculty members on leave from CSU. His past research experience represents a valuable resource to our project.

VII. Acknowledgements

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