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THE PERSIAN GULF REGION

A CLIMATOLOGICAL STUDY

BY

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PREFACE

This technical note documents and consolidates work done to complete USAFETAC Project Number 703-30 for 5WW/DNC, Langley AFB, VA 23665-5000. The project leader was Capt William F. Sjoberg, USAFETAC/ECR. Lead researcher and writer was Mr Kenneth R. Walters, Sr., USAFETAC/ECR. USAFETAC's Operating Location A at Asheville, NC made a major contribution in providing special data summaries. The authors are indebted to Mr Keith Grant of the British Meteorological Office for his outstanding cooperation and many contributions of data. Companion documents to this work provide detailed electrooptical transmittance climatology and refractivity data for the Persian Gulf region; see USAFETAC/TN-88/003, *Persian Gulf Transmittance Study*, and USAFETAC/TN-88/004, *Persian Gulf Refractivity Study*.

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Chapter 1

INTRODUCTION

AREA OF INTEREST. This study describes the climatology of the Persian Gulf, the Strait of Hormuz, the Gulf of Oman, and their adjacent land areas for a radius of 150NM. Land areas include portions of Iran, Iraq, Kuwait, Bahrain, the United Arab Emirates, and Oman.

STUDY CONTENT. Chapter 2 describes geography in the areas of interest. Chapter 3 discusses the phenomena of the monsoon climate as it affects the Persian Gulf region. Subsequent chapters (one for each of the four "seasons" or climatological regimes listed below) describe the "semipermanent climatic controls" and "transitory synoptic features" common to each of the four seasons. "Mesoscale synoptic features," "typical weather," and "sea surface conditions" are then discussed for each season in each of four major geographical subdivisions (the Persian Gulf proper, the Strait of Hormuz, the Gulf of Oman, and the Omani Arabian Sea Coast) that make up the entire Persian Gulf region.

CLIMATOLOGICAL REGIMES. The four climatological regimes (or "seasons") described here are the same as those used in the "Forecasters' Handbook for the Middle East/Arabian Sea" and are further discussed in Chapter 3. They are:

- The Northeast Monsoon (December-March)
- The Spring Transition (April-May)
- The Southwest Monsoon (June-September)
- The Fall Transition (October-November)

CONVENTIONS. The spellings of place names and geographical features are those used by the United States Defense Mapping Agency Aerospace Center (DMAAC). Distances are in nautical miles. Elevations are in feet with a meter (m) or kilometer (km) value immediately following. Temperatures are in degrees Fahrenheit with a Celsius conversion (°C) following. Wind speeds are in knots. Precipitation amounts are in inches, with a millimeter (mm) conversion following.

DATA SOURCES. The authors used a number of United States and foreign climatological and meteorological studies from the collections of the Air Weather Service Technical Library (AWSTL) as well as summarized data from the Air Weather Service Worldwide Climatic Database. An extensive bibliography is provided. As the reader will note, there are many other excellent studies on the climatology of the Persian Gulf region--notably the AWS 100-series Forecaster Memos (FMs) and at least one "Follow-On Training" slide/tape module. Forecasters interested in this region should acquire and become familiar with at least the following:

- NEPRF Contractor Report 83-06, *Forecasters' Handbook for the Middle East/Arabian Sea*, AD-A134312.
- NEPRF Technical Report 83-03, *Navy Tactical Applications Guide*, Volume 5, Part 1: "Indian Ocean Red Sea/Persian Gulf Weather Analysis and Forecast Applications," AD-A134412.
- NEPRF Technical Report 79-06, *Winter Shamal in the Persian Gulf*, AD-A077727.
- "Terminal Forecast Reference Notebook," USCENTAF ELF One.

RELATED REFERENCES. *Station Climatic Summaries--Asia* (USAFETAC/DS-XX/035), published by the USAF Environmental Technical Applications Center (USAFETAC), gives standard weather station summaries for specific locations in the Persian Gulf area; the latest version of this document is available from the Defense Technical Information Center (DTIC). DoD users may order through AWS staff weather officers or direct from: AWSTL, FL4414, Scott AFB IL 62225-5458. Detailed electrooptical and refractivity data for the Persian Gulf region are available in two companion works to this study:

- USAFETAC/TN-88/003, *Persian Gulf Transmittance Study in the 8-12 Micron Band*
- USAFETAC/TN-88/004, *Persian Gulf Refractivity Study.*

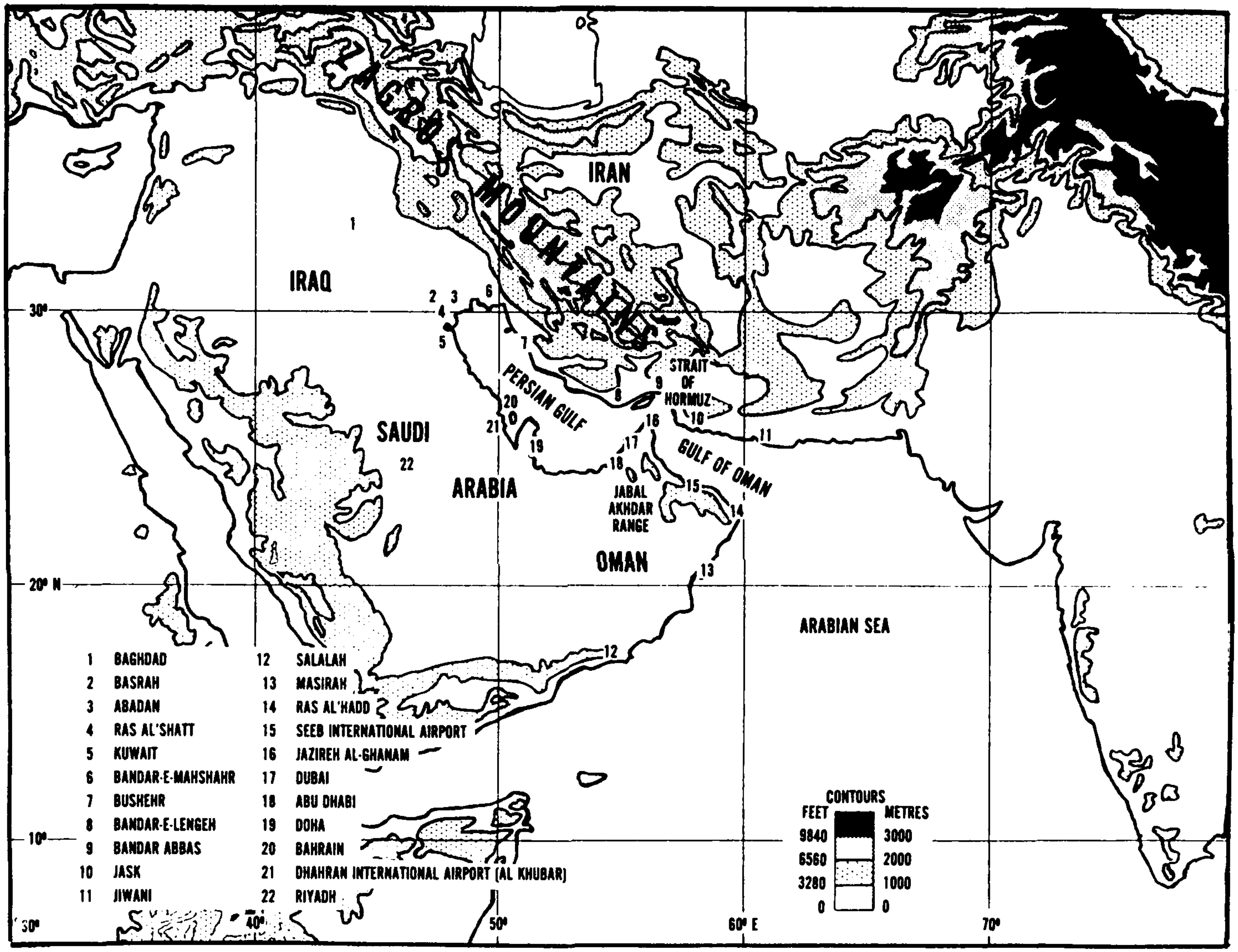

Figure 1. Topography of the Persian Gulf Region.

Chapter 2

PERSIAN GULF GEOGRAPHY

MAPS AND CHARTS. Figure 1 shows the general geography and topography of the Persian Gulf region. For more detail, readers are urged to acquire and use DMAAC navigation charts. The Tactical Pilotage Chart (TPC) and Operational Navigation Chart (ONC) series are recommended. Note that weather stations in Iran and Iraq have transmitted virtually no weather data since the start of the Iran-Iraq war in 1980. Readers should consult the current version of the "AWS Master station Catalog" for the most recent weather station information.

THE PERSIAN GULF itself extends in a great 530 nautical mile concave curve from the Shatt al'Arab (Euphrates River) delta to the Strait of Hormuz. Widths from the Shatt al'Arab to Abu Dhabi average between 130NM to a little over 150NM. East of Abu Dhabi, the gulf narrows rapidly to 70NM just east of Dubai. Gulf waters are relatively shallow--average depth varies from 65 to 200 feet (20 to 60m). Deeper waters occur only on the immediate western side of the Strait of Hormuz where depths reach 300 feet (90m).

The Iranian Shore. Terrain on the Iranian, or northern, shore of the Persian Gulf is in sharp contrast to the rest of the region. Numerous mountain ranges, oriented parallel to the Persian Gulf-Gulf of Oman, front a narrow (20 to 40NM) coastal plain from the Tigris-Ehprates delta southeastward for 105NM or to just under 20NM southeast of Bushehr. Southeast and east of this point to the Strait of Hormuz, the major ranges rise almost immediately inland from the coast. The highest mountains are inland of the northwestern half of the gulf; here, numerous peaks range from 11,000 feet (3,355m) to more than 14,000 feet (4,270m). The highest peak reaches 14,465 feet (4,410m) in the Kuh-E Dinar range near 30°57'N, 51°26'E.

The Northwestern Shore. Salt marshes at the northwestern end of the Persian Gulf extend from Kuwait to the Iranian coast near 30°N, 50°09'E, and inland from 15 to 70NM. The greatest inland salt marsh penetration is between Kuwait and Bandar-E Mahshahr, where they reach almost to Basrah. Except for immediate river banks, desert lies beyond the salt marshes. Most of these deserts are covered with a top layer of fine, powdery soil that serves as the source for major dust and sand storms.

The Southern Shore is nearly flat from the Shatt al'Arab southeastward to the Omani Peninsula. The shoreline itself is smooth, the only exception being the Qatar Peninsula on the east shore of the Gulf of Bahrain. Al Khubar (Khobar), the site of Dhahran International Airport, marks the west side of this narrow, elongated indentation. Bahrain Island lies in the middle of the mouth of the Gulf of Bahrain. Terrain in Saudi Arabia inland of the shoreline is a mixture of sand dunes, wadis (dry washes), and low gravel ridges. Sand dune fields are concentrated within 50NM of the coast from Kuwait to Dhahran; south of Dhahran these fields extend inland from 75 to 200NM. Elevations rise slowly inland to about 1,700 feet (520m). South of Abu Dhabi, and extending southwest to the mountains of extreme eastern Yemen, is the "Empty Quarter." There are almost no permanent human inhabitants here in the sand dunes and ridges.In the Oman Peninsula the sand dune fields become mixed with sand ridges. These extend south and eastward to within 50 to 75NM of the mountain range along the Gulf of Oman-Arabian Sea coast. Salt flats are common within 15NM of the coast along the entire southern gulf shore.

THE STRAIT OF HORMUZ. At Dubai, the Persian Gulf begins its rapid narrowing into the Strait of Hormuz. Although the strait averages 50NM in width, the narrowest part is slightly under 30NM. Depth averages from 130 to 260 feet (40 to 80m).

THE GULF OF OMAN extends south and then southeastward from the Strait of Hormuz into the Arabian Sea. The generally accepted boundary between the Gulf of Oman and the Arabian Sea is an imaginary line drawn from Jiwani on the Iran-Pakistan frontier south-southwestward to Ras al Hadd--the easternmost point of Oman. Widths rapidly increase from 30NM at the eastern end of the Strait of Hormuz to 130NM wide at Muscat and finally to 200NM where it joins the Arabian Sea.

The Iranian Coast. From the Strait of Hormuz to the Iran-Pakistan border, mountain ranges form the coast and rise rapidly. Narrow (10-15NM) plains are located around the mouths of the rivers flowing into the Gulf. Elevations within 40NM of the coast exceed 5,000 feet (1,525m); within 90NM, peaks exceed 10,000 feet (3,048m).

The Omani Coast. A range of mountains runs the length of Oman from Jazireh-al Ghanam in the Strait of Hormuz to 20NM west of Ras al Hadd. Elevations range from 5,000 to 9,000 feet (1,525 to 2,745m). The highest known elevation is 9,777 feet (2,980m) in the Jabal Akhdar range near 23°14'N, 57°17'E. There is a narrow (15 to 30NM) coastal plain between Shinas and Muscat. To the west of this mountainous spine, elevations are less than 1,700 feet (520m).

The Omani Arabian Sea Coast. A narrow (10-20 mile) coastal plain is backed by hilly, sometimes mountainous, terrain along the entire coast. Maximum elevations reach 2,500 feet (760m).

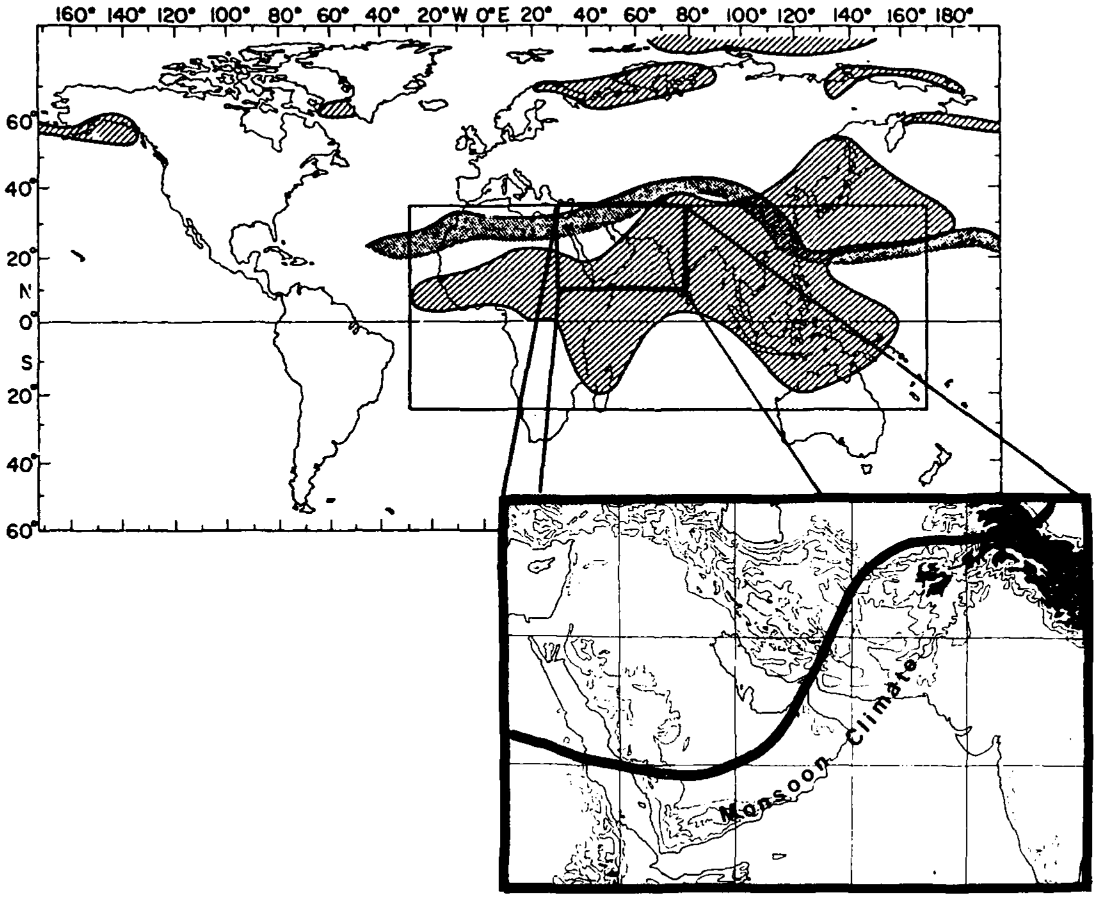

Figure 2. Delineation of the "Monsoon Region" (from Ramage, 1971). Khromov (1957) defined a "monsoonal" area as one with opposing seasonal wind flow. In this simplistic definition, Khromov ignored the requirement that monsoon winds blow *steadily* from a seasonal direction. The hatched areas in Figure 2 indicate the "monsoonal area" according to Khromov's definition. Klein (1957) postulated that "monsoonal areas" must show low frequencies of surface cyclone-anticyclone alternations in summer and winter. The heavy line with southward shading indicates the northern edge of the "monsoonal area" according to Klein. The rectangle encloses (also simplistically) what is generally accepted as the monsoon region of the world. Ramage, however, qualifies this neatly rectangular expression; those qualifications are discussed in Chapter 3. Note in the enlarged inset that Khromov's dividing line arcs across the Strait of Hormuz and separates the Persian Gulf itself from the Gulf of Oman and the Arabian Sea.

Chapter 3

THE MONSOON CLIMATE

THE MONSOON DEFINED. "Monsoon" is the English adaptation of the Arabian (and Indian) word "Mausum," the literal translation for which is "season." The term is generally applied to areas where there is a seasonal reversal of the prevailing winds. Unfortunately, some meteorological schools of thought have applied this idea too loosely. For example, the Russians and the Germans have implied that the Russian Arctic and Berlin have "monsoon climates." A similar designation, but with more justification, has been given the United States Southwest by some American meteorologists. The generally accepted definition of a "monsoon climate" is one by Professor Colin Ramage of the University of Hawaii, who provides these four criteria:

(1) Prevailing seasonal wind directions between summer and winter must change by at least 120 degrees.

(2) Both summer and winter mean wind speeds must equal or exceed 10 knots (3 meters/sec).

(3) Wind directions and speeds must exhibit high degrees of steadiness.

(4) No more than one cyclone/anticyclone couplet occurs during January or July in any 2-year period within any 5-degree latitude/longitude rectangle.

Applying these criteria to the Persian Gulf region, we find that the area *south* of July's Monsoon Trough (or Intertropical Convergence Zone, ITCZ) position definitely has a monsoon climate (See Figure 25, page 36). Areas *north* of the ITCZ, although influenced by monsoonal circulation, do *not* have monsoon climates.

SEASONS OF THE SOUTHERN ASIA MONSOON. The southern Asia monsoon in the Persian Gulf region is characterized by two distinct seasons separated by two short (30 to 45 day) transition periods.

The Northeast Monsoon (December through March) is dominated by northeasterly low-level flow controlled by a deep Australian thermal low center and an Asiatic high-pressure region centered over Siberian Russia. Upper-level flow is sustained westerly, with the subtropical jet over southern Arabia eastward into India.

The Spring Transition. In April and May the northeasterly circulation rapidly breaks down and is replaced by the Pakistani Low pressure center and its associated secondary lows in Saudi Arabia and Saharan Africa. The ITCZ moves rapidly north into the intensifying heat lows. Southern hemisphere southeasterly trade winds cross the Equator, recurve to become southwesterly, and flow across the Arabian Sea into India. The initial surge occurs within a period of 7 to 15 days from the time of the first sustained cross-equator flow. It follows either the development of a mid-tropospheric vortex in the Bay of Bengal or an "onset vortex" in the extreme northern Arabian Sea. The latter moves westward to affect Oman.

The Southwest Monsoon. The onset surge at the end of the Spring Transition marks the start of the Southwest Monsoon that lasts from June through September. Southwesterly flow has a direct affect on the Arabian Sea coast of Oman, the Gulf of Oman, the Arabian Sea coast of Iran, southern Pakistan, and India. Low-level flow is sustained southwesterly. Upper-level flow is sustained easterly; the Tropical Easterly Jet (TEJ) flows across India into East Africa at 150mb.

The Fall Transition. In October and November, the Pakistani heat low collapses as days become shorter. Cooling over Siberian Russia reestablishes the Asiatic High pressure centers and the ITCZ migrates southward once again. Low-level northeasterly flow is reestablished over southern Asia and the cycle repeats itself.

TROPICAL STORM FORMATION. Tropical storms affecting the northern Arabian Sea are confined to the spring and fall transitions. These are the only times when the ITCZ is over the Arabian Sea between 15° and 25°N and strong vertical shears are absent--both of which are necessary for tropical storm formation.

CAUSES OF THE MONSOON. The massive circulation reversal referred to as the monsoon is still not completely understood. Its ultimate cause--the seasonal variation in incoming solar radiation--is obvious. Solar radiation results in the fall formation and spring decay of the Asiatic High, as well as the spring formation and fall decay of the south Asian Low. What is still nknown are the threshold gradients that trigger these transitions. The latest research suggests that the late springtime combination of latent heat released by pre-monsoonal thunderstorms over southern India, along with late springtime heating over the Tibetan Plateau, rapidly forms an upper-level high pressure area over extreme northern India and the Himalayas. The strong winter westerly circulation is replaced by strong summer mid- and upper-level tropospheric easterly circulation. This circulation provides the sustained outflow necessary for extended precipitation over southern Asia. In the fall, diminishing heavy convection over northern India, combined with cooling over the Tibetan Plateau, has the opposite effect. Low-level circulation characteristic of the approaching monsoon season precedes the reversal in upper-level flow. However, the monsoon has not officially begun until the characteristic upper-level circulation has been established.

Chapter 4

THE NORTHEAST MONSOON

(December - March)

SEMIPERMANENT CLIMATIC CONTROLS

THE MEDITERRANEAN STORM TRACK. This is the main source of low pressure systems and cool air during this season. Extensive thunderstorms and heavy rains accompany the movement of a secondary low across the Saudi Arabian peninsula. Figure 3 shows mean January storm tracks representative of the Northeast Monsoon. Track A, which moves northeastward through Turkey into the Caucasus mountains, is the primary track for secondary low formation in northern Saudi Arabia-Iraq. Track B, across Lebanon-Israel-Syria into the Persian Gulf, is normally associated with the "winter shamals" that will be discussed later. Track C runs across southern Egypt and the northern Red Sea into central Saudi Arabia. It is associated with a mean jet stream position over the southern Mediterranean or northern Africa and often results in formation of a secondary wave over the central Red Sea. This, the least active of the three tracks, occurs in late winter and early in the spring transition.

THE PERSIAN GULF TROUGH. This relatively weak semipermanent feature results from a combination of heating over the Persian Gulf and an induced "lee-side trough" resulting from the high pressure centers over Iran and northwestern Saudi Arabia. It forms a natural pathway for low pressure centers moving out of southern Iraq. Intensification and movement onto the Arabian Persian Gulf coast as a transient feature often occurs as the result of a combination of the following three factors: (1) the passage of a cold front down the Gulf, (2) increased ridging over Iran, and (3) temporary weakening of the Saudi Arabian high pressure area. See further discussions in the section titled "The Persian Gulf Proper and Adjacent Land Masses."

THE SAUDI ARABIAN HIGH is centered over northwestern Saudi Arabia as an eastward extension of the Saharan high pressure ridge.

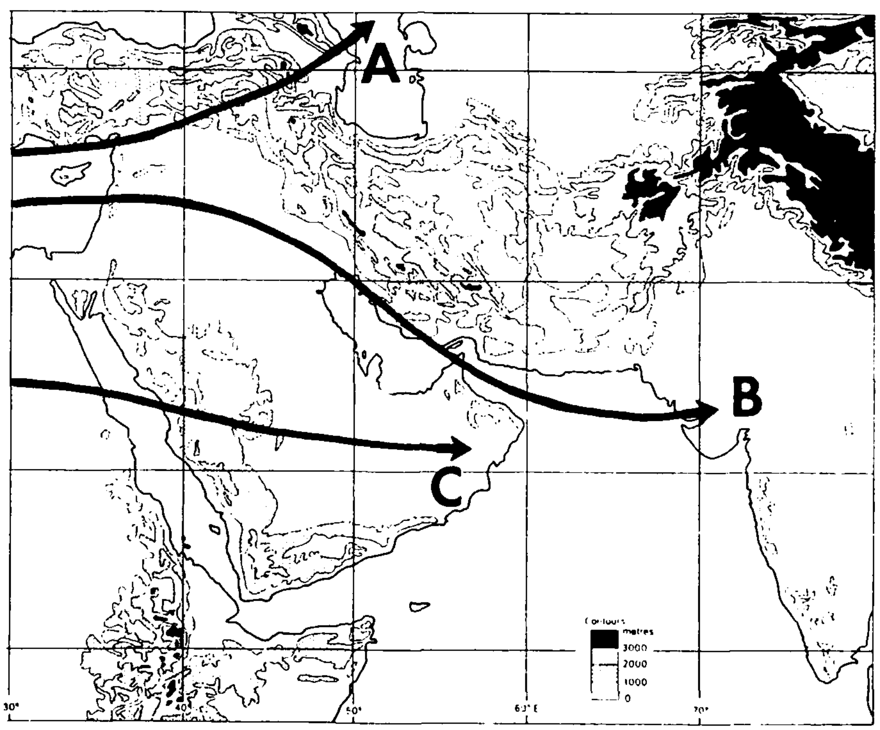

Figure 3. Mean Winter Storm Tracks.

NORTHERLY AIRFLOW COMPONENT. The prevailing mean airflow component, as discussed in Chapter 3, is *northerly* over the entire region. This northerly flow, however, is interrupted by the passage of upper air troughs and their associated surface low pressure areas and surface fronts/shear lines. See Figures 4 and 5 for typical surface and 500mb analyses. Mean January flow at 850, 700, 500, 300, and 200mb (5,000, 10,000, 18,000, 30,000, and 39,000 feet) is shown in Figures 6 through 10.

THE SIBERIAN HIGH has its primary axis across central Russia and a mean center over eastern Siberia. Since direct northerly flow around the south side of this ridge is blocked by the Caucasus, Northern Iranian, Hindu Kush, and Himalaya mountain systems, the cold Siberian air is forced to spill southwestward through Iran and eastern Turkey into Iraq and the northern portion of the Persian Gulf. Snow cover over the Zagros mountains maintains (and even intensifies) this cold air, with consequent strengthening of downslope winds off the Zagros into the northeastern side of the Gulf.

ARABIAN PENINSULA/IRAN UPPER AIR RIDGE. 500mb high pressures centers are located over extreme western Arabia and over the Zagros mountains in southwestern Iran. At 300mb, this ridge is displaced southward to between 20 and 22°N.

THE POLAR JET STREAM is located near 30°N. December core speeds are 90 knots. In January it dips to latitudes between 27 and 29°N with speeds of 110 knots, then shifts back northward to just above 30°N with maximum speeds of 80 knots in March. Actual positions vary considerably; in January, flow around the bottom of a deep 500mb low may reach as far south as 20°N. Under these conditions, it merges with the subtropical jet stream.

THE SUBTROPICAL JET STREAM. During this season, the Subtropical Jet flows from west to east over the Arabian Peninsula. Mean position is between 25 and 28°N; at 200mb, core speeds exceed 110 knots over the Peninsula. Deep upper air lows may displace the jet south to near 20°N.

WARM PERSIAN GULF WATERS. By mid-January, surface water temperatures average 70°F (21°C). Although considerably cooler than during the Southwest Monsoon, they are about 3°F (1.6°C) warmer than that of the air passing over them. By April, however, Gulf water temperatures average 74°F (22°C)--only 1°F (0.6°C) more than the air temperature. Higher evaporation rates from the Persian Gulf result in a steady northwestward flow of surface water through the Strait of Hormuz into the Gulf; the current just west of the Strait reaches 2 to 4 knots. A counter-current flows southeastward along the bottom down the Persian Gulf and out into the Gulf of Oman.

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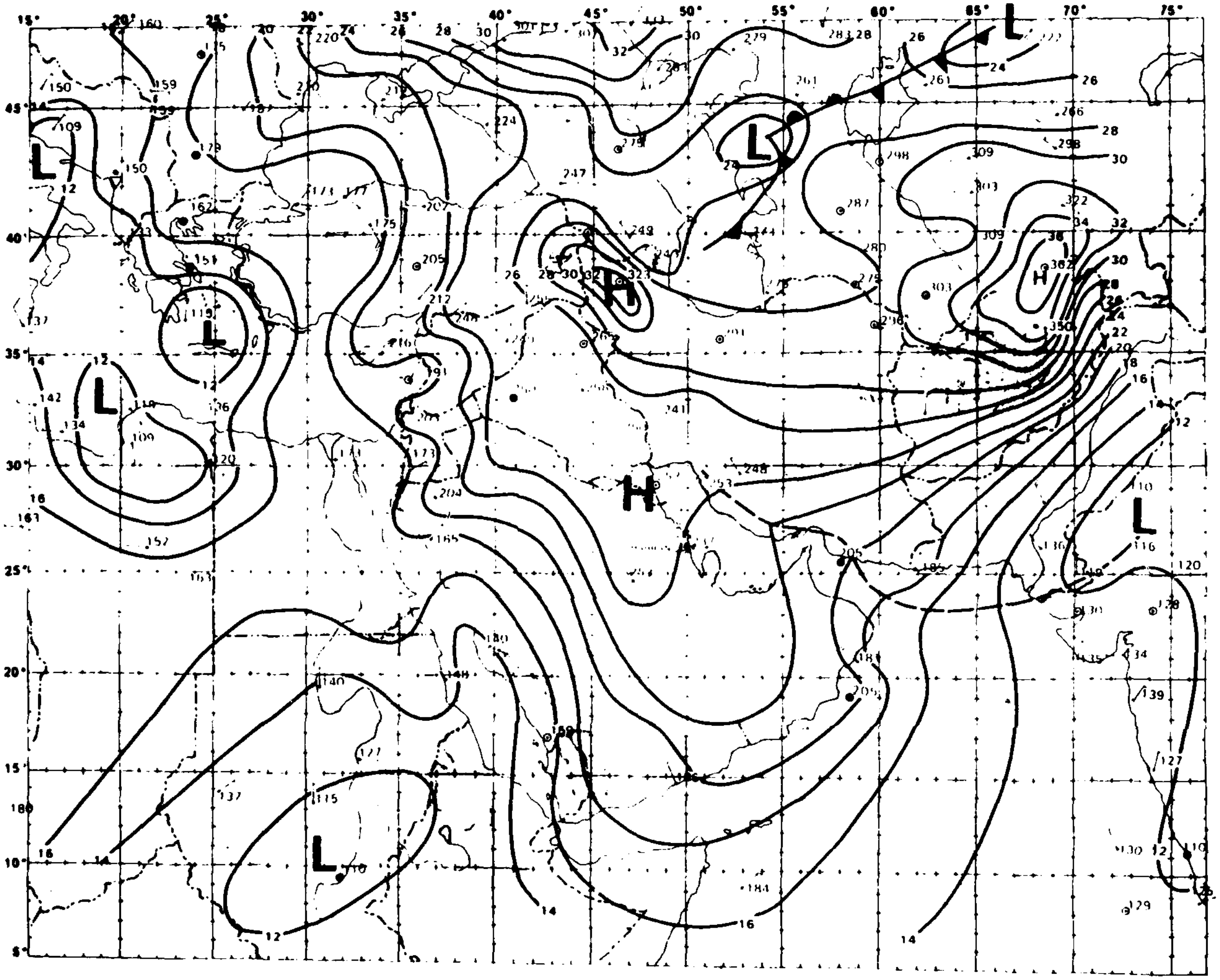

Figure 4. Typical Northeast Monsoon Surface Analysis.

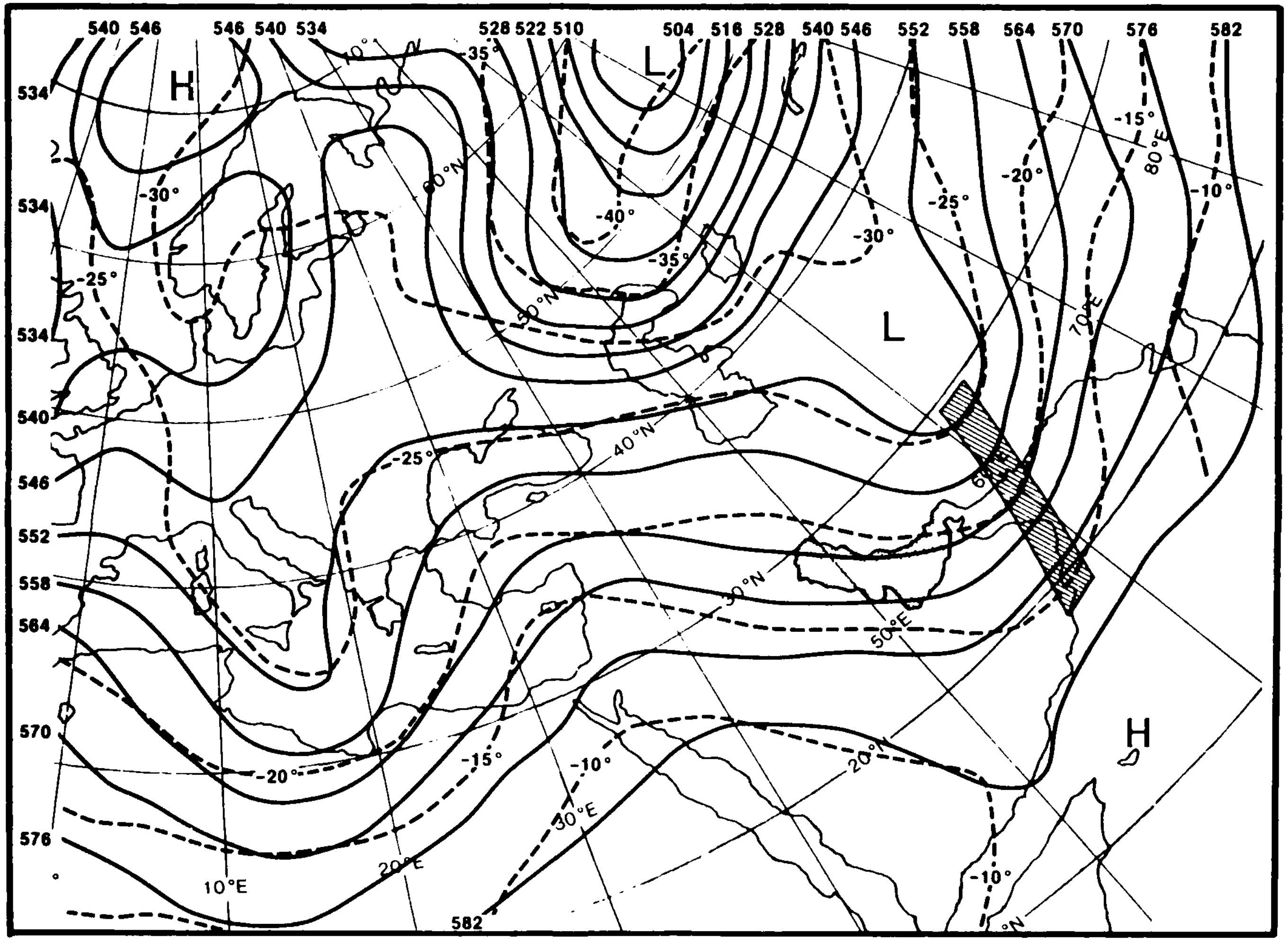

Figure 5. Typical Northeast Monsoon 500mb Analysis.

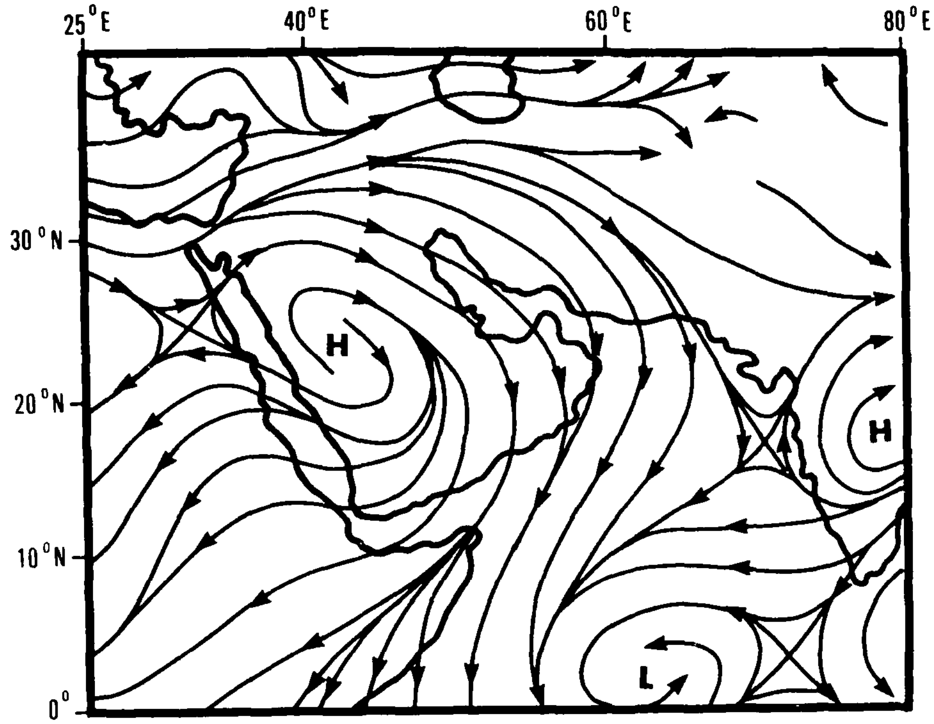

Figure 6. Mean January 850mb flow.

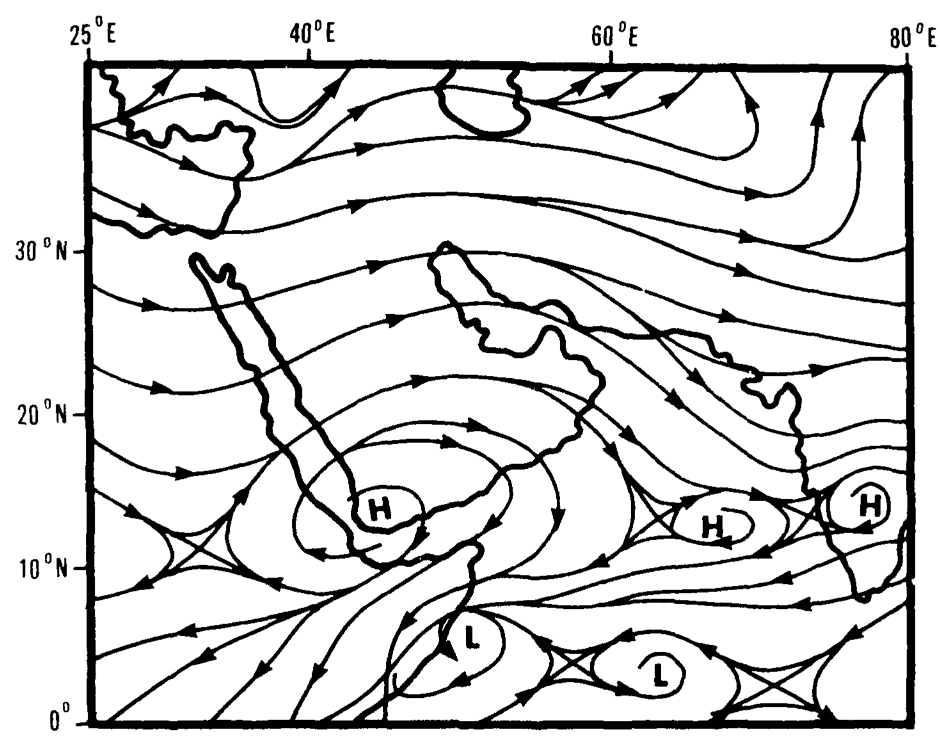

Figure 7. Mean January 700mb Flow.

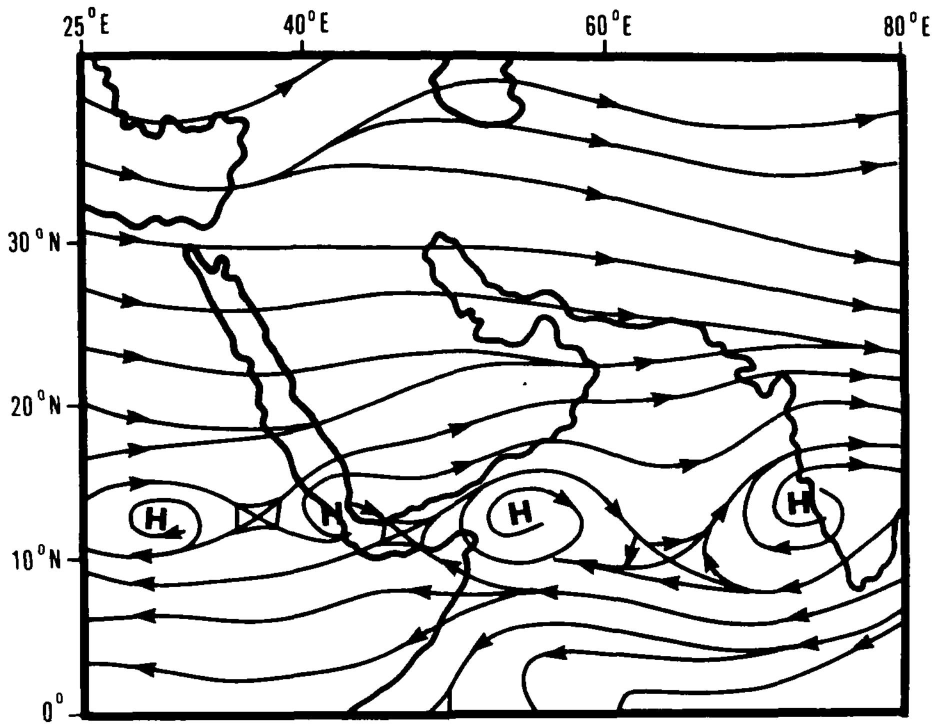

Figure 8. Mean January 500mb Flow.

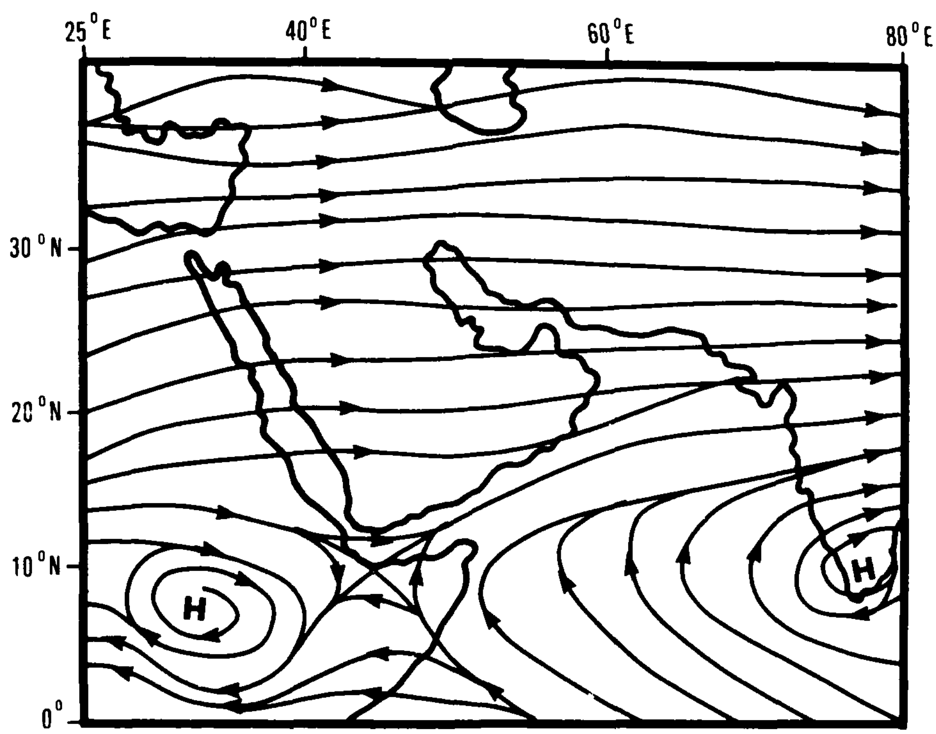

Figure 9. Mean January 300mb Flow.

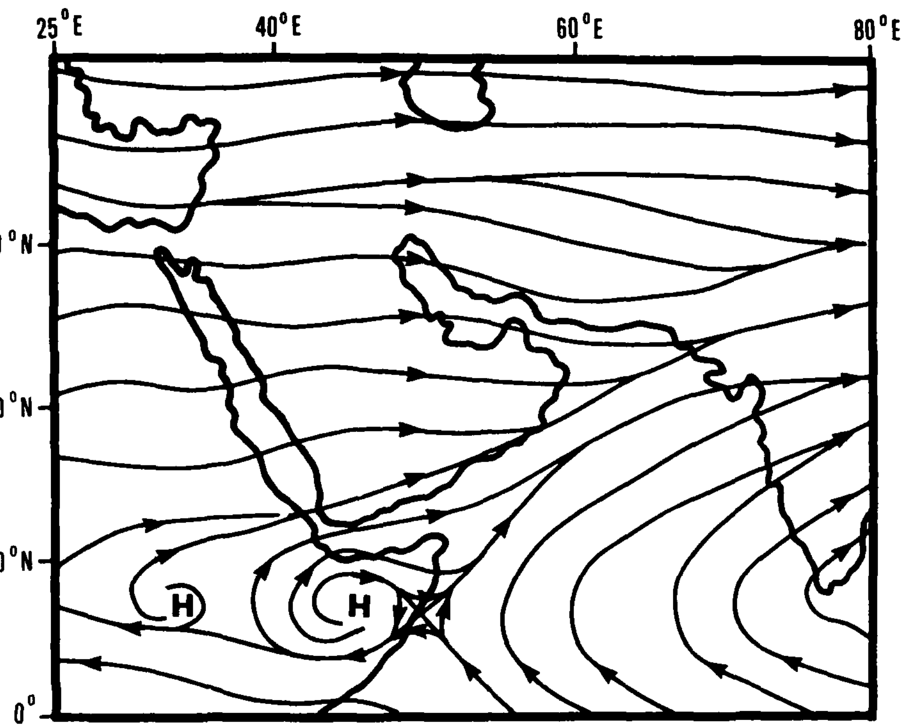

Figure 10. Mean January 200mb Flow.

THE OMANI CONVERGENCE ZONE (OCZ). During normal northeast monsoon conditions, there is a convergence zone over Oman south of the Hajar mountains. It lies parallel to, and about 100 to 150 miles inland of, the coast of the Arabian Sea. Figure 11 shows its mean January position. Low-level northwesterly flow coming out of southeastern and southern Saudi Arabia meets the northeasterly monsoonal flow that has been deflected inland due to strong sea breeze circulation. This zone does not exist when there is southwesterly flow ahead of cold fronts, or northwesterly flow behind.

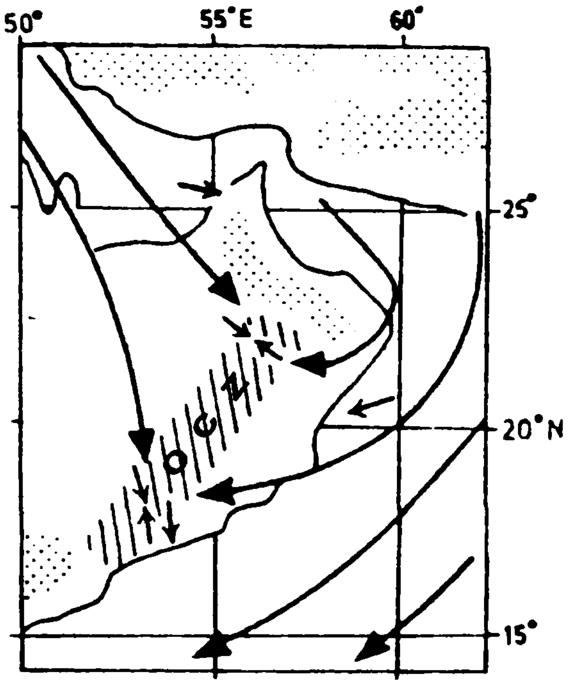

Figure 11. Mean January Position of the OCZ.

SURFACE COLD FRONT/STRONG UPPER-LEVEL TROUGHS IN THE WESTERLIES. From mid-December through mid-March these fronts (with their associated upper-air troughs and often accompanied by closed 500mb low centers) cross the region routinely. Occurrence is most common when a blocking high over northern Europe results in a high speed core in the westerlies across the Mediterranean into Iraq. The characteristic middle and high clouds associated with these troughs show up well on both visual and IR satellite imagery. These systems are accompanied by the following phenomena:

Transitory Saudi Arabian Highs form in response to the subsiding air beneath upper air ridges moving across the area from the west. These cells break off from the quasi-permanent Saudi Arabian ridge and move eastward and southeastward across the Peninsula following cold fronts.

Northwestern Arabian Sea Highs form in response to surface lows that move into northern Saudi Arabia. Essentially, these highs are the "cut-off" southeast portions of the normal Arabian Peninsula ridge. As the low tracks eastward or southeastward, high pressure spilling southward behind the cold front absorbs the independent southwestern Arabian Sea pressure center.

"Aziab" is the Arabic name for the hot and dry low-level southerly winds that blow occasionally over Saudi Arabia in March. These winds occur ahead of a secondary low that often results from the northeastward extension of the Sudan low that moves eastward towards the Persian Gulf as a wave on a slow-moving cold front (Track C in Figure 5). These winds cause temperatures to rise dramatically; Riyadh has reached 90°F (32°C) during very strong Aziab conditions.

"Kaus" is the local name for the southerly or southwesterly winds that blow over Oman, the United Arab Emirates, and the Persian Gulf in advance of a surface low pressure center. These winds cause the most extensive low cloud and precipitation areas found during this season.

Strong Prefrontal and Frontal Thunderstorms form in and near the Persian Gulf. Satellite imagery has shown conclusively that thunderstorms associated with cold front passage down the Gulf are similar to those found in the United States Middle West. The favored formation area for prefrontal squall lines is the central and southern Gulf.

Vortex Phenomena in the form of waterspouts have been observed in the southwestern Persian Gulf during December. Although no known reports of this phenomenon were made prior to 1970, local Arabic words and tradition indicate that such phenomena have in fact occurred in the past. The recorded cases occurred in areas of localized convergence and resultant heavy cumulus activity behind cold fronts or shear lines.

SURFACE CYCLOGENESIS. Three favored locations for cyclogenesis in this area, in order of most frequent occurrence, are:

Southeastern Iraq-Northern Persian Gulf. Secondary lows form in these regions in response to cold air advection, warm water, and airflow channeling through the Iraqui and Iranian mountains, notably the Zagros.

The Western Gulf of Oman. Secondary lows form here for the same reasons as in southeastern Iraq and the Northern Persian Gulf. The "channeling" here, however, is through the Zagros Mountains of Iran along the northern Gulf of Oman coast and through the Omani Peninsula Mountains along the southwest side off the Gulf of Oman. This combination of airflow modification induces cyclonic flow if a strong east-west ridge lies over Iran.

Northeastern Sudan-Northern Red Sea-Western Saudi Arabia. A weak, inverted low-pressure trough stretches northward into Sudan from East Africa during most of the Northeast Monsoon season. Passage of a cold front southeastward across Saudi Arabia, combined with its associated upper-level trough approaching Sudan from the west, often triggers the formation of a secondary low on the front over northeastern Sudan and the Red Sea. The Red Sea serves as a potent but localized moisture source for cyclogenesis here. The low then moves eastward as a wave on the front. Under proper conditions, this center will become the primary surface low affecting Saudi Arabia and the southern Persian Gulf. This location is most active during late winter (primarily March) and during the spring transition as the strength of cold air outbreaks diminishes.

MESOSCALE SYNOPTIC FEATURES. The following features are common to the Persian Gulf proper and its immmediately adjacent land areas:

Gulf Cyclogenesis. Cold frontal stagnation in the southern Gulf results in cyclogenesis northwest of the Omani Peninsula-United Arab Emirates. This occurs when the associated upper-air trough slows sharply or becomes stationary in this area. Formation of a cutoff low at the base of the upper-air trough enhances it. Development is rapid over the warm Gulf water. Under such conditions, strong low-level winds build rapidly. Wind directions shift from south to southeast to northeast, and finally to northwest, as the low moves through the Strait of Hormuz into the Gulf of Oman. Precipitation, along with extensive low, middle, and high cloud layers, occur on both sides of the Gulf. The greatest extent and precipitation intensity occurs on the Iranian side. Moderate turbulence and icing are found over both the Omani Peninsula and the Iranian shore.

The Winter Shamal. "Shamal" is an Arabic word for "north." It refers to the strong northerly and northwesterly winds that occur in the Persian Gulf and over its immediate land areas following passage of cold fronts southeastward. The Shamal produces the most widespread hazardous weather known to this region. Its causes are similar to those for the strong northerly winter winds at Travis, McClellan, Mather, Beale, and Castle AFBs, and NAS Lemoore in California's Central Valley. Large pressure gradients develop behind cold frontal passages due to upper-level subsidence rapidly building surface high pressure over western Saudi Arabia and Iraq. The strong northwesterly low-level winds are then quickly reinforced by northwesterly upper level winds behind the middle level trough. Shamals here are of two types:

The 24-36 Hour Shamal. These begin with the passage of the front. When the associated upper air troughs are rapidly moving short waves, winds die after 24 to 36 hours; hence the name. Such cases are relatively common, occurring two or three times a month during the Northeast Monsoon season. Winds typically reach 30 to 40 knots. Figures 12 and 13 are representative surface and 500mb analyses of the phenomenon.

The 3-5 Day Shamal. Occuring one to three times a winter, this phenomenon produces the strongest winds and highest seas found in the Gulf. Over exposed Gulf waters, sustained winds reach 50 knots and produce 12- to 15-foot waves. This shamal arises from the temporary stagnation of a 500mb short wave over or just east of the Strait of Hormuz, or from the establishment of a mean long wave position in the same area. In either case, the result is a strong northwesterly surface wind that continues for 3 to 5 days. Persistent dust and sandstorms on the scale of the Southwest Monsoon normally occur only during these events. A detailed explanation of this phenomenon, including forecasting technique, is given in NEPRF Technical Report 79-06, *Winter Shamal in the Persian Gulf*. Figures 14 and 15 are representative surface and 500mb analyses of the 3-5 day shamal.

The Persian Gulf Trough intensifies in or just northeast of the Persian Gulf after a low and its associated frontal system passes the Strait of Hormuz, resulting in high pressure building over Iran. These troughs maintain stronger than normal winds over the Saudi Arabian shore and downslope winds on the Iranian coast that reinforce normal nocturnal downslope land breezes. If the Iranian high pressure cell is extremely well developed, conditions similar to the "Bora" of the Yugoslav Adriatic coast can develop. Data on maximum downslope wind speeds is not available, but dynamic and topographic considerations indicate that speeds better than 50 knots over and just offshore of the immediate Iranian coast are possible. Recent ALPEX research suggests that only a shallow layer immediately above the ridges accelerates; air between the top of this shallow accelerated layer and the undisturbed higher level wind field is slow moving and extremely turbulent. Under the synoptic circumstances described above, conditions similar to those found in ALPEX research might occur over and southwestward of the Zagros into the Persian Gulf northeast of the Persian Gulf Trough. Weakening of the Iranian High and/or the Persian Gulf Trough ends the severe downslope wind, or "Bora." Persian Gulf Trough strength normally decreases rapidly within 24 to 48 hours after frontal passage through the Strait of Hormuz and marks the end of the "Shamal."

TYPICAL WEATHER. The following weather conditions may be expected in the immediate Persian Gulf area during the Northeast Monsoon:

General Sensible Weather. With no upper-air troughs and associated fronts over this region, the only sensible weather consists of high clouds over the Persian Gulf and the Arabian Peninsula. Skies are often clear, but fog can reduce visibilities in coastal regions. Radiational cooling in the relatively moist air near the water will cause fog to develop after sunrise; visibilities remain between 2 and 3 miles well into the morning. Patchy stratus is found during the late night and early morning hours along and just inland of coasts. Favored locations are shallow marshy areas--mostly at the head of the Gulf around the Shatt Al'Arab--and along the United Arab Emirate coastline in the extreme southern Gulf. Except in this coastal fog, visibilities are normally good.

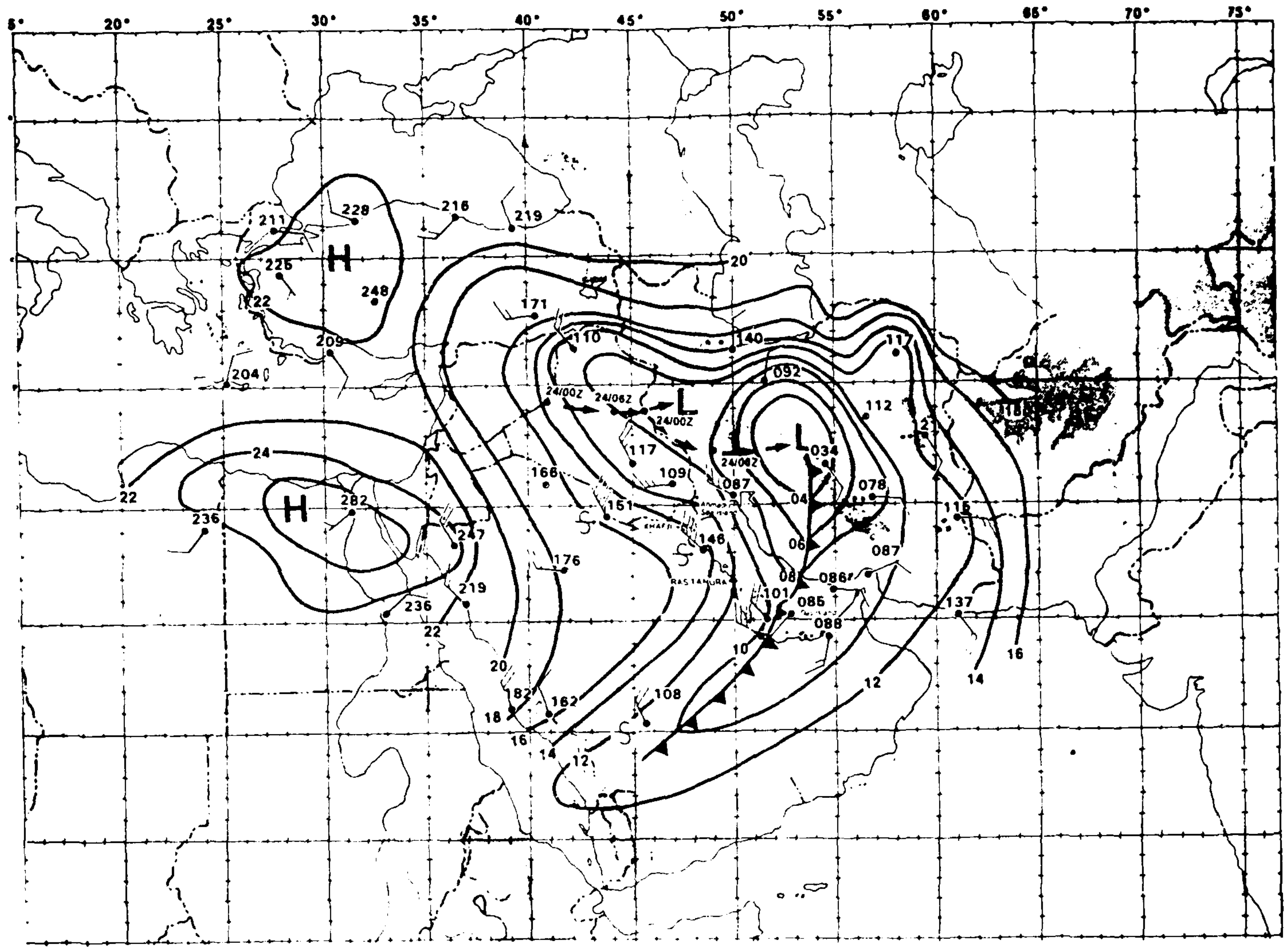

Figure 12. Represent tive Surface Chart for 24-36 Hour Shamal (1200Z 24 January 1973)

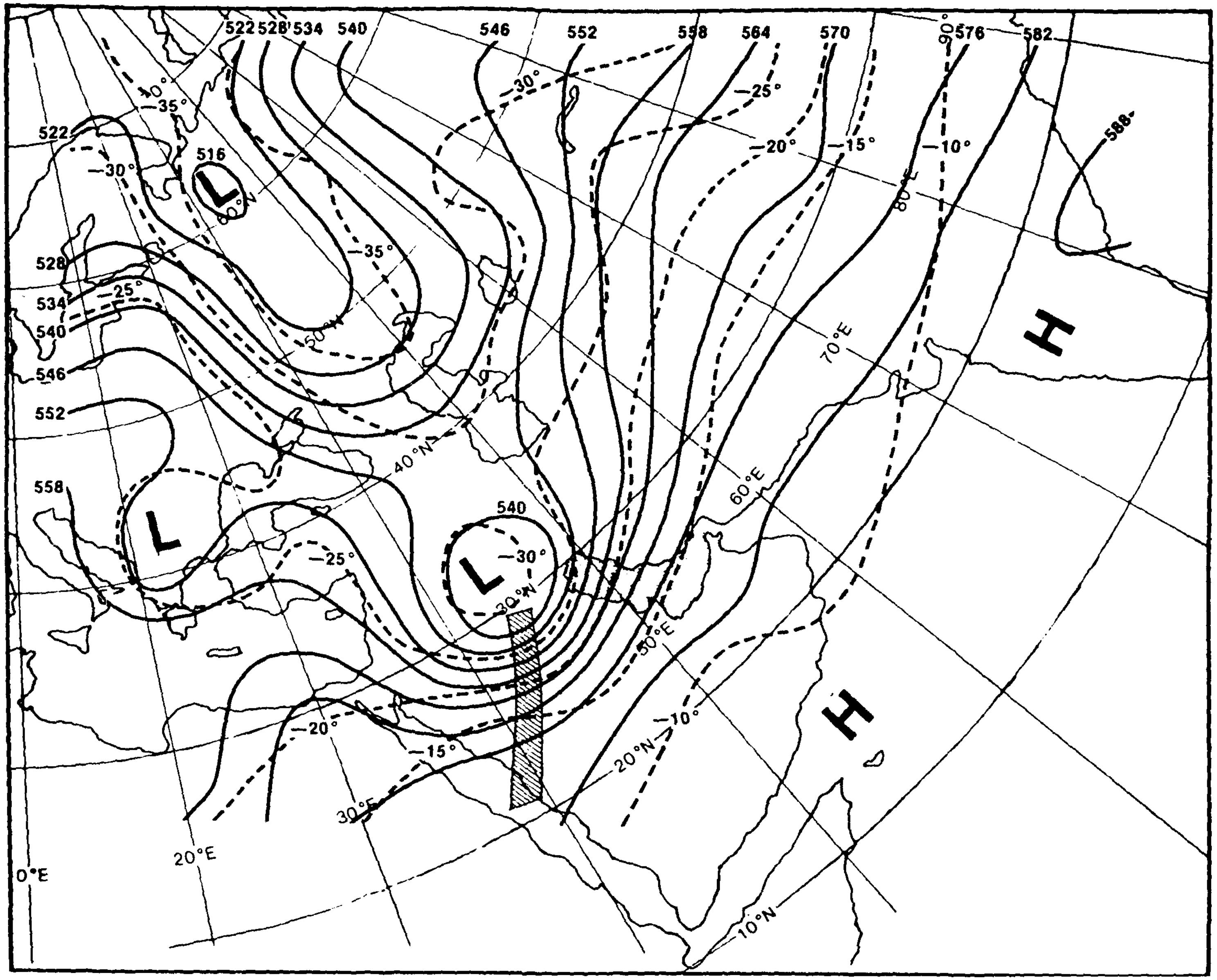

Figure 13. Representative 500mb Chart for 24-36 Hour Shamal (1200Z 24 January 1973)

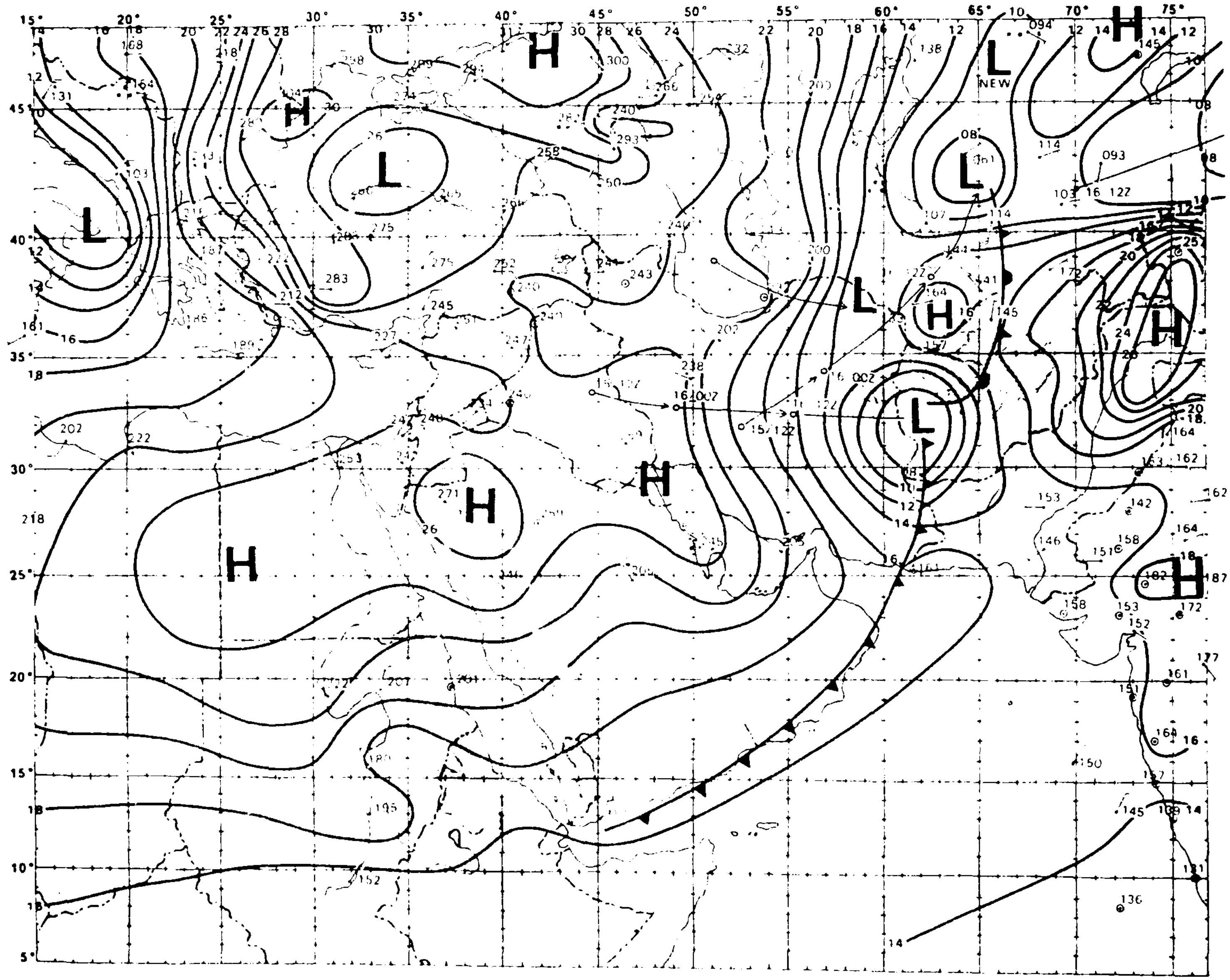

Figure 14. Representative Surface Chart for 3-5 Day Shamal (0000Z 17 January 1973)

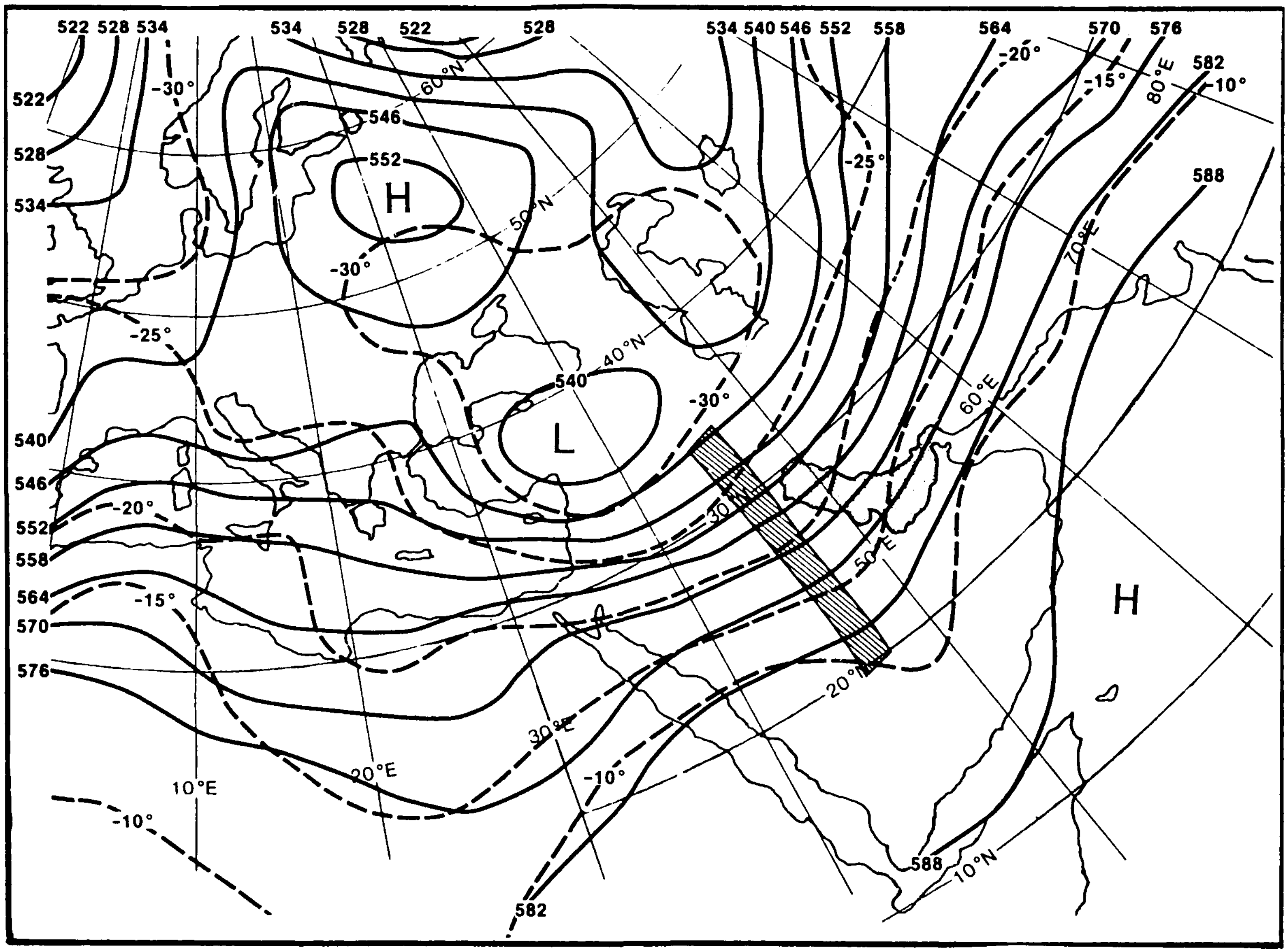

Figure 15. Representative 500mb Chart for 3-5 Day Shamal (0000Z 17 January 1973)

Sky Cover. Well-developed high and middle cloud decks are associated with upper air troughs. Light to occasionally moderate icing occurs in these decks above the 7,000 to 9,000 foot (2.1 to 2.7 km) freezing level. Low clouds with 1,000 to 1,500 foot (30u to 450 m) ceilings occur in the immediate area of the Persian Gulf. These low clouds advect westward around the north side of low pressure cells moving down the Persian Gulf. They can extend inland over Saudi Arabia as far as Riyadh. Low clouds normally clear within 4 to 6 hours after frontal passage. However, when appreciable rain has fallen, cold air stratocumulus will form for 1 to 2 days after frontal passage. In the absence of strong post-frontal surface winds, fog forming in those coastal areas near the head of the Gulf will persist throughout for the daylight hours for the first 24 to 48 hours after frontal/trough passage.

Dust. Widespread dust that restricts visibility to less than 3 miles normally occurs with the *first frontal passage of the season.* Light precipitation during the winter binds soil particles together; winds above 25 knots are needed to raise dust. Visibility fluctuations occur as a function of low-level wind speed--the stronger the winds, the lower the visibility. Visibilities can go as low as 50 meters *immediately after the first frontal* passage, at the height of a very strong "Shamal," or with an "Aziab," described below. Dust with northwesterly or northerly winds is initially picked up from the Iraqi deserts to the southwest and west of Basrah. During March, an "Aziab" (a hot and dry southerly wind) precedes a secondary low moving eastward into central Saudi Arabia. Dust associated with an "Aziab" comes from the "Empty Quarter," or extreme southern Saudi Arabia. By March, almost no precipitation has fallen over these areas, and most of the area is dry sand once again.

Winds are generally northwesterly at 10 to 15 knots over the northern half of the Gulf. Winds over the southeastern half reflect the west-to-east orientation of the mountains on the Iranian shore. The south-to-north alignment of the mountains on the Omani Peninsula of the Arabian coast combine with these other features to "turn" the prevailing winds--first westerly, then southwesterly, finally southerly--as one approaches the Strait of Hormuz from the west. Speeds decrease to 5 to 10 knots. Land and sea breeze circulations, of course, modify this pattern. There are two areas with winds significantly higher than those observed along the Arabian Peninsula coast (See Figure 16). During December and January, the area just northeast of the Qatar Peninsula sees speeds 10 to 15 knots higher than at Dhahran or Bharain. *In late February and March*, the area just off the Iranian coast near Lavan Island east-northeast of Qatar has winds 10 knots higher than the rest of the area. Southwesterly or southerly low-level high speed wind maximums, or "low level jets" (LLJs), occur ahead of low centers throughout the area. LLJs are *reinforced over the eastern side of the Persian* Gulf due to the channeling effects of the Zagros Mountains. There is no data that provides vertical profiles, but dynamic considerations indicate that core speeds may approach 50 knots 1,000 to 2,000 feet (305 to 610 m) above the surface along and just offshore of the Iranian coast. Sustained strong northwesterly winds--30 to 50 knots--occur with the "winter shamals" that will be discussed later.

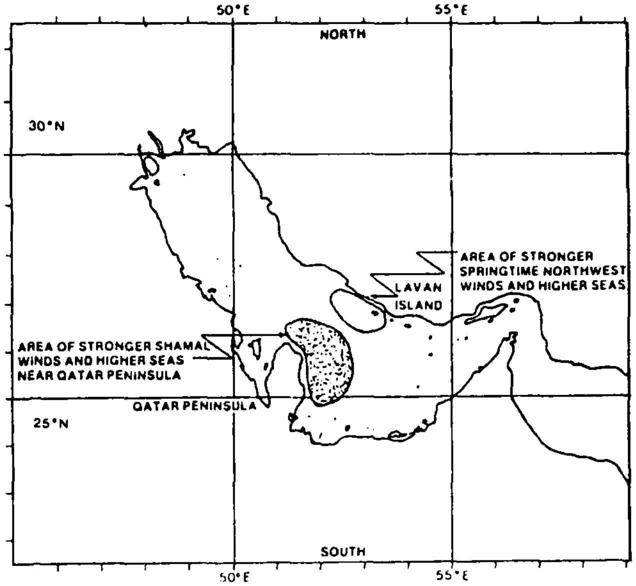

Figure 16. ***Areas of Stronger Shamal Winds.***

Thunderstorms--often severe--occur along cold fronts as well as in prefrontal squall lines that form over the northern Gulf from late December through early March; satellite imagery is extremely useful for locating them. Cloud bases are relatively high, averaging 4,000 to 5,000 feet (1,200 to 1,500 m) except over the Persian Gulf. Tops often exceed 40,000 feet (12.2 km) and tops of 50,000 feet (15.2 km) have been reported. Surface hail and gusty winds near 50 knots have also been reported. As in the United States, severe icing and turbulence are associated with these storms.

Precipitation on the Arabian side of the Gulf averages 2 to 3 inches (50 to 75mm) a year; almost all during this season and almost all from thunderstorms. There is considerable precipitation variability; some winter months may receive more rainfall than the mean yearly totals. "Kaus" winds ahead of the storm systems mentioned above result in extended periods of low cloud and drizzle over the middle and southern Persian Gulf, the Iranian coast, and the southern Zagros Mountains. Such flow usually occurs ahead of a low center moving down the Gulf. Higher elevations see thunderstorms and steady rain resulting from forced lift up the mountain slopes. Increased icing as well as moderate mechanical turbulence are found along the Iranian shore and over the mountains. The effects of these winds can be seen in the precipitation totals--4 to 5 inches (100 to 125m) a year, or 60% higher than on the Arabian side of the Gulf. The area around Bushehr receives almost 13 inches annually--5 inches in December alone. As on the Arabian coast, there is large variability; some winter months receive more precipitation in a month than the mean yearly totals.

Air Temperature. Daytime maximum temperatures along the immediate coast average between 65 and 75°F (19 and 23°C). Inland, temperatures rise to 70 to 85°F (21 to 29°C). Minimum temperatures along the coast fall to 45 to 65°F (7 to 19°C). Despite the warm Persian Gulf waters, dew points along even the immediate northern coastline range from 30°F (-1°C) to 40°F (3°C). The southern Arabian coast has higher dewpoints--55 to 60°F (13° to 16°C)--due to winds coming directly off the water. Dew points drop rapidly as one moves inland from the immediate coast. Riyadh averages a 30°F (-1°C) dew point through the winter. Minimum temperatures drop accordingly. Beyond 20 to 30 miles inland, minimum temperatures drop to 35 to 45°F (3 to 7°C). Dew points, however, rise rapidly when a "Kaus" wind is blowing. Riyadh has reported rises to 59 or 61°F (15 to 16°C) just before passage of a cold front.

SEA SURFACE CONDITIONS, Persian Gulf.

Water currents in the Persian Gulf have a general counter-clockwise circulation. A steady flow of surface water enters the Gulf through the Strait of Hormuz. This surface current flows toward the west and then northwest as it hugs the Iranian shore. At the northern end of the Gulf, it turns southeasterly to parallel the Arabian coast. Finally, it turns northerly along the west side of the Omani Peninsula to join fresh Gulf of Oman water entering through the Strait of Hormuz. Mean speeds are less than 1 knot. Maximum calculated speed for a 100-year worst case of combined wind and tidal currents, was 8 knots at Jubail. As water increases in density, it sinks, moves southeastward, and flows back into the Gulf of Oman as a bottom current through the Strait of Hormuz. 85% of all wave heights average less than 6 feet in the western Persian Gulf. Predominant directions along the Arabian coast are, as might be expected, from 330 through 360 degrees. However, under the influence of a "24 to 36 Hour Shamal," waves routinely reach 8 to 10 feet; for a "3 to 5 Day Shamal," heights reach 12 to 15 feet. The usual "decay time" to reach the normal 6 foot heights after the ending of a "Shamal" varies from 6 to 18 hours, depending on the duration and strength of the "Shamal." "Kaus" winds will establish a 6 to 8 foot southwesterly wave; greatest heights are found along the Iranian shore. Note that these are "open water" waves; oil companies operating in the Gulf have reported higher waves immediately offshore during favorable conditions.

Water Temperatures. In the shallow waters of the Gulf, temperatures cool rapidly during late fall and early winter. Surface water temperature ranges from 72-76°F (21-24°C) in December to 66-72°F (18-22°C) in February before rising to 68-74°F (20-23°C) in March. Temperatures in extremely shallow coastal waters reach 60°F (15°C) in January. Available temperature soundings in the western Persian Gulf show a bottom temperature of 61°F (16°C) at 60 meters. Temperatures show a steady and gradual decrease in temperature between the surface and the bottom of about 5°F (3°C). Thermoclines are not evident.

MESOSCALE SYNOPTIC FEATURES. The features that affect the Persian Gulf proper and its adjacent land masses also affect the Strait of Hormuz.

TYPICAL WEATHER. The following weather conditions may be expected in the Strait of Hormuz and its immediately adjacent land areas:

General Sensible Weather. Sensible weather over the Strait during the northeast monsoon season normally consists of patchy low stratus and stratocumulus, occurring most frequently during late evening and early morning. Onshore cloudiness occurs only along the Iranian coast as a function of land-sea breeze circulation.

Sky Cover. Well-developed high and middle cloud decks are associated with upper-air troughs. Ceilings range from 7,000 to 9,000 feet (2.1 to 2.4 km). Lower ceilings--1,000 to 1,500 feet (300 to 425 m)--normally only occur just preceding or in the immediate area of low pressure centers. Light or occasionally moderate icing and turbulence occur above 8,000 to 10,000 feet just ahead of and with the passage of upper troughs or surface low pressure systems and their associated fronts. Icing and turbulence are stronger over the Omani Peninsula and Iranian mountains.

Winds. Low-level airflow reflects a combination of: (1) weak outflow from the Persian Gulf, (2) pronounced land-sea breezes (especially along the Iranian shore), and (3) a general northerly to northeasterly flow off the Iranian coast. Complicating this pattern is the terrain-induced venturi effect. Although precise data for the Strait itself is not available, it appears that in the absence of a dynamic surface low or "Shamal," wind speeds are determined by local land-sea breeze relationships and terrain peculiarities.

Winds along the north shore of the Strait are northeasterly to easterly during the night and early morning, and southerly to westerly during late morning and afternoon. Along the southern shore and under similar conditions, winds are southwesterly to westerly east of the Strait during the night and early morning, and southeasterly to southerly west of the Strait. Speeds average 3 to 7 knots. Late mornings and afternoons have pronounced sea breezes that are southwesterly to west-northwesterly west of the strait and northerly to northeasterly east of the strait. Sea breeze speeds reach 12 to 20 knots.

During "Shamal" conditions, low-level winds turn westerly to west-northwesterly approaching the Strait. Windspeeds over the Strait and along the Iranian shore reach 25 to 30 knots (in gusts) during sustained Shamal conditions; on the Omani shore, gusts reach 30 to 35 knots. As the "Persian Gulf Trough" forms and moves southwestward across the Gulf, downslope winds blow off the Iranian coast. Strong winds are rare and normally confined to the strongest stages of a "3 to 5 Day Shamal."

Dust. Almost always advected from Saudi Arabia or Iraq, dust is normally confined to the first cold front passages of the season. However, southwesterly flow late in the season ahead of developing low pressure areas, either in the Persian Gulf or in central Saudi Arabia, may bring blowing dust or sand into the Strait of Hormuz from the Saudi Arabian "Empty Quarter." Such occurrences rarely last longer than 12 hours.

Thunderstorms occur over the mountains on both sides of the Strait, but are confined to areas immediately preceding, and with the passage of, cold fronts or upper troughs. Some may be severe. Tops often exceed 40,000 feet (12.2 km); severe thunderstorm tops have been reported above 50,000 feet (15.2 km). Prefrontal squall line thunderstorms tend to be strongest over the Omani Peninsula; embedded pre-warm front thunderstorms are strongest over the Zagros Mountains on the Iranian shore. Most embedded thunderstorms are associated with southern Persian Gulf cyclogenesis.

Precipitation. Light rain, rainshowers, and occasional thundershowers occur with low pressure areas, cold fronts, and upper troughs. The greatest amounts fall on the Iranian side. As with the rest of the region, precipitation is extremely variable. While Bandar Abbas averages 4.7 inches (120mm) during the winter, some years see no rain at all and others have seen as much as 13.2 inches (335m).

Air Temperature. Maximum temperatures average from 70 to 85°F (21 to 29°C); minimums from 55 to 65°F (13 to 18°C). Temperatures inland are modified by increased elevation and the sea breeze.

SEA SURFACE CONDITIONS, Strait of Hormuz.

Water Currents. Flow through the Strait consists of tidal ebb and flood. During ebb conditions, currents of less than 1 knot flow predominantly from the Persian Gulf through the Strait into the Gulf of Oman. During flood tide, currents of less than 1 knot flow in the opposite direction, from the Gulf of Oman through the Strait into the Persian Gulf. 85% of all wave heights average less than 4 feet (1.2 meters).

Water temperatures are similar to those found in the Persian Gulf. They decrease from 75-76°F (24°C) in December to 73°F (22°C) in January, but increase to 74°F (23°C) in March.

MESOSCALE SYNOPTIC FEATURES. Low pressure waves may form in the Gulf of Oman on slow-moving fronts that are oriented northeast-southwest. Extensive low cloudiness with rain or drizzle occurs on the east side of these waves. Under "Shamal" conditions, the Strait of Hormuz acts as a venturi; winds increase markedly to the immediate south and southeast of the Strait proper. Once a "Persian Gulf Trough" has moved south off the Iranian coast, a bow-shaped cloud line--with the apex of the bow pointing toward the Strait of Hormuz--forms in the middle of the Gulf of Oman. This cloud line marks convergence between the west-northwesterly winds flowing over the Omani peninsula and the northerly to northeasterly winds flowing off the Iranian coast. The cloud line's dissipation marks the end of a "Shamal" episode.

TYPICAL WEATHER. The following weather is typical of the Strait of Hormuz and its shores during the Northeast Monsoon:

General Sensible Weather. Only high clouds--often jet stream associated--are normally observed here during the Northeast Monsoon. Visibilities remain excellent, except along the Iranian shore near dawn, when visibilities often fall into the 3 to 5 mile range, probably caused by very light wind conditions that allow the moist sea air, advected inland by the prior afternoon's sea breeze, to condense. Morning land breezes, reinforced by heating and the synoptic northerly flow, dissipate the haze and fog.

Sky Cover. Extensive middle and high cloud layers occur only in advance of upper troughs and the occasional surface low that moves eastward into Pakistan and India. Ceilings range from 7,000 to 8,000 feet (2,100 to 2,400m). Low cloud ceilings of 1,000 to 1,500 feet (300 to 450m) are normally confined to the Iranian shore ahead of developing low pressure waves on slow-moving cold fronts. Patchy low cloud ceilings form over the Gulf of Oman and the Omani coast, but clear within 6 to 12 hours after the surface low moves eastward. Middle clouds break with the passage of the upper trough.

Dust. Widespread dust that restricts visibility is confined to the coasts and immediate offshore Gulf areas during a strong "Shamal." Dust raised by northerly winds on the back side of a "Persian Gulf Trough" following a Shamal have been observed in satellite imagery. Visibility drops as low as 3 to 5 miles. Worst conditions are found at the mouth of rivers or canyons. Dust settles rapidly once winds drop below 25 knots. Protected locations, such as Seeb International Airport on the Omani coast, rarely experience visibility restrictions due to dust during the Northeast Monsoon.

Winds. Winds over the entire Gulf area are normally light and northeasterly, reflecting the monsoonal flow. Synoptic scale gradients immediately southeast of the Strait of Hormuz result in weak east-northeast to northeast circulation. Added to this is the effect of a terrain-induced low-level cyclonic eddy east of the Strait of Hormuz. Winds near coastlines show a pronounced land-sea breeze effect because of markedly higher terrain and temperatures inland. Although mean surface winds (as shown in climatic summaries) are northeasterly and relatively light, nighttime land breezes are southwesterly to west-southwesterly (downslope) at 4 to 8 knots. The sea breeze establishes shortly after 0900L and persists through 1900L as north-easterly to easterly onshore flow that reaches 15 to 20 knots in late afternoon.

Ahead of an approaching Persian Gulf cold front winds turn southeasterly, increasing to 15 to 25 knots. With cold frontal passage, winds veer to become northwesterly at 20 to 30 knots. As the "Shamal" builds, winds increase to 25 to 40 knots. Speeds decreasing to less than 25 knots signal the ending of a "Shamal."

Thunderstorms. Isolated thunderstorms form over the Gulf of Oman and along the Iranian coast immediately ahead of an upper trough and its associated surface cold front. The strongest thunderstorms are found over the Omani mountains with cold frontal passage. Tops range from 40,000 to 50,000 feet (12.2 to 15.2km).

Precipitation. Normal precipitation for the season is between 3 and 5 inches (75 to 125mm), but isolated thundershowers may bring much more. Jask, on the Iranian shore, has reported 5.6 inches (140mm) in January; Jiwani, Pakistan, 8.7 inches (220mm). Seeb International Airport, on the Omani coast about 25 miles northwest of Ras al'Hadd, has also reported 5.6 inches (140mm) in January.

Air Temperatures. Maximum temperatures in January range from 70°F (21°C) to 80°F (26°C) along the Iranian coast. Open water temperatures reach 70-75°F (21-23°C). Omani coastal temperatures average 75°F (23°C). Minimums range from 45 to 55°F (7 to 13°C) depending on exposure.

SEA SURFACE CONDITIONS, Gulf of Oman.

Water currents are easterly at 0.4 to 0.6 knots in January, but by late February an anticyclonic gyre establishes itself near 20°N 65°E; current flow west of 65°E ranges from easterly at 15°N to south-southwesterly at 20°N to westerly at 24°N. Speeds average 0.5 knots. Wave heights increase to 2 to 4 feet during normal northeast monsoon conditions. Average wind speeds increase from less than 6 knots just east of the Strait of Hormuz to 10-11 knots as the Arabian Sea is reached.

Water temperatures decrease from 79°F (25°C) in December to 73°F (21°C) in February, then rise to 75°F (23°C) in March.

MESOSCALE SYNOPTIC FEATURES. None affect the Omani Arabian Sea Coast.

TYPICAL WEATHER. The following weather conditions are to be expected in the Omani Arabian Sea Coast during the Northeast Monsoon:

General Sensible Weather. In the absence of upper troughs or fronts, only high clouds associated with the sub-tropical jet stream are found here. Visibilities are unlimited.

Sky Cover. Isolated heavy cumulus occurs when stronger onshore winds reach the Omani Convergence Zone (OCZ)--see Figure 16. Extensive middle and high cloud decks also spread over the region ahead and during passage of upper troughs Towering cumulus or thunderstorms occur over higher mountains with the passage of cold fronts or upper troughs.

Dust. Blowing dust from Saudi Arabia at the height of a Shamal poses the only visibility restriction. Dust has been observed well offshore both by satellite imagery and by embarked US Navy aerologists. Visibilities may briefly fall to 3 to 4 miles.

Winds. Synoptic scale winds east of the OCZ are northeasterly at 3 to 5 knots; west of the OCZ, northwesterly at 5 to 8 knots. These large scale patterns, however, are distorted and often overridden by mountain-valley breezes and, along the coast, by land-sea breezes. Winds offshore are predominently northeasterly at 5 to 10 knots along the coast; further out they increase to 10 to 15 knots.

Thunderstorms occur throughout the season with either surface cold frontal passages or upper troughs. Bases average 4,000 to 5,000 feet (1,200 to 1,500m); tops can reach as high as 50,000 feet (15.2 km) with the rare severe storm. Most thunderstorms occur in the Hajar Mountains along and just behind cold fronts during January. An occasional thunderstorm is also found among the very isolated showers that occur when stronger onshore winds reach the OCZ.

Precipitation. Precipitation along the immediate coast ranges from 1 to 2 inches (25 to 50mm). As with the rest of the Persian Gulf region, precipitation is extremely variable from one year to the next, but occasional thundershowers toward the end of winter have produced 2 to 4 inches (50 to 100mm). There are few weather reporting stations in Oman above 1,400 feet (425m) MSL inland to the main mountain range and data is extremely scarce. However, research by British meteorologists using oil company records indicates that a total of 0.8 inches (20mm) may occur on 4 or 5 days during the season. The Hajar Mountains receive up to 4 inches (100mm), most from thunderstorms along and just behind cold fronts during January. Icing and turbulence are primarily associated with the cumuliform buildups.

Air Temperatures. Maximum temperatures at elevations below 1,400 feet (425m) average 75 to 90°F (23 to 32°C). But they decrease with altitude, ranging from 40 to 45°F (4 to 7°C) in the highest mountains. Minimum temperatures along the immediate coast average 50 to 55°F (10 to 13°C); at higher elevations inland, minimums drop to as low as 20 to 25°F (-7 to -4°C) on the highest peaks.

SEA SURFACE CONDITIONS, Nothwestern Arabian Sea.

Water currents average southeasterly at 3 to 5 knots. Wave heights increase from 3 to 6 feet near the coast to 5 to 10 feet beyond 50 miles offshore.

Water temperatures cool from 77°F (24°C) in December to 75°F (23°C) in January; with increasing solar radiation, they climb back to 77°F (24°C) in March.

Chapter 5

THE SPRING TRANSITION

(April--May)

MAJOR CLIMATIC CONTROLS

FLOW PATTERN REVERSAL. The Spring Transition sees the reversal of synoptic scale flow patterns; completion of this reversal marks the end of the Spring Transition and the start of the Southwest Monsoon. The actual onset of the Southwest Monsoon is apparently triggered by a mid-tropospheric cyclone over either the northern Arabian Sea (see "Onset Vortex") or the Bay of Bengal. Incoming solar radiation increases dramatically. Changes in circulation occur at low levels first. The Northeast Monsoon circulation gradually loosens its grip on the region as low-level anticyclonic flow over the Arabian Sea is replaced by *cyclonic* circulation. Although the complete transition averages 30 to 45 days, actual onsets and endings vary by station location and from one year to the next. The change can be rapid. The end of the transition season is signaled by southerly cross-equatorial flow from the Southern Hemisphere moving northward along the east coast of Africa, then turning southwesterly, and finally reaching the Indian coast. Once this moist southwesterly flow reaches western India, numerous pre-monsoonal thunderstorms occur over northern and western India. Latent heat of condensation from these thunderstorms, combined with the increasing effectiveness of Tibet as a high-level (500mb) heat source, builds a high-level anticyclone over the Himalayas and Tibet. The result is that high-level *westerlies* are replaced by high-level *easterlies* essential to the maintenance of the Southwest Monsoon.

STRENGTHENING CONTINENTAL LOW PRESSURE CENTERS. These centers are connected by a thermal trough that builds through northeast Africa, Saudi Arabia, and central Iran. Northeast Monsoon pressure gradients weaken early in the transition. By the middle of May, however, strengthening gradients associated with extensive thermal low-pressure areas effectively block the effects of the weakening Siberian Anticyclone and restrict cold air outbreaks to early April.

THE UPPER-LEVEL (ABOVE 300MB) SUBTROPICAL RIDGE. This ridge, which was oriented east-west between 5 and 10°N during the Northeast Monsoon, strengthens and moves northward. This movement is directly related to the northward shift of the Monsoon Trough/Intertropical Convergence Zone (ITCZ) and rising upper-level pressure above the shallow continental thermal lows. By the end of the Spring Transition, the ridge is anchored by the upper-level high over Tibet.

INTERACTION BETWEEN THE POLAR AND SUBTROPICAL JETS is greatly reduced. As the mean position of the Polar Jet moves northward, winter short-wave upper-air troughs all but disappear. Occasional strong upper-level northwesterly winds are possible early in the period. Weak upper-level *flow patterns are* common over the Arabian Sea during the transition. The Subtropical Ridge separates the easterly flow aloft south of 15°N from the westerly flow between 15 and 35°N. As the ridge moves northward, strong upper-level easterly flow becomes established over the entire region.

MEAN MAY FLOW at 850, 700, 500, 300 mb, and 200mb (5,000, 10,000, 18,000, 30,000 and 40,000 feet) is shown in Figures 17, 18, 19, 20, and 21.

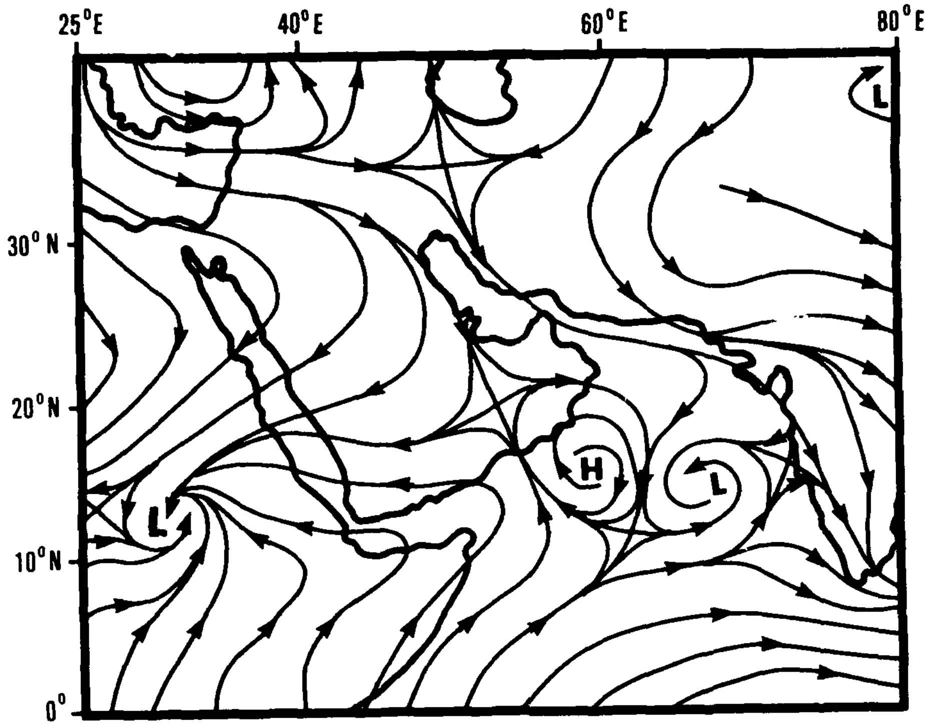

Figure 17. Mean May 850mb flow.

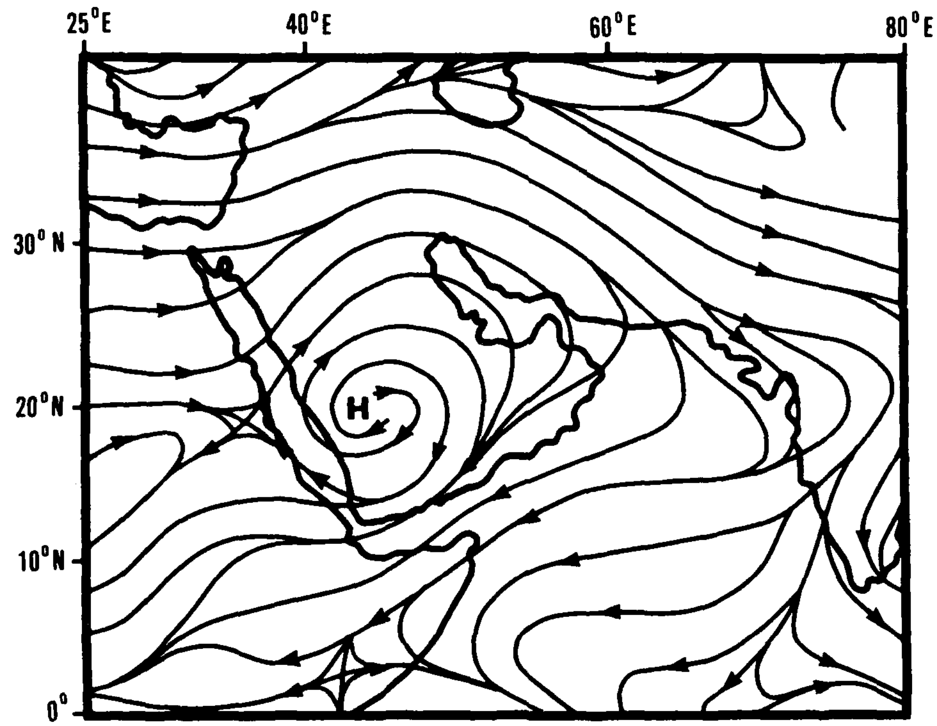

Figure 18. Mean May 700mb Flow.

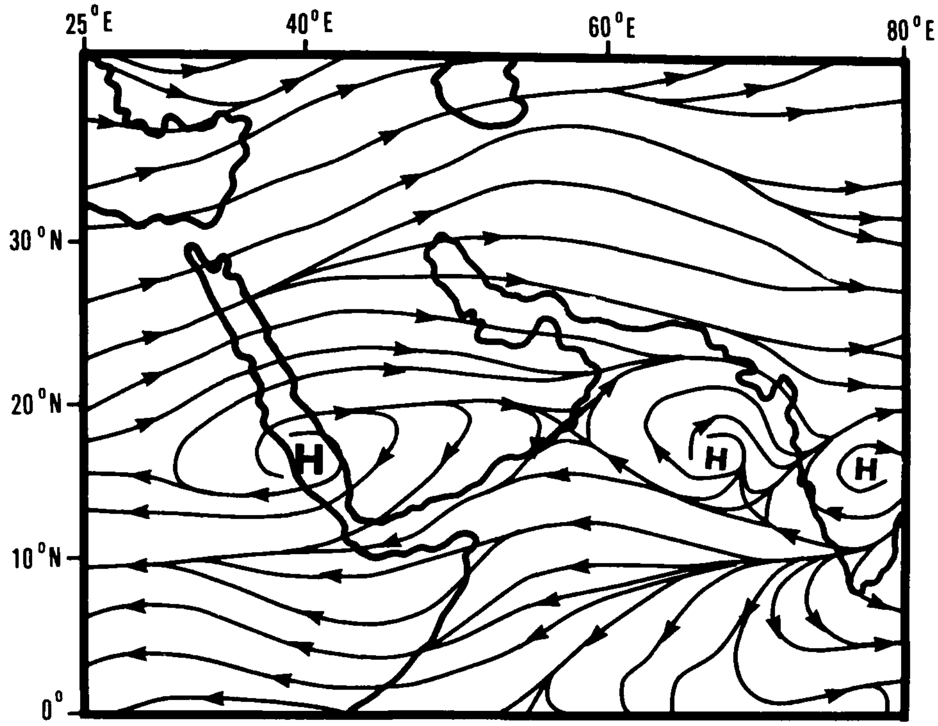

Figure 19. Mean May 500mb Flow.

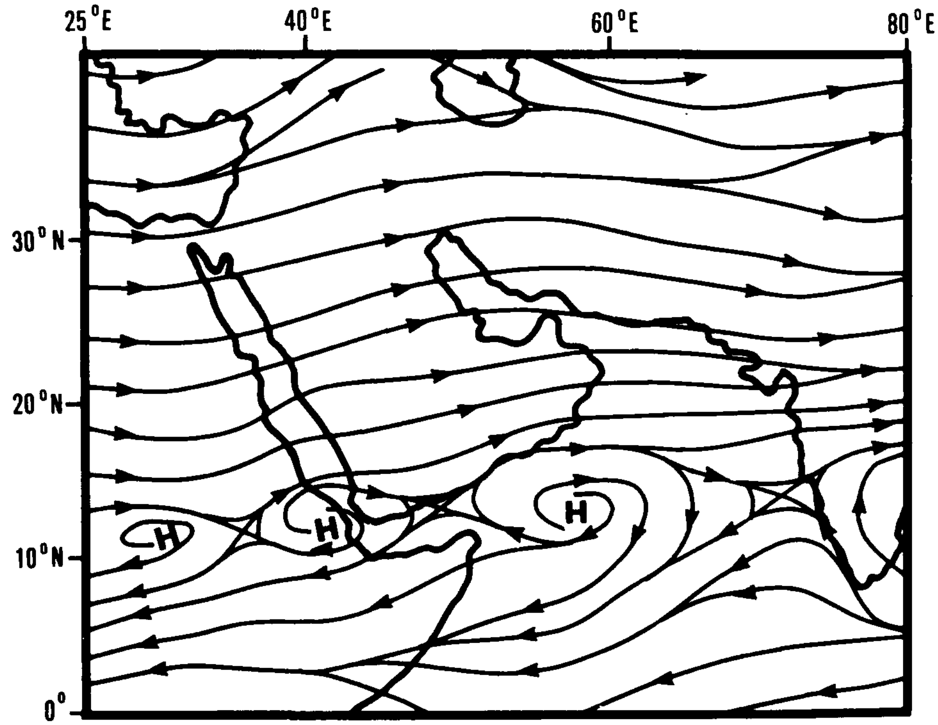

Figure 20. Mean May 300mb flow.

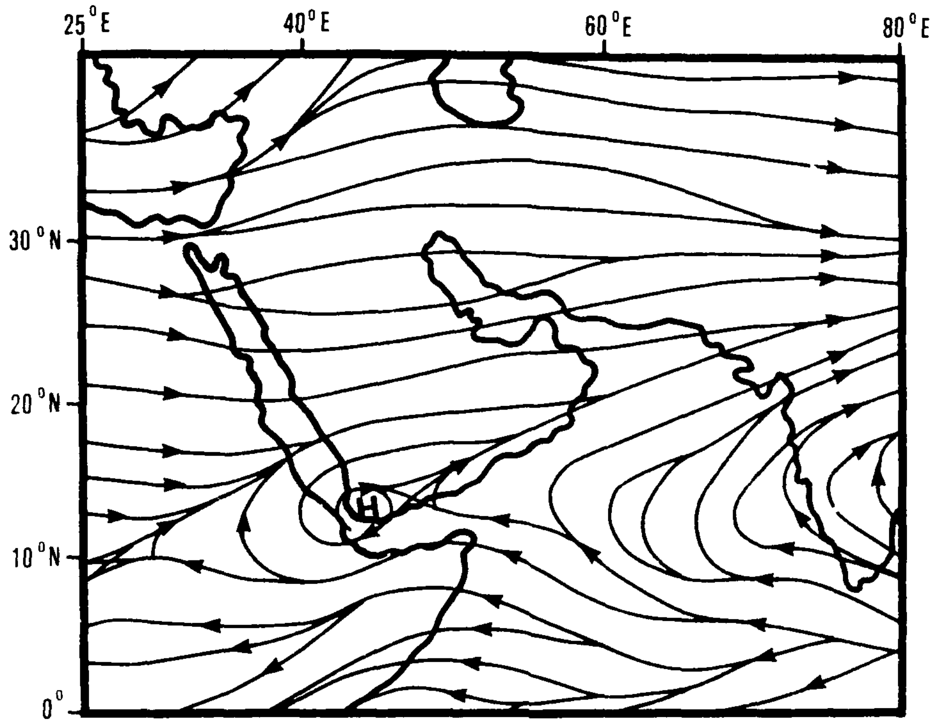

Figure 21. Mean May 200mb Flow.

TROPICAL CYCLONE FREQUENCY is highest during transition seasons, for these reasons:

- Weak cross-equatorial flow into the Southern Hemisphere provides upper-level divergence favorable for cyclone development.
- Vertical shear is weak.
- Low-level convergence increases due to rapid strengthening of the low-level thermal "heat lows" in Pakistan, Afghanistan, Iran, and Saudi Arabia.
- The Monsoon Trough/ITCZ migrates northward to locations between 15 and 25°N.

TROPICAL STORMS. The meteorological satellite has provided for more accurate location and tracking of Arabian Sea storms; reported frequencies are naturally higher since the early 1970s, but storms in this area are still relatively infrequent. Between 1890 and 1950, only 14 were recorded in the Arabian Sea during April and May. Between 1891 and 1969, only eight storms reached the Omani Coast; favored landfall was near Salalah. Storms usually form in the eastern Arabian Sea between 10 and 15°N, and between 70 and 75°E. The strongest have extensive layered clouds, low ceilings, heavy rain, and high winds out to 300 miles of the center. Flash floods are common. Mean April/May storm tracks are shown in Figure 22.

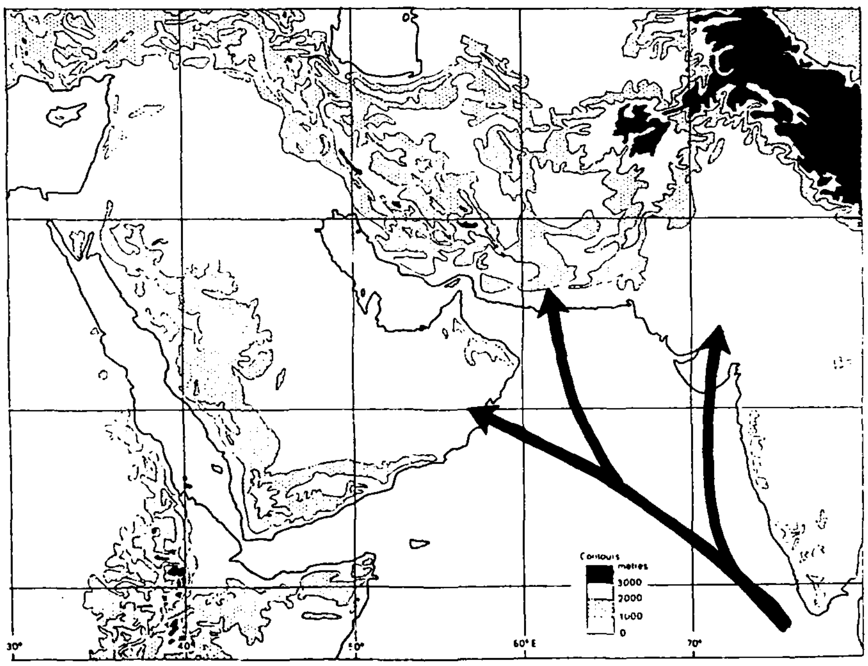

Figure 22. Mean Tropical Storm Tracks--April and May Combined.

THE ONSET VORTEX. The tropical "onset" vortex, *resembling a tropical storm, occurs only* at the end of the Spring Transition and marks the start of the Southwest Monsoon (hence the name). Statistically, it occurs about about 1 year in 2 in the Arabian Sea. In other years, a similar vortex forms in the Bay of Bengal. Occurrence ranges from mid-May to mid-June and is apparently the "trigger" for the deep lower-level southwesterly flow that marks the Southwest Monsoon. *These cyclonic systems form* at mid-tropospheric levels over the surface Monsoon Trough (ITCZ) just north of the nose of the Southwest Monsoon current. Movement is generally westward toward the Omani Peninsula, southeastern Saudi Arabia, or the Gulf of Oman. Initial movement, however, is northward to about 20°N, then westward or west-southwestward into the Arabian Peninsula. *Layered clouds form over the entire region* within 300 miles either side of the track. There are heavy cumuliform buildups and rainshowers within 50 miles of the center. Convective clouds and precipitation are greatly intensified over the Omani Mountains even when the vortex does not actually reach them.

THE DESERT FRONT. Actually a mean polar frontal position *over the northern* Red Sea, the desert front is not active every year. It does, however, represent a relatively rare storm track that lies across southern Egypt and the northern Red Sea into central Saudi Arabia. This storm track often results in the formation of a secondary wave over the central Red Sea as the mean jet stream position is displaced southward over the southern Mediterranean or northern Africa. Extensive thunderstorms *and heavy rains* accompany the movement of the secondary low across the Saudi Arabian peninsula. This track is only present in late winter (March) and during the spring transition. In May 1972, Riyadh, Saudi Arabia, twice experienced passage of a desert front. Although variations in temperature and wind may help identify the surface frontal position, there are times when this disturbance loses its surface characteristics; when it does, the only indications are in its associated weather and upper-level trough. These fast-moving fronts/troughs can affect a station's weather for 2-3 hours; they are often restricted to the area west of the Strait of Hormuz. Mean position of the desert front is shown in Figure 23.

THE OMANI CONVERGENCE ZONE (OCZ). The OCZ marks the boundary at which the predominant low-level northwesterly flow meets the intensifying southwesterly flow ahead of the Southwest Monsoon. Although the OCZ is mainly delineated by wind shear across it, occasional convective activity can be found over higher terrain. By the end of the Spring Transition, the Monsoon Trough/ITCZ has moved into the OCZ. Figure 24 gives the mean April location of the OCZ.

LAND-SEA BREEZES become the dominant feature along coastlines *during "undisturbed" (normal)* conditions. Sea breezes are considerably stronger than land breezes because of strong daytime temperature gradients. The land-sea breeze effect can cause abrupt changes in temperature, relative humidity, and wind direction.

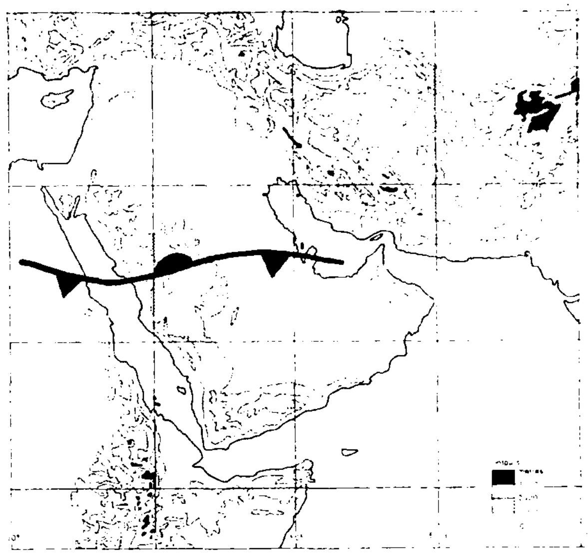

Figure 23. Mean Position of the Desert Front.

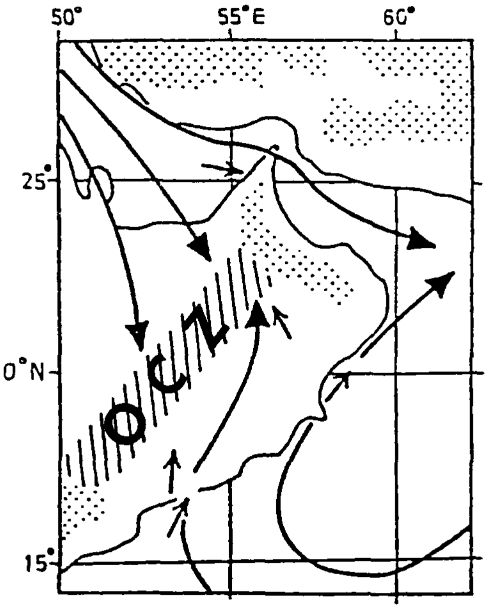

Figure 24. Mean April Position of the OCZ.

MESOSCALE SYNOPTIC FEATURES. As the Spring Transition progresses, the Omani Convergence Zone (OCZ) moves northwestward into the extreme southern Persian Gulf. This movement is due to the strengthening thermal lows over Saudi Arabia combined with increasing southwesterly flow over southeastern Arabia and the Arabian Sea.

TYPICAL WEATHER. The following weather conditions are typical of the Persian Gulf proper during the Spring Transition:

General Sensible Weather. Cloud cover is nearly nonexistent save for the rare thunderstorm. The few instances of jet stream cirrus are almost totally restricted to upper-level westerlies early in the period. Fog can occasionally occur early in the period, but only in early morning. Flooding in the Tigris-Euphrates River Plain is common, and caused by melting snow from the mountains of Iran and Iraq. Flooding has become more of a problem since 1980 when flood control levees were destroyed during the Iraq-Iran war.

Sky Cover. Middle and high cloud decks occur only with those few upper-air troughs that penetrate the area early in the Transition. Ceilings range from 10,000 to 14,000 feet (3.1 to 4.3 km). Lower ceilings are associated with thunderstorms, which see. Light icing and turbulence occur in middle cloud decks near the trough axis.

Winds. Weak low-level winds reflect the macroscale pattern reversal. Late in the period, wind speeds increase to reflect the development of strong continental thermal lows. April speeds average 5-7 knots, increasing to 10-12 knots in May. Directions continue to be northwesterly in the northern Persian Gulf, westerly in the southern Gulf, and turning southerly as one approaches the Strait of Hormuz. On the immediate coast, winds show large diurnal changes due to land-sea breezes.

Dust and Sand. The most significant weather is the increasing frequency of blowing dust and sand. Late season frontal zones (desert fronts) can advect dust or sand across the entire northern part of the Arabian Peninsula. Late in the Spring Transition, strengthening northwesterly winds cause lower visibilities, with highest frequencies in the northern part of the Persian Gulf. Visibilities drop to less than 6 miles during the day; in the afternoon, with higher wind speeds, visibilities drop to less than 3 miles. Basrah, Iraq, and Kuwait, Kuwait, both average nearly 10 days a month with blowing sand or dust. Blowing dust or sand also occurs with the rare thunderstorm--most of which occur early in the Transition. Visibilities in stronger thunderstorms may drop to as low as a half mile; near-zero visibilities are possible with severe thunderstorms. When strong winds are not sustained, dust settles rapidly.

Thunderstorms. Tops often exceed 40,000 feet (12.2 km); bases average between 4,000 and 6,000 feet (1,200 and 1,800 meters.) The usual severe icing and turbulence can be expected. Hail should be assumed when the classic Miller AWSTR-200 wet bulb zero heights above terrain are met. Thunderstorms during the Spring Transition have several causes:

- **Fronts.** An occasional Mediterranean frontal system reaches the region early in the transition season. Although considerably weaker than fronts that occur during the Northeast Monsoon, these can be strong enough to trigger thunderstorms.
- **Intense heating** over coastlines allows convection to penetrate low-level inversions.
- **Strong sea breezes** lift moist air orographically over nearby coastal mountain ranges.
- **Mid-level unstable air** associated with an upper-level trough (or with a weak Mediterranean front) is lifted orographically over the Zagros mountains.

Late in the transition, but very rarely, thunderstorms may also form over mountains along and southeast of the OCZ.

Precipitation. Rainfall decreases steadily during the transition. Its convective nature results in high variability from one location to another and from one year to another. Mean values of 0.50 to 1.00 inches (13 to 25mm) early in the transition decrease to less than 0.50 inch (13mm) by early May, then to near zero by the start of the Southwest Monsoon. Much more may fall over the Zagros during isolated thunderstorms; flash floods have occurred.

Air Temperatures. Temperatures rise significantly during the Spring Transition. Daytime maximums in coastal regions climb to between 95 and 97°F (35 and 36°C). Mean May temperatures on the north shore of the Persian Gulf are even higher; for example, 101°F (38°C) at Abadan, Iran, and 102°F (39°C) at Kuwait. Inland temperatures in Saudi Arabia stay within a few degrees of coastal temperatures. Zagros Mountain temperatures are nearly 5°F (2.8°C) cooler than coastal regions. Minimum April temperatures at most locations range from 62 to 65°F (16 to 19°C), warming rapidly to 73 to 75°F (22 to 23°C) in May. Iranian mountain locations are nearly 10°F (5°C) cooler in both months. Dewpoints in coastal regions range from 50 to 53°F (10 to 11°C). Dewpoints drop dramatically inland.

SEA SURFACE CONDITIONS, Persian Gulf.

Water currents in the Persian Gulf circulate counterclockwise. A steady flow of surface water enters the Persian Gulf through the Strait of Hormuz. The surface current flows toward the west, then northwest as it hugs the Iranian shore. At the northern end of the Gulf, it turns southeasterly to parallel the Arabian coast. Finally, it turns northerly along the west side of the Omani Peninsula to join fresh Gulf of Oman water entering through the Strait of Hormuz. Speed is less than 1 knot. Maximum calculated speed for the 100-year worst case of both wind and tidal currents was 8 knots at Jubail. As water increases in density, it sinks, turns southeastward, and flows back into the Gulf of Oman as a bottom current through the Strait of Hormuz.

Water temperatures rise rapidly during the Spring Transition. Surface water temperatures range from 73 to 76°F (22 to 23°C) in April to 80-82°F (26-27°) in May. Temperatures in extremely shallow coastal waters may get 5 to 7°F (2.8° to 3.8°C) warmer. With the warming surface waters, there tends to be an increasing temperature difference between the surface and the bottom (about 195 feet or 60m); by May the bottom is about 10°F (5.6°C) cooler. There is no evidence of thermoclines. Wave heights are less than 4 feet (1.2m) more than 80% of the time.

MESOSCALE SYNOPTIC FEATURES. None apply specifically to the Strait of Hormuz.

TYPICAL WEATHER. The following weather conditions are typical of the Strait of Hormuz during the Spring Transition:

General Sensible Weather. Cloud cover decreases from near 3 eighths in April to 1 eighth in May. This is the only season of the year in which the usual late evening and early morning patchy low stratus and stratocumulus are absent. Visibilities are excellent.

Sky Cover. Middle and high clouds are found only with the infrequent late winter front or trough. Ceilings average 12,000 to 14,000 feet (3.7 to 4.3 km). Light mixed icing and light to moderate turbulence--especially over the Zagros mountains on the Iranian shore--are associated with these layers. Convective clouds may form in late afternoon, especially along the Strait's Iranian shore. These clouds are caused by a combination of strong land-sea breeze interaction and mechanical lifting over nearby higher terrain. They have relatively high bases at 5,000 to 7,000 feet (1,500 to 2,100 m).

Winds. General flow is southwesterly to west-northwesterly west of the Strait and northerly to northeasterly east of the Strait. Low-level flow reflects a combination of the weak inflow from the Gulf of Oman, pronounced land-sea breezes (especially along the Iranian shore), and a general easterly to southeasterly flow around the southern end of the terrain-induced leeside Gulf low. Bandar Abbass (on the Iranian shore) maintains the mean southerly flow found in the other seasons while Dubai, United Arab Emirates, finds its mean wind direction changing from westerly to southerly. The absence of disturbances leaves the flow pattern of the southern shore of the Strait to the local patterns of the leeside low and land-sea breeze circulation. Complicating these patterns is the pronounced venturi effect through the narrowest part of the Strait. Sea breezes strengthen in May as thermal lows build over the continents.

Dust is confined to rare cases of advection from the northern Persian Gulf or central Saudi Arabia following frontal passages. Visibilities normally remain above 6 miles, but visibilities as low as 3 miles are possible if the source region is central Saudi Arabia. Lower visibilities are possible only with an active desert front.

Thunderstorms. Although rare, thunderstorms can occur over the mountains on either side of the Strait. Storms are stronger over the Zagros mountains. Causes and characteristics are much the same as for those in the Persian Gulf proper, which see.

Precipitation occurs only with the rare thunderstorm and is confined to mountainous areas without reporting stations. No measurements are available, but crude estimates derived from similar situations in Arizona give values of 0.25 to 0.75 inches (6 to 19mm).

Air Temperatures. Maximum temperatures average from 97 to 99°F (36 to 37°C). Minimums rise from the lower 70s (about 22°C) on the Iranian shore in April to the upper 70s (about 24°C) by May. On the Arabian shore, temperatures are slightly lower, warming from the upper 60s (near 20°C) in April to the low 70s (near 22°C) in May. Temperatures farther inland are cooler due to increased elevation and the diminishing sea breeze effect.

SEA SURFACE CONDITIONS, Strait of Hormuz.

Water currents through the Strait are mainly tidal ebb and flood. During ebb conditions, currents of less than 1 knot flow predominantly from the Persian Gulf through the Strait into the Gulf of Oman. Flood tide currents (also less than 1 knot) reverse to flow from the Gulf of Oman into the Persian Gulf. Waves heights are less than 4 feet (1.2m).

Water temperatures warm from near 77°F (24°C) in April to 82-83°F (27-28°C) in May.

MESOSCALE SYNOPTIC FEATURES.

Tropical Cyclones. Tropical cyclones that originate in the Arabian Sea only reach the Gulf of Oman about once every 4 years. They produce layered clouds, low ceilings, heavy rains, and high winds. In the rare cases of landfall, expect flash floods in and near mountains on either coast. Moderate icing and moderate to severe turbulence are common, but turbulence and icing are heavier over the mountains on either shore. Ceilings can be as low as 1,000 to 1,500 feet (300 to 460m) with layers through 40,000 feet (12.2km). Visibilities can be as low as half a mile, and winds can be of hurricane force. There are no records of maximum wind speeds; not many of these storms passed over reporting stations, and those that did destroyed the anemometers. Although more than 10 inches (250mm) of rain were recorded in a storm that made landfall near a reporting station, there have undoubtedly been higher amounts.

Omani Gulf Low. This mesoscale low is located in the western Gulf of Oman; it dominates during the early part of the transition season. It is caused by a combination of a Zagros Mountain lee side effect and the mountainous terrain along the Omani coast. As the Northeast Monsoon weakens, so does the low. Establishment of the Southwest Monsoon destroys this mesoscale feature. See "Winds."

TYPICAL WEATHER.

General Sensible Weather. This is perhaps the most settled season of the year in and around the Gulf of Oman. Skies are normally clear with excellent visibilities. Mid-latitude disturbances from the Mediterranean rarely have the support to reach this far south. The OCZ moves into the extreme southern Persian Gulf; the Monsoon Trough/ITCZ has yet to appear.

Sky Cover. Late in the Transition season, cirrus layers are sometimes advected westward from tropical disturbances in the eastern Arabian Sea. These layers reach the area only when the upper-level easterlies have set up south of the subtropical ridge. The cirrus dissipates near the eastern portion of the Gulf of Oman due to strong mid-tropospheric subsidence.

Winds. The light and shifting synoptic gradient during the first part of this season leaves winds over land at the mercy of local effects such as land-sea breezes and/or mountain-valley breezes. Low-level winds along the immediate Iranian shore turn east-northeasterly and increase in speed during daylight hours as one approaches the Strait of Hormuz. This is due to the strengthening sea breeze influence as well as the Omani Gulf Low described earlier. Toward the end of the season weak southwesterly flow, often masked by local effects, appears along the Omani coast. Speeds average 3 to 5 knots.

Dust is almost unknown. Blowing dust or sand may occur with the rare thunderstorm over higher mountains on either side of the Gulf Of Oman.

Thunderstorms. A very rare thunderstorm may occur over higher mountains on both the Iranian and Omani shores of the Gulf. The most common cause is locally induced convection resulting from the lifting of moist Gulf air over nearby coastal mountain ranges. Although infrequent, the most common location is in Oman's Jabal Akhdar range. Thunderstorm tops often exceed 40,000 feet (12.2 km); bases average between 4,000 and 6,000 feet (1,200 and 1,800 meters.) The usual severe icing and turbulence should be expected. Hail should be assumed when the classic Miller AWSTR-200 wet bulb zero heights above terrain are met.

Precipitation. Except for that from the rare tropical cyclone, precipitation is thunderstorm-associated, almost always falling in mountains where there are no reporting stations. Crude estimates based on similar situations in Arizona indicate amounts to be 0.25 to 0.75 inches (6 to 19mm).

Air temperatures increase rapidly due to the combination of decreased cloud cover and undisturbed (normal) weather conditions. Maximum temperatures on both shores of the Gulf of Oman warm from between 87° and 89°F (30 to 31°C) in April to between 94 and 96°F (34 to 35°C) in May. Minimum temperatures on the southern coast rise from near 80°F (26°C) in April to 85°F (29°C) in May. Maximum temperatures on the northern coast are nearly 5°F (2.8°C) cooler.

SEA SURFACE CONDITIONS, Gulf of Oman.

Water currents become southwesterly, averaging only half a knot throughout the Gulf of Oman and northern Arabian Sea. Wave heights are less than 4 feet (1.2m) nearly 90% of the time.

Water temperatures range from 78° to 79°F (near 25°C) in April to 83 to 85°F (near 29°C) in May.

MESOSCALE SYNOPTIC FEATURES.

Tropical cyclones originating in the Arabian Sea may affect the Omani Coast, but incidence is not high. On the average, one of these storms may make landfall on the Omani coast in only 1 year out of 4. For characteristic conditions, see "Mesoscale Synoptic Features" for the Gulf of Oman and Adjacent Coasts.

Onset Vortex. The onset vortices that mark the end of this transition season and the start of the Southwest Monsoon (see "Transitory Synoptic Features") reach the Omani Arabian Sea coast less than 25 percent of the time. Layered clouds occur from 1,000 to 3,000 feet (300 to 1,000m) up to 35,000 to 40,000 feet (10.7 to 12.2km) over the entire region within 300NM of the vortex center. There are heavy cumuliform buildups and rainshowers within 50 miles of the center, and moderate icing and turbulence within 150 miles of the center. Flash floods in and near the Omani mountains are common even when the vortex does not actually make landfall.

TYPICAL WEATHER.

General Sensible Weather is excellent. This is the most cloud-free season of the year here; visibilities are excellent.

Sky Cover. Multilayered cloud decks are confined to those associated with the very rare tropical cyclone (see "Mesoscale Synoptic Features").

Dust. As wind speeds rise late in the season with increasing southwesterly flow, and the ground becomes baked by high temperatures, the number of days a month with blowing dust or sand increases. By season's end, blowing dust or blowing sand occurs on 4 or 5 days a month.

Winds. Winds switch to southwesterly in late May or early June to herald the end of the Transition Season. Northeasterly winds at Masirah become southwesterly by May. Winds at Salalah move from the southeast to southwest. Wind speeds are near their annual minimum. Early morning light winds increase throughout the day to 7-9 knots by mid-afternoon. Winds over the northwest Arabian Sea become southwesterly by mid-April at 4 to 7 knots. Directions stay constant through May, with speeds increasing to 10 to 15 knots just before the onset of the Southwest Monsoon.

Thunderstorms. Although none have actually been recorded here, they probably do occur. British meteorologists working with oil exploration companies in the interior have observed rare cumulonimbus over the mountains to the southwest.

Precipitation occurs only with tropical storms, thunderstorms, or the passage of an onset vortex. Amounts in excess of 10 inches (255mm) have been recorded.

Temperature. This is the warmest season of the year. Maximum and minimum temperatures are at their highest annual mean at both Salalah and Masirah. Maximums average from 90 to 96°F (32 to 35°C); minimums from 77 to 78°F (near 24°C).

SEA SURFACE CONDITIONS, Northwest Arabian Sea.

Water currents begin to establish themselves as southwesterly at 1 to 2 knots by the end of the season.

Water temperatures climb to their highest values of the year, reaching between 79 and 81°F (26 and 27°C). The fact that water temperatures are at their warmest now, rather than later in the summer, is a result of the low cloud cover and extensive upwelling that establishes almost coincidentally with the onset of the Southwest Monsoon.

Chapter 6

THE SOUTHWEST MONSOON

(June--September)

MAJOR CLIMATIC CONTROLS

A MASSIVE THERMAL LOW-PRESSURE TROUGH dominates this season. This trough has its primary axis along the Persian Gulf, with a secondary center over south central Saudi Arabia. It is a westward extension of the summer thermal low centered in extreme western Pakistan. The entire system is anchored by a combination of terrain (the Zagros mountains along the Iranian Persian Gulf shore) and the extremely hot and dry air over the Arabian Peninsula.

AN UPPER-AIR RIDGE has formed over the Arabian peninsula and Iran. 500mb high pressure centers are located over extreme western Arabia and over the Zagros mountains in southwestern Iran.

THE MONSOON TROUGH/INTERTROPICAL CONVERGENCE ZONE (ITCZ) enters the study area about 200NM inland of Salalah on the southwestern Omani Arabian Sea coast and follows the Omani mountain crest to the Strait of Hormuz. After crossing the Strait of Hormuz it lies at or near the 1,640 foot (500m) contour line of the Zagros Mountains--or about 25 to 30 miles inland of the Iranian coast. Upon reaching extreme western Pakistan near Jiwani, the Monsoon Trough/ITCZ turns north-northeastward. Unlike in other tropical regions, the Monsoon Trough/ITCZ here marks the boundary between moist tropical air at low levels and hot, subsiding air above. It is, therefore, normally inactive. It slopes gradually upward towards the southeast, and is the cause of the extremely strong elevated inversion south and east of its surface position. In southeastern Saudi Arabia and Oman, the Monsoon Trough/ITCZ absorbs the Omani Convergence Zone found during the Northeast Monsoon and the Spring Transition. Figure 25 shows the mean July surface position of the Monsoon Trough/ITCZ.

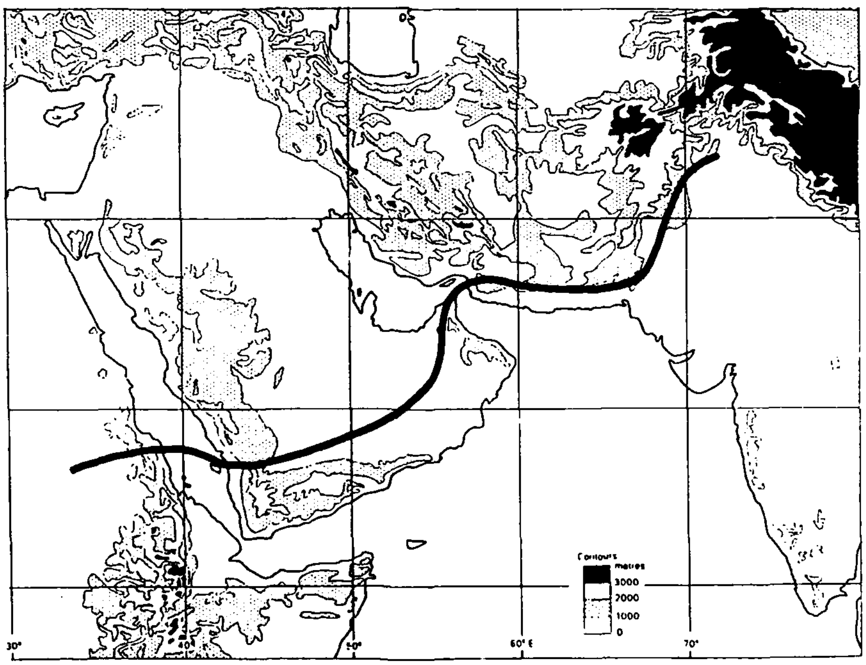

Figure 25. Mean July Surface Position of the Monsoon Trough/ITCZ.

Figure 26 is a mean July 1200Z sounding for Salalah, on the Arabian Sea Omani coast. Although the sounding is based on limited data, the inversion profile shown is believed to be representative of the southeastern Arabian Peninsula and immediately offshore that lie in the "Southwest Monsoon," discussed next.

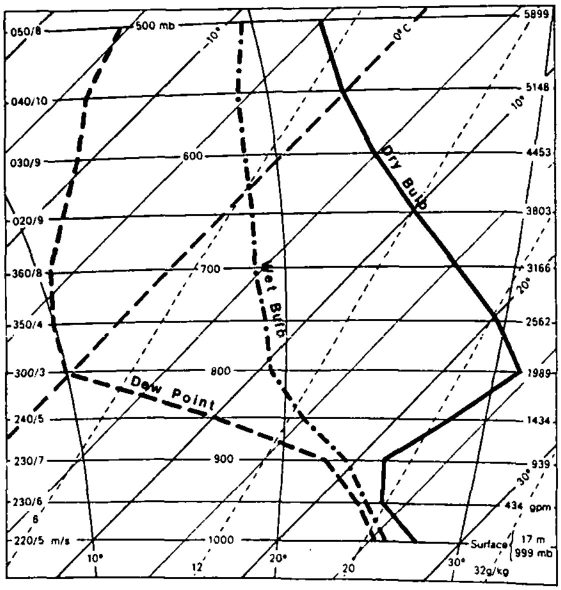

Figure 26. Mean Winds, Temperatures, and Geopotentials--Salalah, 1200Z, July 1980.

THE SOUTHWEST MONSOON, for which this season is named, is a deep and strong sustained flow of southwesterly to westerly winds over the entire Indian Ocean north of the Equator. Flow depth over the Central Arabian Sea and the Indian Ocean extends from the surface to above 500mb. This flow lies on the equatorward side of the Monsoon Trough/ITCZ. Strongest speeds are over eastern Africa and immediately offshore of Arabia. The core current of this high-speed air is known as the "Somali Jet." Normal maximum depth of the moist tropical air in this airflow along the Arabian Coast and in the Gulf of Oman is 2,000 to 3,000 feet (0.6 to 0.9km). It is capped by a strong inversion that rises toward the southeast over the Arabian Sea. This inversion marks the Monsoon Trough/ITCZ.

STRONG UPWELLING along and just off the Omani Arabian Sea coast assists in the maintenance of the high-speed winds of the Southwest Monsoon. It also results in a stratocumulus deck offshore that turns onshore in the lee of peninsulas. This deck behaves like California coastal stratus.

THE TROPICAL EASTERLY JET (TEJ). The northern edge of the TEJ crosses the southern Arabian Peninsula and the northern Arabian Sea from east to west. Maximum speeds (in the area of this study) are 50 to 75 knots between 40 and 45,000 feet (12.1 and 13.6km).

TWO IMPORTANT AIRFLOW FEATURES.

- **A northwesterly current** at all levels over the Arabian Peninsula. Extremely dry, this flow is the primary atmospheric cause for the prevailing dust layer found throughout the region. Embedded in this current is the Summer Shamal that occurs over and just west of the Persian Gulf. This enhancement of the prevailing northwesterly and northerly flow is normally strongest during June and July.

- **Mid-level easterly to southeasterly flow** at 700 through 500mb over Iran and at 600 through 500mb over the Omani Peninsula. It originates with the mid- and high-level anticyclone centered over Central Iran and western Pakistan.

MID-LEVEL MOISTURE over the Irani coast of the Gulf of Oman, the Zagros Mountains and westward over the Omani Peninsula. During periods of stronger flow, isolated thunderstorms develop over all three areas.

A PERSISTENT MID-LEVEL TROUGH at 600 and 500mb over the southern portion of the eastern Arabian Peninsula separates the northwesterly and southerly flows. Experienced British meteorologists think this relatively weak trough is the cause of the occasionally thick altocumulus layers found here.

EXTREMELY WARM PERSIAN GULF WATERS. The shallow waters of the Gulf heat rapidly and remain hot throughout the summer. Surface water temperatures by mid-July are above 90°F (32°C). High evaporation rates result in a steady northwestward flow of surface water through the Strait of Hormuz into the Gulf; the current just west of the Strait reaches 2 to 4 knots. A counter-current flows southeastward along the bottom down the Persian Gulf and out into the Gulf of Oman. Note that the surface current into the Persian Gulf flows *against* the prevailing northwesterly winds.

MEAN JULY FLOW at 850, 700, 500, 300, and 200mb (5,000, 10,000, 18,000, 30,000, and 40,000 feet) are shown in Figures 27 through 31.

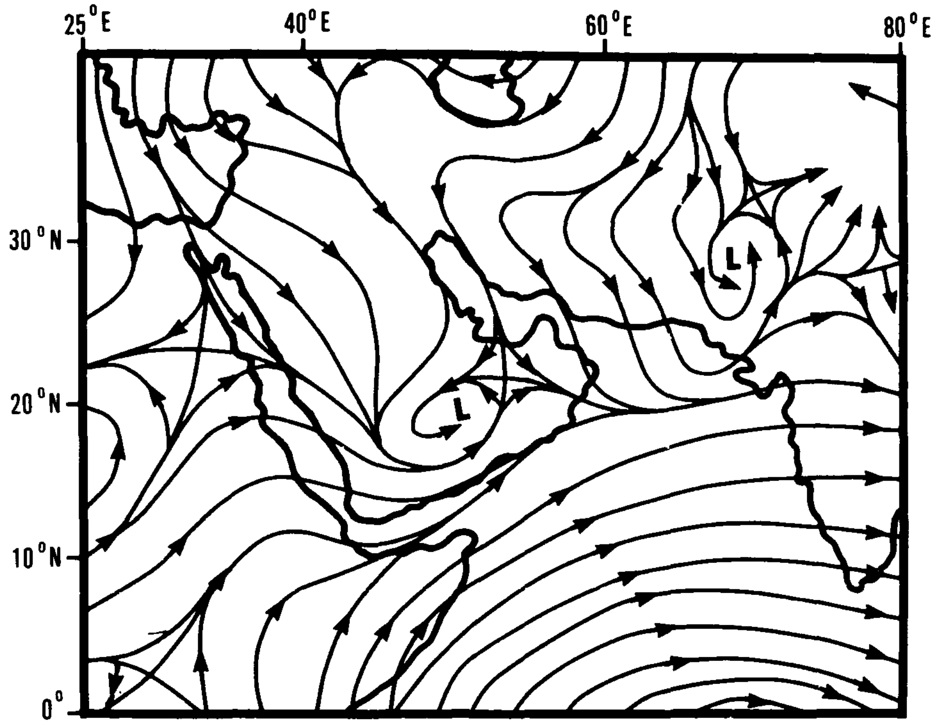

Figure 27. Mean July 850mb Flow.

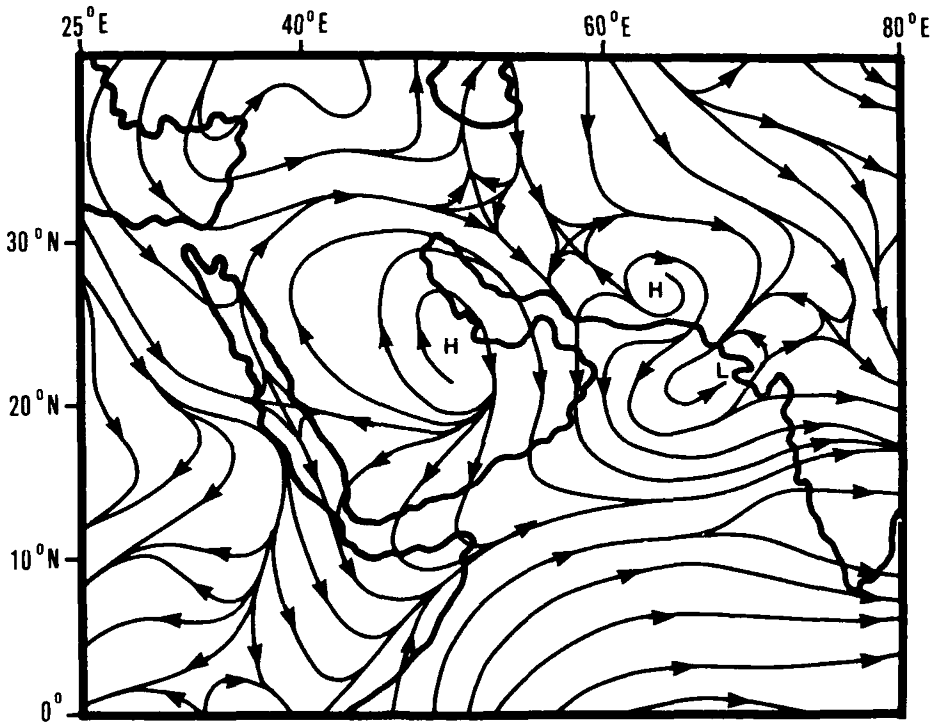

Figure 28. Mean July 700mb Flow.

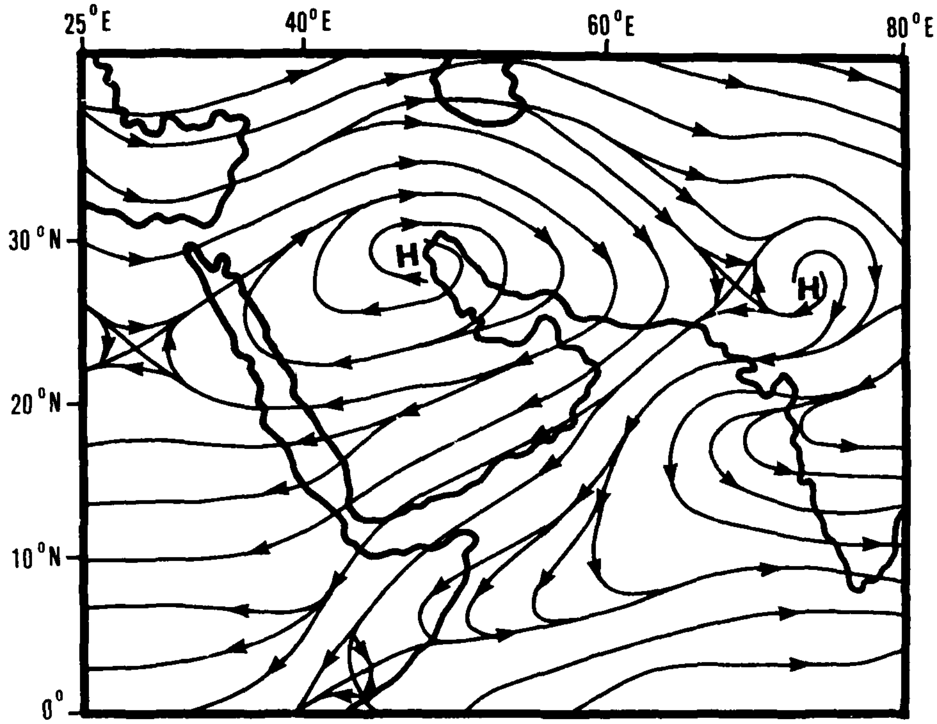

Figure 29. Mean July 500mb Flow.

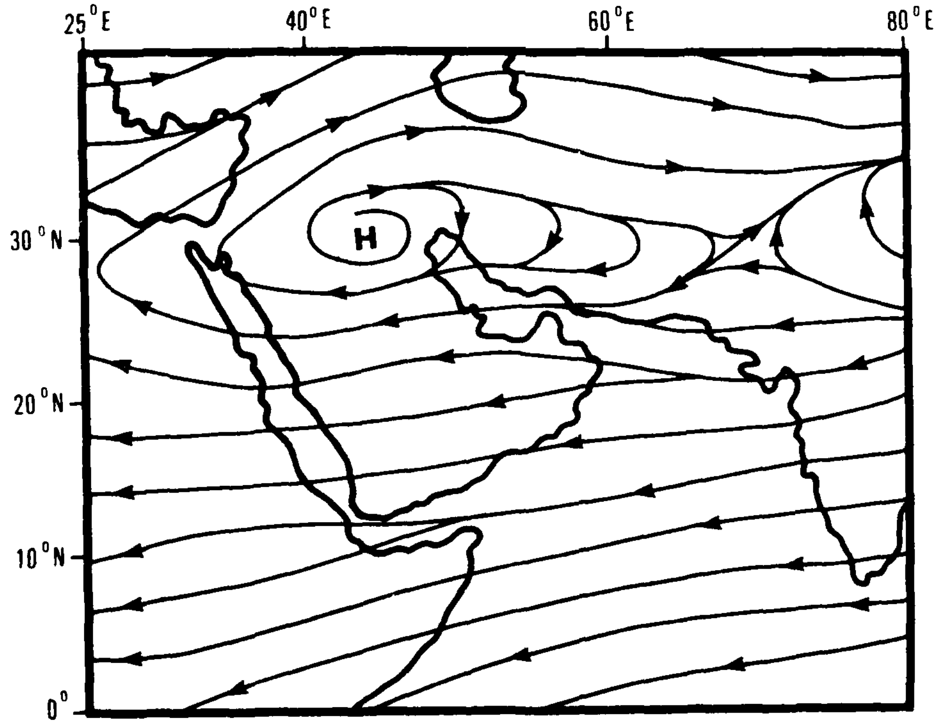

Figure 30. Mean July 300mb Flow.

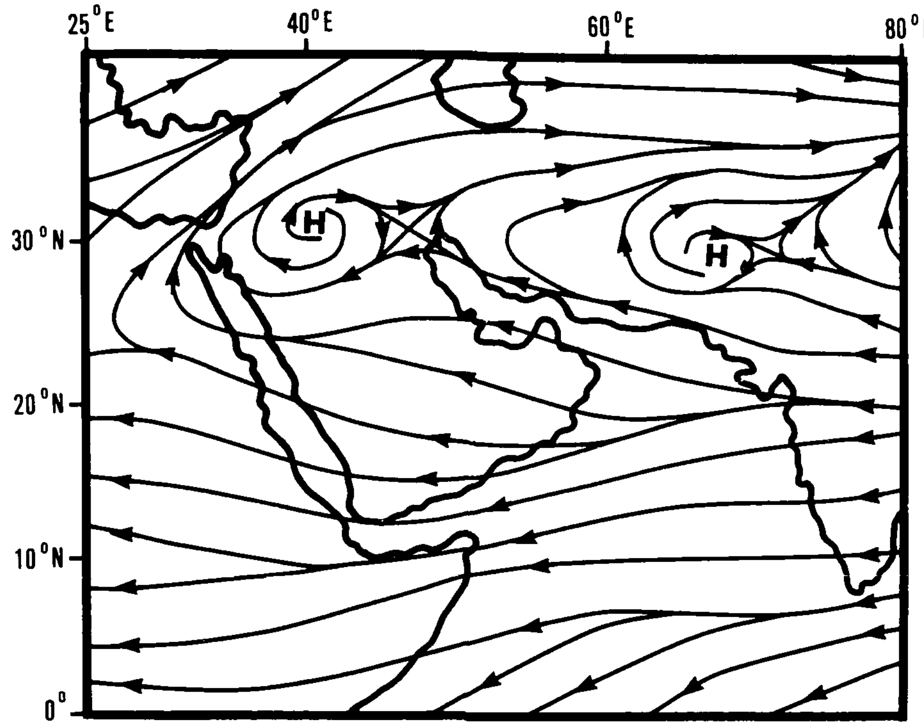

Figure 31. Mean July 200mb Flow.

WEAK UPPER-LEVEL TROUGHS IN THE WESTERLIES. In June and early July these troughs may penetrate southward into the Arabian Peninsula when a blocking high over northern Europe results in a high-speed wind core in the westerlies across the Mediterranean into Iraq. The characteristic middle and high clouds associated with these troughs show up well on visual and IR satellite imagery.

NORTHWESTWARD MOVEMENT OF THE MONSOON TROUGH/ITCZ into the southern Persian Gulf and Arabian Peninsula. The Monsoon Trough/ITCZ normally lies over southeastern Arabia and the Strait of Hormuz, and along the Iranian Gulf of Oman shore, but under certain conditions, it will move further northwestward into the southern part of the Persian Gulf. This movement results from pulses in the Southwest Monsoon that are most prevalent in July, August, and early September. Pulse origins are:

Easterly troughs moving westward over the Indian Ocean in the southern hemisphere trades. These trade winds, recurving toward the east after crossing the equator, become the "southwest monsoon." Increased mass transport behind the troughs reinforces the Somali Jet and results in higher wind speeds.

Shear lines moving northeastward up the Mozambique Channel between Africa and Madagascar. These shear lines originate as southern hemisphere cold fronts. The ridges following them provide the additional mass that, after merging with the ex-southern hemisphere trade winds over eastern Kenya and Tanzania, results in increased wind speeds of the Somali jet.

THE ONSET VORTEX has been thoroughly discussed under the Spring Transition in Chapter 5. However, readers should remember that this feature actually *straddles* the end of the Spring Transition and the start of the Southwest Monsoon. It is an Arabian Sea tropical vortex associated with the onset of the Southwest Monsoon. It occurs in 1 out of 2 years. Either this vortex, or a similar one in the Bay of Bengal, seems to be a necessary condition for establishment of the upper-level anticyclone over Tibet and the Himalayas. This anticyclone, which acts as the monsoon outflow, in turn is necessary for formation and maintenance of the upper-level tropical easterlies. For further details, see "Transitory Synoptic Features" under "The Spring Transition."

TROPICAL CYCLONIC STORMS/CYCLONES are late spring-early summer phenomena, almost always the remains of Bay of Bengal cyclones that cross India, regenerate in the Monsoon Trough-ITCZ over the extreme northern Arabian Sea, and then move toward the west. June storm tracks are shown in figure 32.

Tropical storm occurrence drops off markedly with the onset of summer as the monsoon trough/ITCZ moves northwestward to a line through the southeast Arabian Peninsula across the Strait of Hormuz and eastward along the Iranian Gulf of Oman coast into extreme western Pakistan. Eleven storms were recorded during the month of June between 1890 and 1950. Between 1891 and 1969, five made landfall on the Omani coast. Occurrences in July through September are rare; only seven were observed over the Arabian Sea between 1890 and 1950. Storms that do form and survive the influence of colder water found in the extreme eastern Gulf of Oman and along the northeastern Arabian coast make landfall near Salalah on the central Omani coast.

One storm is known to have crossed the northern Arabian Sea during August; it made landfall at Masirah. Winds of 47 knots and a total storm rainfall of 1.77 inches (45.0mm) were recorded. The surface pressure gradient tightened rapidly in the southern Persian Gulf at the same time; Abu Dhabai and Dubai recorded easterly winds gusting to 37 knots with visibility 5/16 mile (500m) in blowing sand. Masirah has recorded much higher storm rainfall; for example, 17 inches (430mm) fell during the June 1977 storm. Although there are no observing records for the Omani mountains, precipitation amounts are doubtless higher there.

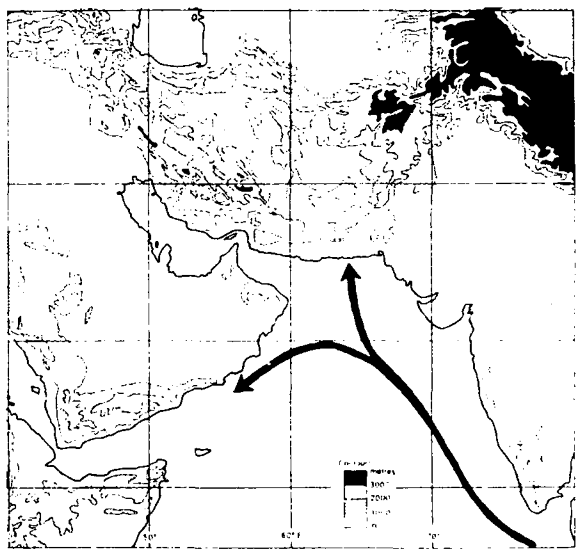

Figure 32. Mean Tropical Storm Tracks, June.

MESOSCALE SYNOPTIC FEATURES. The following features are common to the Persian Gulf proper and its immediately adjacent land areas:

The Summer Shamal describes the prevailing northwesterly winds that occur throughout the Southwest Monsoon season but are strongest from early June through mid- to late July. The Summer Shamal winds result from a combination of flow around the Pakistani semipermanent low pressure area, the Saudi Arabian heat low, the "valley" of the Persian Gulf, and the barrier effect of the Zagros Mountains that induces a mesoscale low pressure area over the gulf near the Iranian shore.

A Mesoscale Lee-side Induced Surface Low lies over the southeastern Persian Gulf, anchored against the Iranian coast. Caused by complex interactions between terrain features (the Zagros and Omani mountains) and the Summer Shamal winds, the low results in low-level easterly and southeasterly winds along the Iranian coast as far northwest as Busheir. The low causes the tightened gradient that is partially responsible for the low-level jet described below.

The Low-Level Jet. From the combination of terrain and synoptic features already described, a high-speed, low-altitude wind maximum, or "low-level jet" (LLJ), persists for most of the southwest monsoon season along the Arabian Coast from about 75 miles southeast of Kuwait to 100 miles southeast of Doha. The changing terrain orientation between Doha and Abu Dhabi results in relaxation of conditions favorable for LLJ formation. Speeds within the LLJ can exceed 50 knots; altitudes of the strongest wind speed cores are between 800 and 1,500 feet (245 and 460m) MSL. As with all LLJs, altitudes and core speeds are subject to diurnal variations; the lowest altitude of the wind maximum, and the highest speeds, occur just before dawn. Figure 33 shows a representative case. In late afternoon, speeds drop to those of the gradient wind.

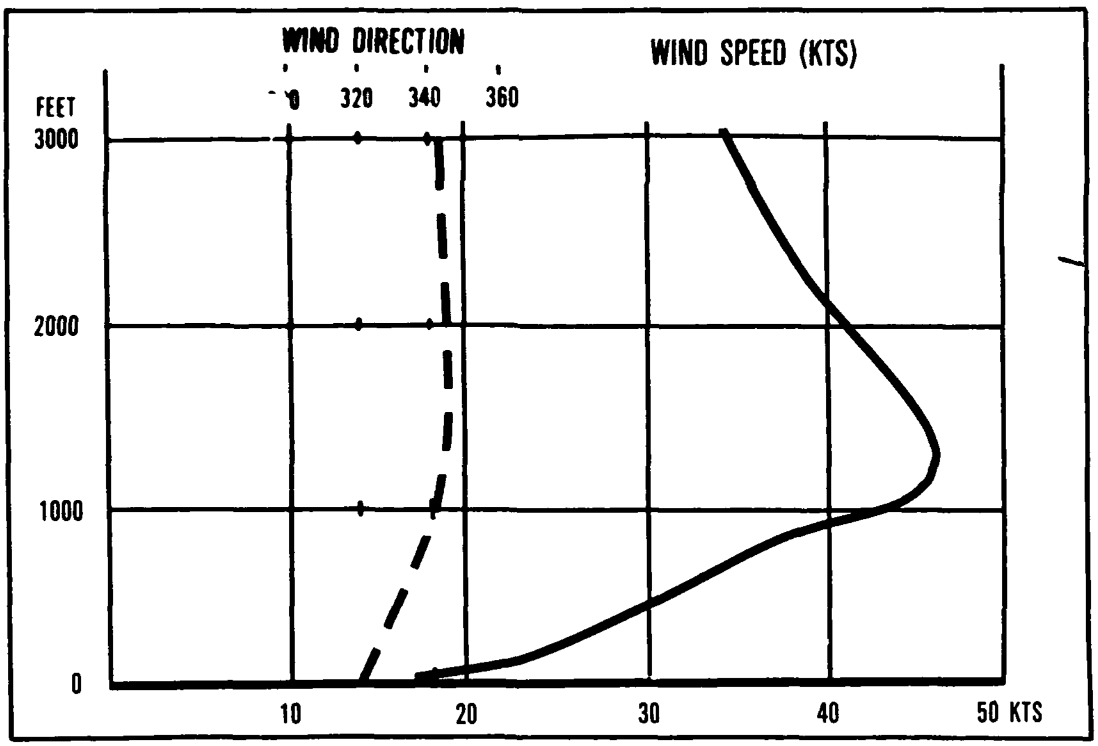

Figure 33. Low-Level Wind Profile Over Bahrain.

Extremely dry soil. Winds above 15 knots pick up dry soil particles to form the ever-present suspended dust that is a characteristic feature of this region during the entire Southwest Monsoon. Winds above 25 knots pick up the heavier sand particles.

Dust Devils. These vortex phenomena occur over land areas throughout the Persian Gulf region. The strongest occur along coast lines in the vicinity of sea breeze "fronts." During late morning and afternoon, rising thermals in the hot air just inland of advancing sea breezes are reinforced and twisted by the moist, cooler air of sea breezes. The resulting dust devils rise to heights of over 330 feet (100 meters). They can be advected inland several miles along the sea breeze "front" before dissipating. Extensive damage has been reported.

TYPICAL WEATHER. The following weather conditions may be expected in the immediate Persian Gulf area during the Southwest Monsoon:

General Sensible Weather over the Persian Gulf and the Arabian Peninsula normally consists of high clouds. Patchy low stratus will form along and just west of the Arabian coast from Dhahran southeastward in late evening. Stratus forms due to a complex combination of land breeze, sea breeze, and summer Shamal strength. The "Terminal Forecast Reference Notebook for Dhahran, Saudi Arabia," contains an excellent discussion of the subject. Similar conditions have been noted by forecasters at Doha, Dubai, and Abu Dhabi. Visibilities throughout the region during June and early July average from 3 to 5 miles in suspended dust. Visibilities after mid-July normally improve to 3 to 7 miles, still in suspended dust.

Sky Cover. Upper-air troughs early in the season produce patchy layered middle and high clouds in which light icing is found. Bases average from 14,000 to 16,000 feet (4.3 to 4.9 km). Very rare thunderstorms may form along the trough axis; tops may reach 45,000 feet (13.7 km).

Dust. *The major Southwest Monsoon weather hazard throughout the Persian Gulf region is the suspended dust and sand raised by the strong northwesterly low-level winds of the "Summer Shamal."* Suspended dust in the atmosphere here restricts visibility to 3 to 5 miles. The tops of this persistent dust layer are between 13,000 feet (3.9km) and 16,500 feet (5.1km) MSL. Visibility in the dust varies as a function of low-level wind speed: the stronger the wind, the lower the visibility. Much of the dust has been picked up from the Iraqi deserts to the southwest and west of Basrah. Critical wind speed for lifting the dust into the atmosphere is about 15 knots--a condition that is nearly constant during June and July. The critical speed is raised to 20 knots after showers, but heavy vehicular traffic lowers it to 10 knots.

Considerably lower visibilities--sometimes near zero--can occur throughout the season as a result of stronger sustained winds caused by shear lines embedded in the westerlies that penetrate into southern Iraq and/or extreme northern Saudi Arabia. These conditions are most common in June and early July and are surface reflections of the weak upper-level troughs that produce the rare thunderstorms to be discussed later. Winds behind these shear lines can exceed 30 knots; peak winds of 35 to 45 knots have been recorded as far west as Riyadh and as far south as Dubai. Such winds generate a "haboob" type wall of dust. Tops of the dust wall have been reported as high as 19,000 to 20,000 feet MSL. In such cases, "clearing" can be said to have occurred once winds drop below 15 knots and visibility returns to the "normal" 3 to 5 miles.

Sustained occurrences of very low visibility are tied to the existence of an Omega block over northern Europe, and the resulting depression of the westerlies to the latitude of the southern Mediterranean. Bahrain visibility distributions (shown in Figures 34 and 35) are representative of normal conditions along the Arabian Persian Gulf coast.

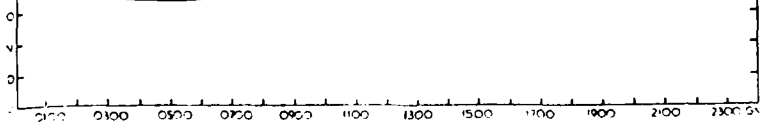

Figure 34. Percentage Frequencies of Visibilities ≤ 3NM, Bahrain.

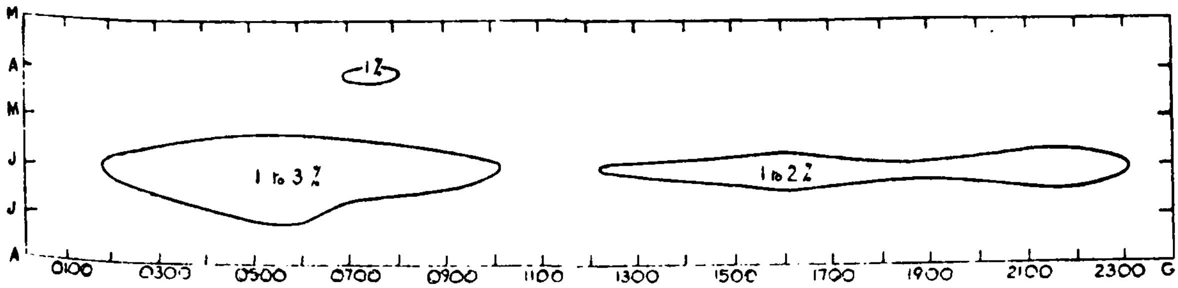

Figure 35. Percentage Frequencies of Visibilities ≤ 1100 Yards, Bahrain.

Winds over the northwestern half of the Gulf are sustained northwesterly at 10 to 20 knots with much higher gusts, all reflecting the "Summer Shamal." A low-level jet (LLJ) along the Arabian Persian Gulf shore from about 75 miles southeast of Kuwait to 100 miles southeast of Doha is a common occurrence. The changing terrain orientation between Doha and Abu Dhabi results in weakening of conditions favorable for LLJ formation. Wind speeds within the LLJ can exceed 50 knots; altitudes of the strongest wind speed cores are between 800 and 1,500 feet (245 and 460m) MSL. Average surface speeds are 15 to 20 knots. Winds in the southeastern half of the Persian Gulf reflect both the circulation around the southern end of the leeside-induced mesolow and the west-to-east orientation of the mountains on the Iranian shore. The south-to-north alignment of the mountains on the Omani Peninsula of the Arabian coast combine with these other features to "turn" the prevailing winds--first westerly, then southwesterly, finally southerly--as one approaches the Strait of Hormuz from the west. Land and sea breeze circulations , of course, modify this pattern, which can only be overcome by a strong "Shamal." Even under these conditions, winds over water and along the Persian Gulf coast of the Omani Peninsula will *back* only as far as westerly. Average speeds over the Iranian side range from 10 to 15 knots, or 5 to 15 knots lower than on the Saudi Arabian shore. The higher speeds on the Arabian-Omani side are not surprising; this is the region of tighter mesoscale gradient in phase with the prevailing macroscale northwesterly flow.

Thunderstorms. The extreme northern portions of the Persian Gulf (including Riyadh, Kuwait, and Basrah, as well as the area of the Zagros mountains southward to Bushehr) will experience a rare mid-level thunderstorm associated with weak troughs in the westerlies. These are most common during June and July; all are associated with troughs in an enhanced and southward-depressed high-speed current in the mid-latitude westerlies. These thunderstorms are similar to those in the southwestern United States; bases are high (above 8,000 feet--2,500 meters), with virga and associated downburst phenomena.

Isolated thunderstorms can form over the southern Zagros Mountains along and inland of the Iranian coast. This activity results from an increase in low-level moisture from either of several rare sources. These sources include: enhancement of the persistent easterly and southeasterly mid-level flow around the upper air Iranian anticyclone; a Bay of Bengal monsoon depression that maintains itself westward into the northwestern Arabian Sea; and a northwestward movement of the Monsoon Trough/ITCZ. The latter allows southwest monsoon moisture to feed northward (or even northwestward) into the Zagros. Intense summer heating provides the necessary trigger in all these cases.

Precipitation reaching the ground, except from very isolated showers over the Zagros Mountains, is nil. Even with the rare thunderstorm, much, if not all, precipitation evaporates before reaching the ground.

Air Temperature. Daytime maximum temperatures along the immediate coast average between 105 and 111°F (40 to 44°C). *Inland*, temperatures rise to 115 to 120°F (45 to 50°C). Minimum temperatures along the coast fall to 75 to 79°F (23-26°C). Despite high Persian Gulf water temperatures, dew points along even the immediate northern coastline range from 56°F (13°C) in June to 66°F (18°C) in September. The southern Arabian coast has marginally higher dewpoints because of flow off the water, but they drop rapidly as one moves inland. Riyadh averages a 35°F (3°C) dew point through the summer, with correspondingly lower minimum temperatures. Beyond 20 to 30 miles inland, minimum temperatures drop to 75 to 85°F (24 to 29°C).

SEA SURFACE CONDITIONS, Persian Gulf.

Water currents generally circulate counter-clockwise. As mentioned earlier, shallow water in the gulf is due to evaporation and an almost total lack of water flowing off the land. Since the water level is lower than the Gulf of Oman, a steady flow of surface water enters the Persian Gulf through the Strait of Hormuz. This surface current flows west, then northwest, as it hugs the Iranian shore. At the northern end of the Gulf, it turns to the southeast and parallels the Arabian coast. Finally, it turns north along the Omani Peninsula to join fresh Gulf of Oman water entering through the Strait of Hormuz. Speeds are less than 1 knot. Maximum calculated speed for a 100-year worst case of both wind and tidal currents, was 8 knots at Jubail. As water increases in density, it sinks, turns southeastward, and flows back into the Gulf of Oman as a bottom current through the Strait of Hormuz. 85% of all wave heights average less than 6 feet. Predominant direction along the Arabian coast is, as might be expected, from 330 through 360 degrees.

Water Temperatures. The temperature of the shallow Gulf water here increases rapidly during late spring and early summer. Surface water temperature ranges from 82-85°F (27-29°C) in June to 90-92°F (42-43°C) in August before dropping to 84-87°F (29-31°C) in September. Temperatures in extremely shallow coastal waters reach 104°F (40°C) on July and August afternoons. Available temperature soundings in the western Persian Gulf show a bottom temperature of 73°F (23°C) at 195 feet (60 meters). Temperatures show a steady and gradual decrease between the surface and the bottom of about 13°F (7°C). There is no evidence of thermoclines.

MESOSCALE SYNOPTIC FEATURES. The mesoscale features that affect the Persian Gulf proper and the Gulf of Oman also affect the Strait of Hormuz; there are no known mesoscale features peculiar to the Strait itself.

TYPICAL WEATHER. The following weather conditions may be expected in the Strait of Hormuz during the Southwest Monsoon:

General Sensible Weather over the strait during the Southwest Monsoon season consists of patchy low stratus and stratocumulus occurring most frequently in late evening and early morning. Onshore cloud occurs only along the Iranian coast in the very shallow Southwest Monsoon air. Visibilities average 5 to 7 miles in dust and salt haze.

Sky Cover. During incursions ("pulses") of Southwest Monsoon air into the southern Persian Gulf, thunderstorms occur along the mountains on both the Iranian and Omani shores. Bases range from 2,000 to 3,000 feet (610 to 915 m); tops reach above 45,000 feet (13.7 km). British meteorologists stationed at Abu Dhabi and Dubai have reported seeing these thunderstorms over the Omani mountains. Unconfirmed reports have been received of mountain flash floods during such "pulses."

Dust is advected into the Strait of Hormuz from the Persian Gulf. During strong "Summer Shamals" in the Gulf, visibilities may drop to less than 3 miles in the Strait. Visibilities below 1 mile--though rare--have occurred, almost always associated with near zero visibilities in the southern Persian Gulf caused by extremely strong "Summer Shamals."

Winds reflect a combination of weak inflow from the Gulf of Oman, pronounced land-sea breezes (especially along the Iranian shore), and a general easterly to southeasterly flow around the southern end of the induced leeside Gulf low. Complicating this pattern is the venturi effect through the narrowest part of the Strait. Precise data for the Strait itself is not available, but it appears that wind speeds here are directly related to "Summer Shamal" strength over the central and northern Persian Gulf. In the absence of a well-developed Shamal, winds along the north shore of the Strait are northeasterly to easterly during the night and early morning, and southerly to westerly during late morning and afternoon. Along the southern shore, "normal" winds are southwesterly to westerly east of the Strait during the night and early morning, and southeasterly to southerly west of the Strait. In late mornings and afternoons, strong southwesterly to west-northwesterly sea breezes blow along the Omani shore west of the Strait and northerly to northeasterly east of the Strait.

Thunderstorms. Isolated thunderstorms occur over the interior Zagros mountains; they are very rarely found in late afternoon over the higher Omani ranges. None have actually occurred over weather reporting stations. Bases are estimated at 4,000 to 5,000 feet (1,200 to 1,500m) MSL; tops at 40,000 to 45,000 feet (12.2 to 13.7 km).

Precipitation is confined to the rare thunderstorm. No statistics are available, but rainfall amounts of 0.5 to 1 inch (12 to 25mm) in the higher mountains are probable. Heavier amounts have caused flash floods.

Air Temperatures. Maximum temperatures along the immediate shore on either side of the Strait average from 90 to 95°F (32 to 35°C). Minimums average from 80 to 82°F (26 to 27°C). Temperatures inland are modified by increased elevation and the diminishing sea breeze.

SEA SURFACE CONDITIONS, Strait of Hormuz.

Water currents through the Strait consists of a tidal ebb and flood. During ebb conditions, currents of less than 1 knot flow from the Persian Gulf through the Strait into the Gulf of Oman. During flood tide, currents of less than 1 knot flow from the Gulf of Oman through the Strait into the Persian Gulf. Wave heights average less than 2 feet (0.6m).

Water temperatures are similar to those found in the Persian Gulf. They increase from 85-86°F (29-30°C) in June to 90-91°F (32-33°C) in July and August. Temperatures fall to 86-87°F (30-31°C) in September.

MESOSCALE SYNOPTIC FEATURES.

The Gulf of Oman low is a result of:

Terrain features and coastline orientation of both the Iranian and the Omani shores

The position of the Monsoon Trough/ITCZ along the Omani mountains-Strait of Hormuz

The cyclonic eddy from the main Southwest Monsoon current. This eddy effect is similar to the one found in summer along the California coast from Santa Barbara west to Point Conception.

TYPICAL WEATHER. Typical weather conditions in and near the Gulf of Oman during the Southwest Monsoon are:

General Sensible Weather over the Iranian coast and the open waters of the Gulf consists of patchy low clouds with bases from 1,000 to 1,500 feet (305 to 460 m) and tops of 2,500 to 3,500 feet (760 to 1,070 m). From early through late morning, ceilings of 800-1,200 feet are common along the immediate coast and just inland. Visibilities along the shore range from 5 to 7 miles, but over open water, from 7 to 10 miles. Salt haze and dust are the main restrictions. The Omani Coast normally has clear skies, with visibilities ranging from 6 to 10 miles in dust and suspended salt haze. Patchy low clouds form over the immediate coasts just after dawn about a third of the time, but skies clear rapidly with morning heating.

Sky Cover. Under the effects of a Southwest Monsoon "onset vortex" or tropical storm, the usual multilayered low, middle, and high clouds are found over an area within 300 miles of the storm track or landfall. But, as has already been discussed under "Transitory Synoptic Features," these storms rarely enter the Gulf of Oman or make landfall on either shore. The rare occurrence here is in June or early July, but one was observed in August.

Dust. Dust and salt haze are normally present here, restricting visibility to 5 to 10 miles. Lower visibilities are only found during a strong "Summer Shamal." Dust raised by the Shamal has been observed on satellite imagery as far east as the central Gulf of Oman. Lowest known visibilities (in extreme cases) were observed as less than 3 miles, but then only briefly.

Winds. A complex wind pattern results from the interaction of the Gulf of Oman low and the pronounced land-sea breeze. Iranian shore winds are east-southeasterly at 9 knots in July and August. The normal land breeze is reinforced by the "fall wind" effect of the high mountains that back the immediate coast. Winds on the coast closer to the Strait of Hormuz show a marked land-sea breeze circulation. Macroscale gradients immediately southeast of the Strait of Hormuz are extremely weak. As a result, night and early morning winds are southwesterly to westerly at 4 to 6 knots; late morning, afternoon, and early evening winds are east-northeasterly to easterly at 8 to 12 knots. Over the Gulf of Oman itself, winds turn southeasterly and increase in speed markedly during daylight hours as the Strait of Hormuz is approached. Night winds along the Iranian shore east of the Strait and over the northern Gulf of Oman tend to be variable due to the opposing influences of the land (mountain) breeze and the gradient winds. Average wind speeds increase from less than 8 knots just east of the Strait of Hormuz to 13-14 knots as the Arabian Sea is reached. Surface winds over the southern half of the Gulf of Oman and on the Omani coast are westerly to west-southwesterly (downslope) at 4 to 8 knots at night. The sea breeze establishes shortly after 0900L and persists through 1900L. This onshore flow is northeasterly to easterly and reaches peak speeds of 15-20 knots in late afternoon.

Thunderstorms are normally only found in the higher mountains on both the Iranian and the Omani coasts; these very isolated storms have the usual high bases. On rare occasions, there is widespread thunderstorm activity (with low cloud bases and heavy rainshowers) over the northern Omani mountains and the Zagros ranges immediately north of the Iranian coast as far northwest as Bandar-e-Lengeh. This activity is caused by a rare strong pulse in the southwest monsoon that combines with the approach of a weak upper-air trough over the Persian Gulf. This combination advects low-level monsoon air from over the Gulf of Oman and the Strait of Hormuz into the extreme southeastern Persian Gulf.

Precipitation. The only precipitation of any significance is from the rare tropical disturbance strong enough to make it to the coast. The precipitation can be heavy--a bit less than 15 inches (380mm) was recorded in one storm that made landfall. Extensive flash flooding has also been reported.

Air Temperatures. Along the Iranian coast and over the Gulf of Oman, maximum temperatures range from 92°F (33°C) in June to 88°F (31°C) in September. Dew points drop from 78°F (25°C) in June to 73°F (22°C) in September. Along the Omani coast, maximum temperatures in July and August are 95 and 91°F (35 and 33°C); dew points average 70 to 75°F (21 to 23°C).

SEA SURFACE CONDITIONS, Gulf of Oman.

Water currents in the Gulf of Oman maintain a cyclonic gyre, reflecting the low-level wind pattern. Speed averages 1 knot. Wave heights average 4 to 6 feet.

Water temperatures decrease from 86°F to 90°F (30 to 32°C) at the Strait of Hormuz to 82-84°F (27-29°C) at the eastern end of the Gulf of Oman.

MESOSCALE SYNOPTIC FEATURES. None have a direct and specific affect on the Omani Arabian Sea coast.

TYPICAL WEATHER. The following conditions are to be expected in the Omani Arabian Sea Coast during the Southwest Monsoon:

General Sensible Weather. Extensive night and morning low clouds (bases from 600 to 1,500 feet, tops between 3,000 and 4,500 feet) increase rapidly after mid-June along the coast and inland about 50 miles. Seaward extent is beyond 100 miles from the shore. These clouds occur after the full onset of the Southwest Monsoon and establishment of the Monsoon Trough/ITCZ inland of the Omani Arabian Sea coast. Low cloud occurrence decreases rapidly after mid-September as the Southwest Monsoon weakens and the Monsoon Trough/ITCZ shifts south. The greatest occurrence of low cloud is on the southwestern part of the Omani coast proper during July and August nearest those regions of the Arabian Sea with the strongest upwelling, or approximately abeam Salalah. Here, stratus ceilings lift from 600 to 1,000 feet (180 to 300m) before dawn to become 2,000 to 3,000 feet (610 to 915m) by mid-afternoon. Low ceilings persist over the coldest water offshore for a distance of 50 to 75 miles from the coast. Drizzle in the predawn hours occurs nearly half the time. Low cloud ceilings decrease rapidly the closer one gets to Ras al'Hadd, due to decreased upwelling; low clouds dissipate onshore after 0900L. Skies are nearly cloudless beyond 50 miles inland.

Sky Cover. Pulses in the southwest monsoon temporarily deepen the maritime moist layer. Under these conditions, maritime air forced onshore can result in isolated thunderstorms, layered clouds, and low ceilings over the main Omani mountain range that leads toward the Strait of Hormuz. These late afternoon and early evening summer thunderstorms over the mountains southwest of Abu Dabi and Dubai have been observed by British meteorologists at both stations and are not unusual.

Dust. Blowing dust is common along the northeastern coast. Strong Southwest Monsoon winds pick up enough dust and sand to reduce visibilities to less than 3 miles on 1 day out of 3. Weather observations over the interior of this region are not available, but suspended dust that restricts visibility to 7 to 10 miles has been reported by oil company exploratory teams.

Winds beneath coastal stratus and stratocumulus decks average 10 to 15 knots, with higher gusts. After clearing, speeds increase to 15 to 25 knots, with higher gusts. Overwater winds beyond 25 to 30 miles offshore average 20 to 30 knots, with some gusts above 30 knots

Thunderstorms occur over the interior Omani mountain ranges in the northeast and the southwest, but they are primarily confined to those rare occasions when pulses in the southwest monsoon current are strong enough to force moist tropical air inland to the mountains.

Precipitation along the coast and offshore is confined to drizzle underneath stratocumulus decks. Amounts are less than 0.05 inches (1mm) Weather records for the interior are not available, but reports of rare flash floods suggest that precipitation there can be heavy.

Air Temperatures. There is a distinct moderation in temperature. The highest temperatures occur in May and June before the onset of the stratus season (July through early September). Although Salalah (17°N, 54°E) is outside the area of this study, its temperatures are representative of those in the Omani-Arabian seacoast's "stratus area." Salalah's maximum temperatures in July and August average 81-82°F (27°C); minimums average 74-75°F (23°C). Masirah (20°41'N, 58°53'E), 100 miles southwest of Ras al Hadd, has a much lower low cloud frequency, with resulting higher temperatures; maximum temperatures average 86-88°F (30-31°C) in July and August. Thumrait (17°40'N, 54°02'E) can be considered representative of inland areas even though it is southwest of the study region. Maximum temperatures here average between 104°F (37°C) in June and 95°F (33°C) in July.

SEA SURFACE CONDITIONS, Northwestern Arabian Sea.

Water currents are southwesterly at 5 to 10 knots. Highest current speeds are about 60 miles offshore.

Water temperatures in June, before full onset of the Southwest Monsoon, average between 80 to 82°F (27°C). By late June, upwelling in response to the Southwest Monsoon has dropped temperatures markedly. During July and August, surface water temperatures average 77 to 78°F (24 to 25°C) at Ras 'al Hadd. They decrease dramatically to 68 to 70°F (20 to 21°C) at the intersection of the coast and 20°N. Water temperatures at Salalah are even lower--about 65°F (near 18°C). The coldest water throughout this portion of the Arabian Sea is immediately offshore.

Chapter 7

THE FALL TRANSITION

(October--November)

MAJOR CLIMATIC CONTROLS

FLOW PATTERN REVERSAL. Like spring, The Fall Transition is a period of major synoptic pattern reversal. Although the complete transition averages 30 to 45 days, actual onset and ending vary by station location and from one year to the next. The change can be very rapid. See Chapter 3.

WEAK LOW-LEVEL CONTINENTAL ANTICYCLONES replace the massive heat lows of the Southwest Monsoon. Surface high pressure centers are typically located in southern Saudi Arabia, central Iran and northern Africa.

STRONG UPPER-LEVEL WESTERLIES delineate the northern extent of the Subtropical Ridge centered near 15°N. Core speeds between 30,000 and 40,000 feet range from 60 to 75 knots. The subtropical jet is now centered just south of the Himalayas over India. Variation in this upper-level flow comes from the infrequent appearance of the Polar Jet. Jet maxima of 40 to 60 knots will move southeastward with a cyclonic disturbance from the Mediterranean.

MEDITERRANEAN CYCLONES and their associated cold fronts begin to penetrate into the Persian Gulf by mid-November as the Mediterranean storm track begins to reestablish itself.

A WEAK MID-LEVEL TROUGH in the northern Red Sea area acts as a steering mechanism and helps to shift Mediterranean cyclones into the Persian Gulf. The trough becomes a persistent mid-level feature throughout the winter months.

THE MONSOON TROUGH/INTERTROPICAL CONVERGENCE ZONE (ITCZ) retreats southward from the extreme southeastern part of the Arabian peninsula and the Arabian Sea coast of Iran and becomes oriented east-northeast to west-southwest near the equator.

TROPICAL CYCLONES can form in the Monsoon Trough/ITCZ while it is still north of 10°N. These rarely effect the Persian Gulf region, averaging only one occurrence every 10 years. The primary area affected is the Gulf of Oman and immediate coastlines. These storms bring multilayered clouds, poor visibilities, heavy rain, and embedded thunderstorms. Turbulence over coastal mountains is intensified. Flash floods are possible. Figure 36 shows mean tropical storm tracks for October and November.

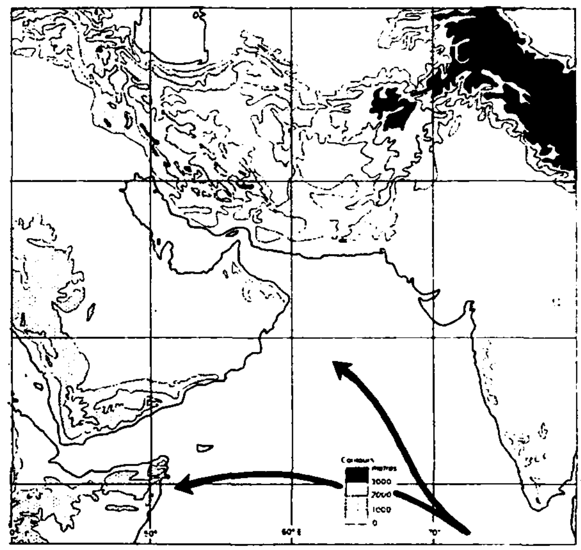

Figure 36. ***Mean Tropical Storm Tracks--October and November Combined.***

SEMIPERMANENT SUDAN LOW. Late in the Fall Transition, this low acts as a source region for cyclogenesis associated with upper-level troughs in the westerlies. As these troughs move southeastward from the Mediterranean, they may trigger a transient low center that moves east-northeastward into the northern Arabian Peninsula.

MEAN OCTOBER FLOW at 850, 700, 500, 300, and 200 mb, (5,000, 10,000, 18,000, 30,000, and 39,000 feet) are shown in Figures 37, 38, 39, 40, and 41.

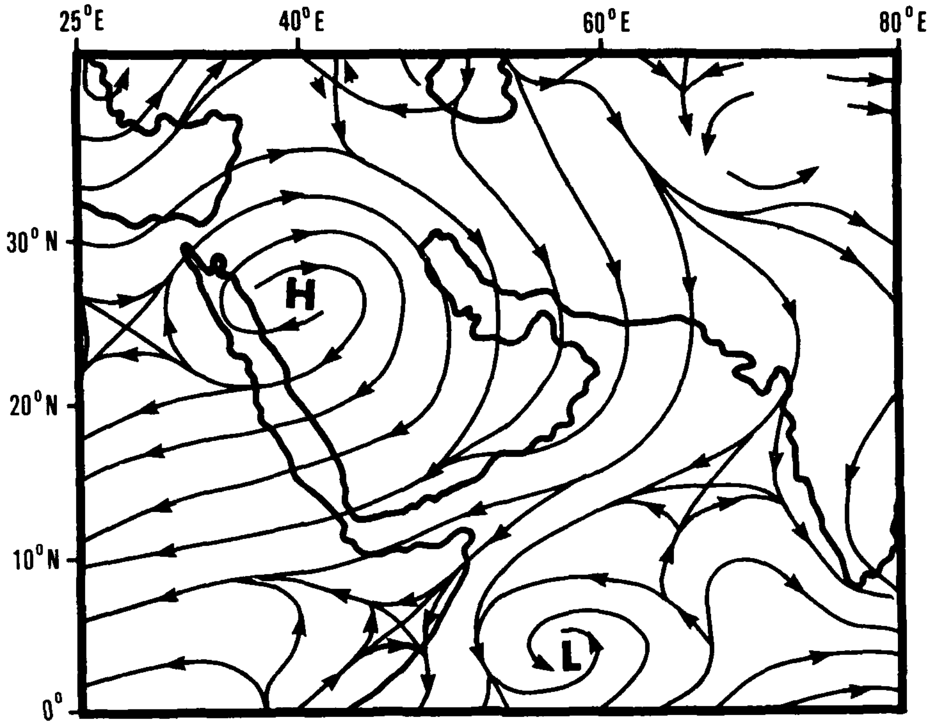

Figure 37. Mean October 850mb Flow.

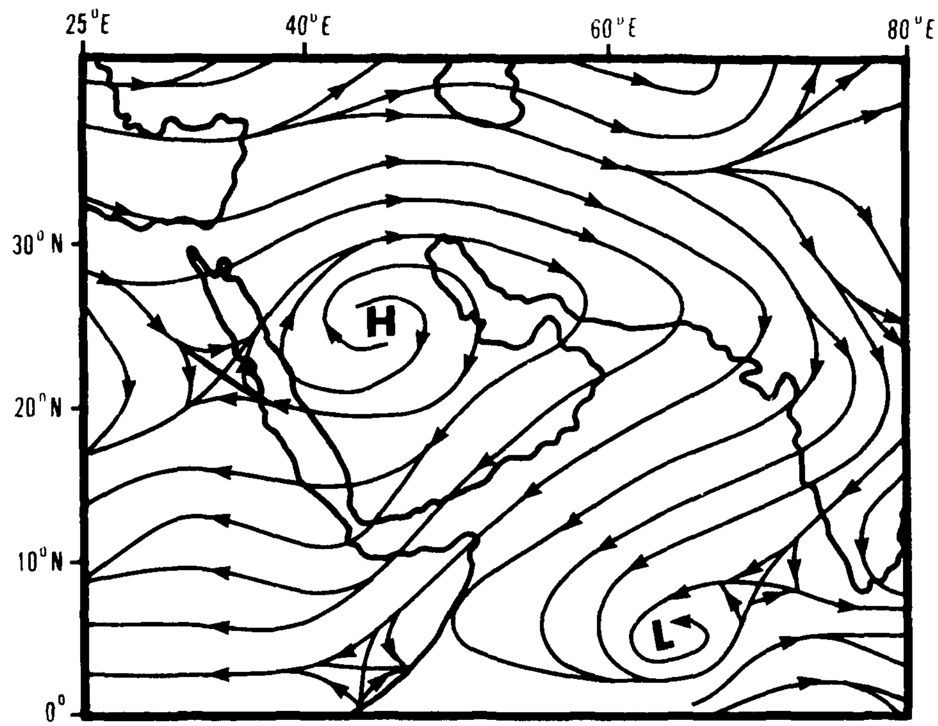

Figure 38. Mean October 700mb Flow.

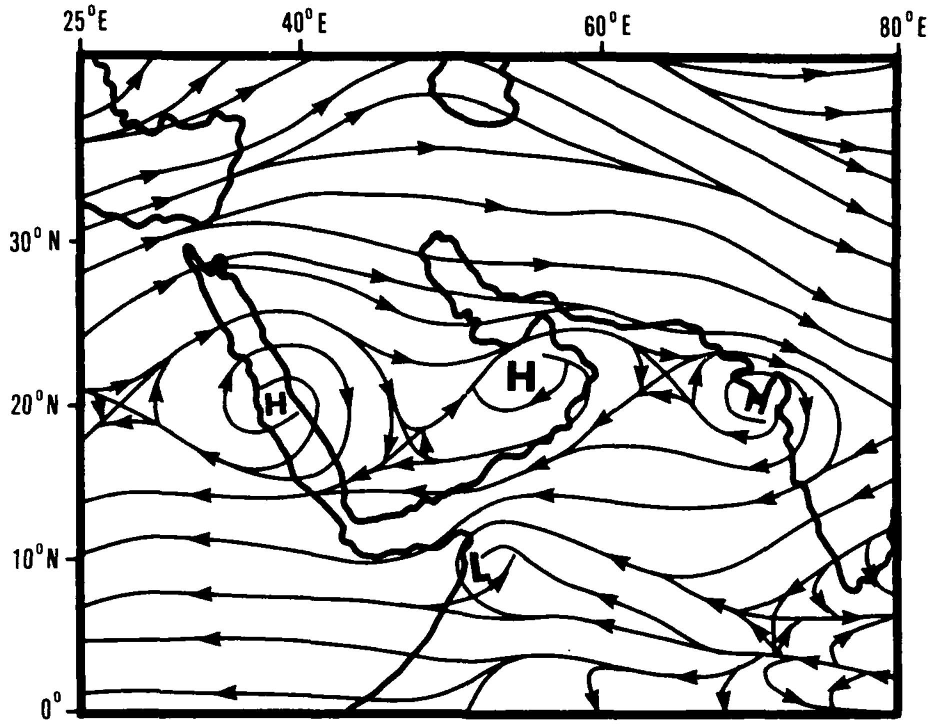

Figure 39. Mean October 500mb Flow.

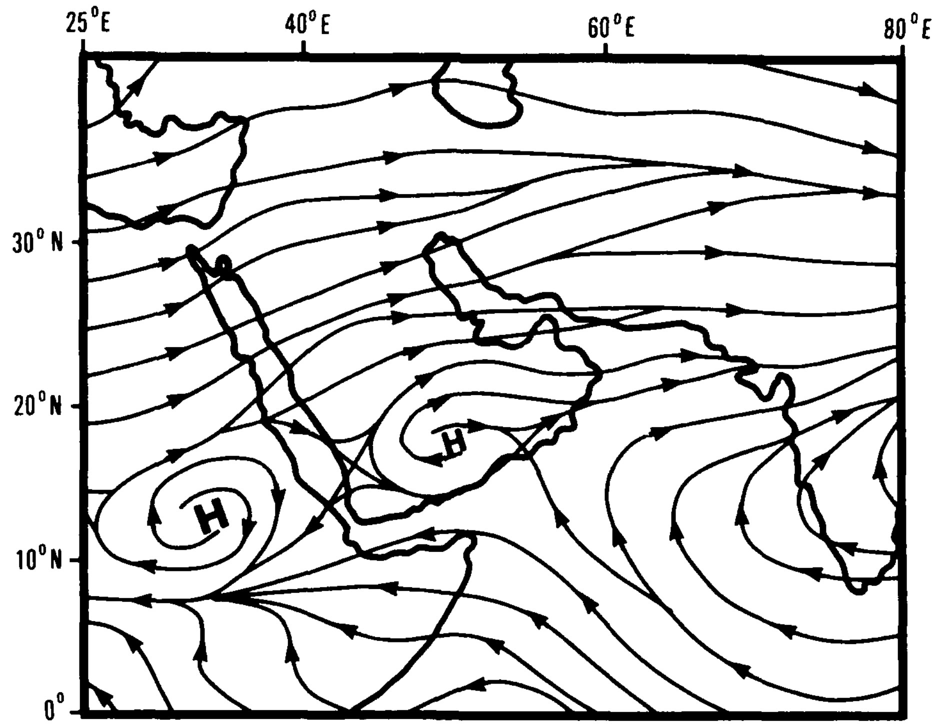

Figure 40. Mean October 300mb Flow.

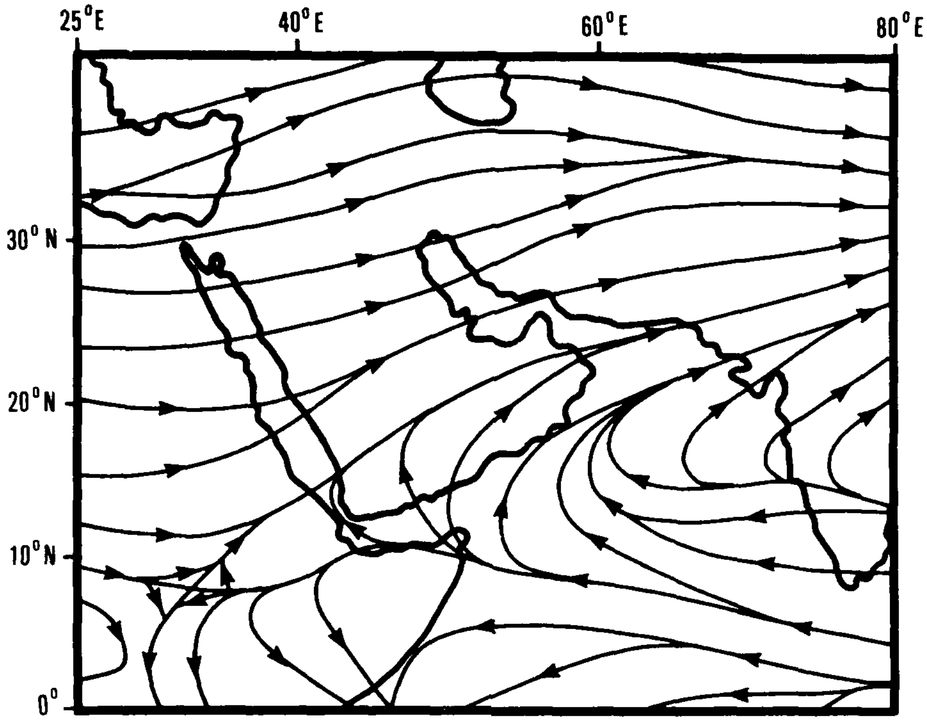

Figure 41. Mean October 200mb Flow.

WEAK UPPER-LEVEL TROUGHS in the westerlies normally begin penetrating southward through the Persian Gulf Region by mid-November, often accompanied by typical surface pressure and frontal systems. Associated weather includes sand and dust storms, squall lines, and thunderstorms throughout most of the region. At least one severe squall line can be expected to move southeastward down the Persian Gulf during this period.

"WINTER SHAMALS" are strong northerly or northwesterly winds that can begin in mid-November. This phenomenon is often the result of intensification of a cyclone (or "low") moving east-southeastward out of the eastern Mediterranean into Syria. As the upper-level trough moves into the Arabian Peninsula it may trigger a secondary transient low in Sudan. This combination often results in cyclogenesis and frontogenesis in the Arabian Peninsula. The secondary low becomes the dominant pressure center and tightens the pressure gradient in the Persian Gulf. Cold air advection over the mountains of Turkey and Iran can drive the cold front as far south as the northern Arabian Sea. The rate of progress of the Winter Shamal is directly dependent on the movement of the upper-level trough. Typically these early Shamals last 24 to 36 hours. However, if the upper-level trough stalls near the Strait of Hormuz (due to a strengthening ridge east or another low forming to the west), the Shamal may last from 3 to 5 days. For a more detailed discussion, see Chapter 4, The Northeast Monsoon.

MESOSCALE SYNOPTIC FEATURES. Land-sea breezes become increasingly important as they become the predominant feature along coastlines during undisturbed ("normal") conditions. Gradient wind direction and speed are often greatly modified by land-sea breezes. The effects are greatest near coastlines with steep terrain gradients.

TYPICAL WEATHER. The following weather conditions may be expected in the Persian Gulf and its adjacent land areas:

General Sensible Weather. Patchy high clouds (mean coverage 1/8) and unrestricted visibilties become the rule.

Sky Cover. The only cloud cover of significance is that caused by low pressure systems or the interaction of Subtropical and Polar jet streams. The lows move into the area from eastern Europe or the Mediterranean. Clouds are usually middle and high; scattered areas of 2,000-3,000ft (610-915m) ceilings and rain-showers occur in the southwesterly flow ahead of the low. Isolated 1,500ft (460m) ceilings occur with rain squalls and thunderstorms in the immediate vicinity of the low and its cold front. Such systems are relatively weak, affecting area weather for 24-36 hours. The Subtropical and Polar jet streams interaction over the Arabian Peninsula often results in two distinct cirrus bands that are easily discernible on satellite imagery. One band curves cyclonically with the Polar Jet; the other turns slightly anticyclonically with the Subtropical Jet. Strong wind shear near the jet maxima are likely to produce complicated vertical and horizontal turbulence patterns. Terrain features can further compound turbulence patterns.

Dust. Blowing dust and sand frequencies decrease sharply as the season progresses. Average visibilities rise dramatically to above 7 miles. The northwestern shore of the Persian Gulf maintains a higher incidence of blowing dust and sand until the first significant rain because of the extreme dryness of its very fine soil. The occurrence of blowing dust and sand is tied to strong convective activity associated with increasing numbers of cold fronts passing through the area.

Winds remain northwesterly, but speeds decrease. Winds back from the northwest to the southwest ahead of troughs or cold fronts moving into the region from Iraq. Winds turn westerly, then southerly, as one approaches the Strait of Hormuz. Speeds are stronger on the Arabian side of the Gulf (10-15 knots); the Iranian coast averages 5-10 knots. The 24- to 36-hour sustained high surface winds characteristic of "Winter Shamals" begin in November. Large pressure gradients develop behind cold fronts due to upper-level subsidence that rapidly builds surface high pressure over western Saudi Arabia and Iraq. The strong northwesterly low-level winds are then quickly reinforced by northwesterly upper-level winds behind the upper-level trough. The associated upper-air troughs are almost always rapidly moving short waves during this transition; surface winds die after 24 to 36 hours. Speeds in such cases typically reach 30 to 40 knots. For a more detailed discussion, see "Winter Shamals" in Chapter 4, "The Northeast Monsoon."

Thunderstorms. Thunderstorms occur along and ahead of cold fronts moving southeastward down the Gulf. Severe thunderstorms occasionally occur with cold fronts or squall lines. The main area affected is the central and southern Gulf and its immediate coastlines. Thunderstorm winds above 50 knots have been recorded in the United Arab Emirates. Although surface hail has not been reported over the Gulf or along its immediate coasts, it has been reported with such storms over the Omani and Zagros Mountains.

Precipitation shows a dramatic increase in this area as the season progresses. The Siberian High strengthens as the upper-level westerlies build; this combination shifts a storm track southward into the Persian Gulf. Average amounts of less than 0.25 inch (6mm) increase to between 0.75 and 1.00 inches (19 and 25mm) by November. Most of the increased precipitation falls over the Zagros Mountains.

Air Temperatures drop significantly. Daytime maximum temperatures along the immediate coast cool to between 85 and 95°F (29 and 35°C). Inland, temperatures decrease even more due to the significant loss of solar insolation and the strengthening of continental anticyclones. The Zagros Mountains bear the brunt of these changes; maximum temperatures there fall to less than 80°F (27°C) near Shiraz and Jahram. Minimum coastline temperatures average 55 to 65°F (13 and 18°C) Inland temperatures can fall to below 45°F (7°C), again at Shiraz and Jahram. Dewpoints on both coasts of the Persian Gulf drop to between 45 and 55°F (7 and 13°C) during this period. Inland, dewpoints fall to between 35 and 45°F (2 and 7°C).

SEA SURFACE CONDITIONS, Persian Gulf.

Water currents show a general counter-clockwise circulation. Shallow water levels are due to evaporation and an almost total lack of water flowing off the land into the Persian Gulf, which is lower than the Gulf of Oman. Consequently, a steady flow of surface water enters the Persian Gulf through the Strait of Hormuz. This surface current flows toward the west and then northwest as it hugs the Iranian shore. At the northern end of the Gulf, it turns southeasterly to parallel the Arabian coast. Finally, it turns northerly along the Omani Peninsula to join fresh Gulf of Oman water entering through the Strait of Hormuz. Speed is less than 1 knot. Maximum calculated speed for a 100-year worst case of both wind and tidal currents was 8 knots at Jubail. As water increases in density, it sinks, turns southeastward, and flows back into the Gulf of Oman as a bottom current through the Strait of Hormuz.

Water Temperatures. By November, water temperatures range from 80 to 82°F (27 and 28°C). They are actually a few degrees higher than the mean air temperature. Water temperature soundings show a temperature decrease of 10 to 15°F (6 to 9°C) in the upper 195 feet (60 m) of the Gulf.

MESOSCALE SYNOPTIC CONTROLS. Land-sea breezes are increasingly important here as they become the predominant feature along coastlines during undisturbed ("normal") conditions. Gradient wind direction and speed are often greatly modified by the addition of land-sea breezes. These effects are greatest near coastlines with steep terrain gradients.

TYPICAL WEATHER. The following weather conditions are to be expected in the Strait of Hormuz during the Fall Transition:

General Sensible Weather during normal conditions is similar to that of the Southwest Monsoon. Patchy early morning low stratus and stratocumulus ceilings decrease on the southern coast; percent frequencies drop from 15-20% in August to less than 5% by late October. The northern coast still sees upslope conditions due to the mountains immediately inland; frequencies decrease more slowly. For example, at Bandar Abbass, Iran, ceiling frequency continues to average 15-20% during October, but drops to near 10% in November. Visibilities, except with thunderstorms and precipitation, are excellent.

Sky Cover. Middle and high cloud ceilings occur ahead of and during the passage of low pressure centers. Ceilings of 2-3,000 feet (610 to 915m) and visibilities of 3-5 miles (5-8km) in rain showers are confined to the immediate vicinity of the low.

Dust. Blowing dust or sand virtually disappears after the first rains of the season. The rare blowing dust that is seen has been advected from the Persian Gulf.

Winds, except during low pressure center passages, resemble those found in the Southwest Monsoon. This flow results from a combination of weak inflow from the Gulf of Oman and pronounced land-sea breezes, especially along the Iranian shore. The venturi effect through the narrow part of the Strait increases wind speeds at that point. Strongest winds continue to be on the southern coast with speeds of 10-12 knots from the northwest. Winds on the Iranian coast, as reflected by Bandar Abbass observations, continue from the south at 7-8 knots.

Thunderstorms occur with squall lines ahead of cold fronts or with cold frontal passages. Although still rare, thunderstorm frequency increases towards the end of November as the Mediterranean storm track becomes established. Bases are between 2,000 and 3,500 feet (610 to 1,070 m); tops can reach 45,000 feet (13.8 km). Isolated thunderstorms--usually associated with squall lines--may approach, or even exceed severe limits.

Precipitation increases dramatically. Average amounts of less than 0.25 inch (6mm) increase to between 0.75 and 1.00 inches (19 and 25mm) by November. Higher amounts (up to 3 inches--75mm) occur over the Zagros Mountains, almost all associated with prefrontal and frontal showers and thunderstorms.

Air Temperatures along the immediate shore on either side of the strait average 85 to 90°F (29 and 32°C). Minimums drop to between 65 and 70°F (18 and 21°C). Temperatures inland are cooler because of increased elevation.

SEA SURFACE CONDITIONS, Strait of Hormuz.

Water currents through the Strait consist of tidal ebb and flood. During ebb conditions, currents of less than 1 knot flow predominantly from the Persian Gulf through the Strait into the Gulf of Oman. During flood tide, currents of less than 1 knot flow from the Gulf of Oman through the Strait into the Persian Gulf.

Water temperatures are similar to those found in the Persian Gulf. Sea temperatures cool from between 85 and 87°F (29 and 31°C) in October to between 81 and 82°F (27 and 28°C) in November.

MESOSCALE SYNOPTIC FEATURES. Land-sea breezes are increasingly important as they become the predominant feature along coastlines during normal conditions. Gradient wind direction and speed are often greatly modified by the addition of land-sea breezes. These effects are greatest near coastlines with steep terrain gradients.

TYPICAL WEATHER. The following weather conditions are to be expected in the Strait of Hormuz during the Fall Transition:

General Sensible Weather in this area is nearly always good. Except for wispy cirrus, skies are clear and visibilities excellent.

Sky Cover. Patchy middle and high cloud decks occur with the infrequent but increasing numbers of low pressure centers and associated fronts that move through the Persian Gulf to the Gulf of Oman near the end of November. These rare lows originate in Eastern Europe or the Mediterranean. Multilayered low, middle, and high clouds occur with the rare tropical cyclone as it moves westward out of the Arabian Sea. Occurrence of tropical cyclones in this area is less than 1% in any given year. The usual weather conditions (low ceilings and visibilities, heavy rain, and, in very rare cases, huricane force winds) may occur with these systems.

Dust is almost nonexistent until the first "Winter Shamal," in late November. Even then, visibilities normally remain above 3 miles.

Winds are predominantly land-sea breezes. The mountains that rise immediately inland of the coast on the western side of the Gulf of Oman give such winds increased strength. Mean wind speeds drop throughout the area, averaging 5 to 8 knots east of the Strait of Hormuz. Stronger winds are associated with increased pressure gradients south of a low pressure center in the Persian Gulf.

Thunderstorms are confined to passages of prefrontal squall lines and cold fronts over the higher Zagros and Omani Mountains. Isolated severe thunderstorms are possible over the latter.

Precipitation shows a dramatic increase in this area as the season progresses. Average amounts increase to between 0.75 and 1.00 inches (19-25mm) by November. Precipitation from the rare tropical storm is enhanced over the mountains inland of the coasts. Exact rainfall records are not available, but 10 to 15 inches (255 to 380mm) has been reported with spring and summer tropical storms. Rainfall over the higher mountains could be in excess of 20 inches (510mm).

Air Temperatures cool gradually, but not as rapidly as along the shores of the Persian Gulf and inland over the Arabian Peninsula and Iran. Diurnal ranges, on the other hand, increase markedly. These go from 5 to 10°F (3 to 6°C) at the end of September to 10 to 15°F (6 to 9°C) by November. Temperatures on the Iranian coast are cooler than those on the Arabian side of the Gulf of Oman due to the effects of the Zagros Mountains. Maximum temperatures are between 80 and 85°F (27 and 29°C) north and between 85 and 90°F (29 and 32°C) south. Minimum temperatures range from 70 to 75°F (21 and 24°C) north and from 75 to 80°F (24 and 27°C) south.

SEA SURFACE CONDITIONS, Gulf of Oman.

Water currents slowly reverse (from the southwesterly and westerly flow of late September to easterly by late November) and reflect the change in monsoonal flow. Speed averages 0.4 to 0.7 knot.

Water temperatures cool slowly. However, as in the Persian Gulf, mean sea surface temperatures become 1 to 2°F (0.6 to 1.2°C) warmer than mean air temperatures. Average sea temperatures cool from between 82 and 85°F (28 and 29°C) in October to between 80 and 81°F (27°C) in November.

MESOSCALE SYNOPTIC CONTROLS. Land-sea breezes are increasingly important as they become the predominant feature along coastlines during normal conditions. Gradient wind direction and speed are often greatly modified by the addition of land-sea breezes. These effects are greatest near coastlines with steep terrain gradients.

TYPICAL WEATHER. The following weather conditions are to be expected on the Omani Arabian Sea Coast during the Fall Transition:

General Sensible Weather improves dramatically. There are normally only patchy high clouds; visibilities are unrestricted.

Sky Cover rapidly becomes 1 to 2/8 cirrus and cirrostratus. Flow from the northeast causes a dramatic reduction in the upwelling of cooler waters along the Omani Coast and eliminates the stratus and stratocumulus decks characteristic of the Southwest Monsoon.

Dust ceases to be a problem as winds become northeasterly and speeds drop drastically from those of the Southwest Monsoon. The change in wind direction during this period shuts off the source of the blowing dust or sand. Occurrences at Masirah, for example, decrease from 8-12 days during September to zero by late October.

Winds along the coast and offshore reflect the strengthening of the Northeast Monsoon behind the Monsoon Trough/ITCZ. The sustained, strong southwesterlies end with the retreat of the Monsoon Trough/ITCZ southward. Behind it, winds switch to and steady at north-northeast. Speeds decrease to between 7 and 10 knots.

Thunderstorms are very rare, occurring only in the high Omani mountains in late November, and only with the passage of Mediterranean cold fronts.

Precipitation is found only in the high mountains in late November with the rare frontal thunderstorm. No rainfall data is available.

Air Temperature. With virtually clear skies, mean maximum temperatures in October rise 1 to 2°F (0.6 to 1.2°C) to 87-88°F (31°C). Conversely, October minimum temperatures cool to between 68 and 72°F (20 and 22°C). November temperatures cool still more. Maximum temperatures range from 78 to 82°F (26 and 28°C) while nights cool to 63-67°F (17-19°C).

SEA SURFACE CONDITIONS, Northwestern Arabian Sea.

Water currents remain southwesterly until onset of the full northeast monsoon. Speeds, however, decrease to 3 to 5 knots by late November. Wave heights average 3 to 5 feet.

Water temperatures rise rapidly as upwelling ceases. Mean temperatures are 81°F (27°C) by early October and remain warm through the season.

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USAFETAC, Scott AFB, IL 62225-5438..6
7WW/DN, Scott AFB, IL 62225-5008..3
6WS, Hurlburt Field, FL 32544-5000..3
15WS/DN, McGuire AFB, NJ 08641-5002...9
17WS/DN, Travis AFB, CA 94535-5000..9
JSOC/Weather, P.O. Box 70239, Fort Bragg, NC 28307-5000..1
3350 TECH TG/TTGU-W, Stop 62, Chanute AFB, IL 61868-5000...2
AFIT/CIR, Wright-Patterson AFB, OH 45433-6583..1
AFCSA/SAGW, Washington, DC 20330-5000..1
NAVOCEANCOMDET, Federal Building, Asheville, NC 28801-2723...1
NAVOCEANCOMDET, Patuxent River NAS, MD 20670-5103..1
NAVOCEANCOMFAC, NSTL, Bay St Louis, MS 39529-5002..2
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NEPRF, Monterey, CA 93943-5006...100
Naval Research Laboratory, Code 4323, Washington, DC 20375...1
Naval Postgraduate School, Chmn, Dept of Meteorology, Code 63, Monterey, CA 93943-5000...............2
Naval Postgraduate School, Henry Knox Library, Monterey, CA 93943-5000.............................1
Naval Eastern Oceanography Ctr, U117 McCAdy Bldg, Attn: Clim Section, NAS Norfolk, VA 23511-5000.....1
Naval Western Oceanography Ctr, Box 113, Attn: Tech Library, Pearl Harbor, HI 96860-5000............1
Naval Oceanography Command Ctr, COMNAVMAR Box 12, FPO San Francisco, CA 96630-5000..................1
AFGL Library, Attn: SULLR, Stop 29, Hanscom AFB, MA 01731-5000.....................................1
Atmospheric Sciences Laboratory, White Sands Missile Range, NM 88002-5501..........................1
U.S. Army Missile Command, ATTN: AMSMI-RD-TE-T, Redstone Arsenal, AL 35898-5250....................1
Technical Library, Dugway Proving Ground, Dugway, UT 84022-5000....................................1
NCDC Library (D542X2), Federal Building, Asheville, NC 28801-2723..................................1
DTIC-FDAB, Cameron Station, Alexandria, VA 22304-6145..2
75th Ranger Btn (Attn: Lt David Musick), Ft Benning GA 31905-5000..................................1
AUL/LSE, Maxwell AFB, AL 36112-5564..1
AWSTL Scott AFB, IL 62225-5438..200