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# A Dual Effect of Upwelling and Easterly Jet Stream on Desert Formation in Southern and Eastern Parts of Yemen

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## Abstract

A compound effect of both Up-welling and the Tropical Jet Stream (TEJ) are the main cause of aridity in the southern and eastern parts of Yemen. Of the most important of these factors that affect rainfall in the southern coasts of Yemen is the phenomenon of water upwelling. Such a phenomenon brings all physical, chemical and biological changes to the sea water in the area. Temperature change that affects water evaporation, is a prominent change caused by water upwelling. Tropical Jet Stream (TEJ) is also another main factor of aridity in the study area. The two phenomena work together to prevent both the Monsoon south easterly and the south westerly winds from accomplishing their function in causing rainfall in the region. The humid Monsoon Winds have been diverted to be parallel to the coast carrying out no positive effect on rainfall in the area.

Then, specification of environmental changes made by Water Upwelling, the Tropical Jet Stream (TEJ) and winds that govern the fall and variability of rain in the study area is the main theme of this paper. It is important to detect the most prominent environmental changes made by the these two phenomena, as climatic factors in the study area, on the rainfall amounts in the study area.

Intensive fieldwork was conducted to collect the necessary research data and information. Seawater and abutting air temperatures had been recorded through a year. Consequent changes in seawater currents had been also observed and recorded. At the same time, climatic data were collected with the help of qualified research assistants. The main intent of this exertion was to detect environmental changes brought by seawater Upwelling and the (TEJ). The collected data have been statistically (and others) analyzed and presented in the present form of a scientific research paper.

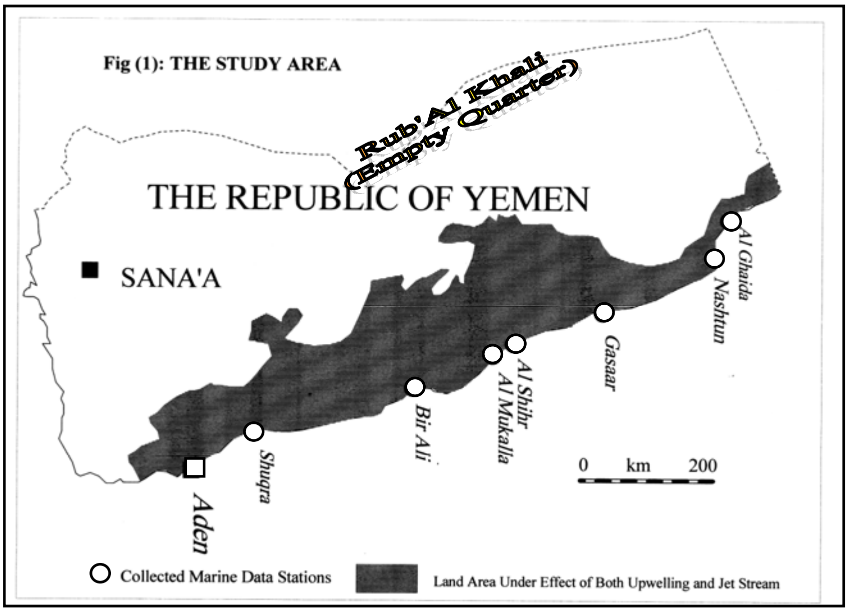
For the sake of analyzing and discussing the research problem, the paper drives through different sub-themes:

- Physical consequences that pertain to temperature variability, and its effects.
- Climatic consequences that pertain to wind movements, humidity; and others.
- Consequent Rainfall variability effect on desert formation in the Study Area.

## Introduction

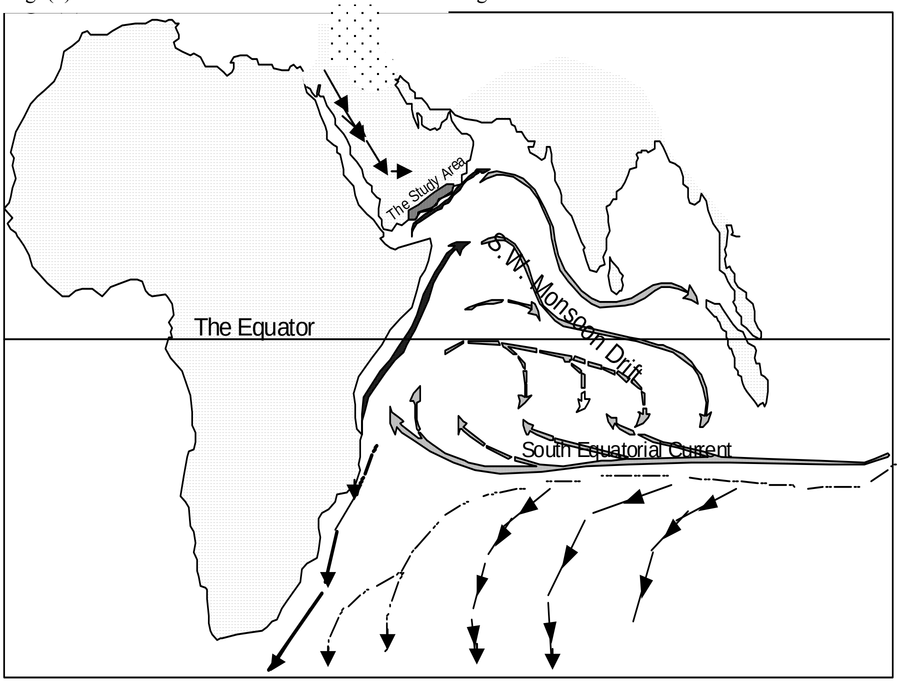
### A Setting

The phenomenon of upwelling in the study area is part of the process in different parts of the world where half of the world fish catch according to Cushing, 1992. The southern coasts of Yemen, located between longitudes 43°30’E and 52°30’E, totaling an area of 220,000 km² represents a highly arid area due to the Upwelling process and its consequences, as well as due to other factors, mainly Tropical Jet Stream (TEJ). Primarily, water upwelling is a phenomenon that coincides with ocean currents, especially warm currents. The Indian Ocean, together with the adjacent Arabian Sea, represent the arena of factors and controls of the Water upwelling phenomenon in the study area. The air circulation cells control the major vertical motion in the atmosphere. On the earth surface, the winds that cause both rains and droughts are strongly directed by Earth's rotation. This produces an easterly component to trade winds in the area. The Earth's rotation also imparts a westerly drift to the path of the surface air giving a counterclockwise circulation of depressions in the Northern Hemisphere as a whole. Depressions in the Northern Hemisphere are, generally, the main cause, in a way or another, of water upwelling phenomenon in the study area.




In general, the circulation system of the Earth is robust. It is difficult to change the broad pattern of the wind cells In detail, though, it may be more fragile: the location of the boundaries between wind cells may change. The vigor of the Inter-tropical Convergence Zone (ITCZ) in the neighboring Africa and Arabia is very variable. Such variability could affect, or otherwise, be affected by the whole system of the circulation, as what happened during the Cretaceous and part of the Tertiary, when one or two of the Poles were ice-free and forests grew in high latitudes, Let alone other changes .

Fig. (2): Indian Ocean Basic Circulation Pattern During Summer Oscillation




Source: *Willett, M; .Gaylard, D & Atkinson( 1984.), p. 6*

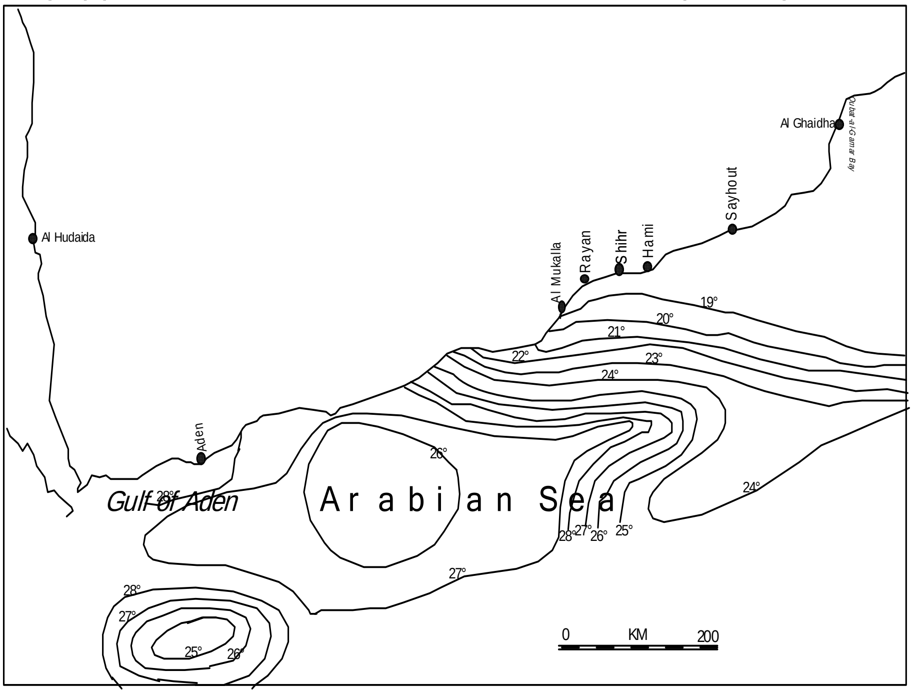
The Red Sea-to-Gulf of Aden water transfer drives drastic changes to the study area. Surface layer of 20 M in winter and 120 M in summer with warm water of fairly high salinity followed by a decrease in temperature and salinity in the surface layer with a maximum of 30% reduction in vertical temperature gradient in waters greater depths down to 2500 M. Further, the currents are directed into the Gulf of Aden during winter and in the opposite direction during summer. They are all a part of the general Indian Ocean water circulation (Fig 2):

The free exchange of water between Gulf of Aden and adjacent Arabian Sea/Indian Ocean has a clear effect on temperature changes. This fact is observed through temperature change from east to west, as it reaches its maximum of 25.18°C in January. Such a situation is reversed in August when temperature changes from west to east, i.e., cooler eastward or/and warmer westward reaching its maximum of 28°C at Aden, and its minimum of 17.5°C at Ras Fartak. (See Fig. 3). Yet, effect of the adjacent water bodies is variable. The Red Sea with average of 26°C temperature in winter and average of 30°C temperature in summer, is relatively warmer than both the Indian Ocean and Arabian Sea, due to African and Asian Continental effects. Its effect is to increase temperature. On the contrary, the Indian Ocean with average of 25.85°C temperature, has a cooling effect. The Arabian Gulf has both cooling and warming effects according to seasonal differences and according to seasonal currents directions. Generally, one can speak about three seasonal periods when the Arabian Sea surface water temperature changes according to adjacent water bodies effects:

For the sake of deeper analysis, the research problem will be tackled through three periods:

a) The period of winter: It is a period of warmer water currents sweeping to the Arabian Sea from the Red Sea between October and February. The direct effect of these currents is increasing the surface temperature with constant effect eastward. Although physical, chemical and biological characteristics remain unchanged, still there is a clear contrast between surface water and under-surface water. Due to non-maritime front formation, no transfer of humidity through wind into the study area. The result is a dry winter season, apart from shanty falls.

Fig. (3): Arabian Sea Lines of Isotherms Under Upwelling Effect




Source: Saleh S. Awad and Kolli, P. (Undated), p. 23

The Oceanic period: During the period between March and June several Indian Ocean currents flow towards the Arabian Sea either from the western side, through the Gulf of Aden, or from the eastern side through Oman Sea. Both currents have cooling effects although at different rates.

b) The Period of Upwelling: During July and end of September which is the period of the in-flow of main ocean currents, i.e., Somali Current that is part of the Equatorial Current, temperature is lower than the first two periods. As this period is the main focus of this study, more details about its effect will be discussed through the paper.

## Materials and Methods

The annual phenomenon of upwelling requires the collection of various oceanographic data on different parameters in the area between Aden and Ras Fartak of southern coast of Yemen. The main aim was to detect the possible causes, factors and consequences of the phenomenon. Obtaining climatic records from different main stations was also a main goal of the fieldwork in the study area. Another main goal was to observe and detect sea currents and other types of water movements. This was done along the coast in the area between Aden and Ras Fartak by different means. The fieldwork itself was conducted through one year during 2000. Other trips were also executed during 2003, 2005 and 2006 to obtain information from different sources.

Collected daily sea water temperature records from different coastal stations and places were computed and analyzed to initialize temperature average along the coast. The same thing was done with the direction and intensity of winds and humidity, as far as data were available. Yet, only little marine climatic data were obtained, because they were not satisfactorily available. In essence, collected data were quality controlled, and through optimal interpretation techniques, projected onto different uses mainly to ensure uniformity in time and space. To relate different data to each other, the collected data were statistically analyzed using mechanical methods, i.e., PC Programmes of SPSS and NCSS. This helped deriving different statistical and numerical relationships and comparisons. At the same time, results have been manifested in forms of maps, tables and others as evidences for different arguments.

## Results

The Process of up-welling starts when the seasonal South West winds begin to blow from the Atlantic Ocean across the Equator to Asia through Africa between May and September. It is enhanced by the Low Pressure Belt over west India and in east Yemen in Hadramout and Mahra that results from the temperature high rise to an average around 35° in May-June ***(***Gurairi and Others, 2000***)***. Also Hulme and Tosdevin, 1988 cited the Tropical Easterly Jet Stream as another factor that enhances the blow of these winds. They try to link the stream as the key upper air circulation feature affecting the whole process. There is a dynamic relationship between the Jet Stream and Asian Monsoon since this tropospheric Jet Stream over the east Africa and southwest Asia has its origin over the equatorial Indian Ocean, and South China.

The second step in the process is that the blowing winds from the Atlantic Ocean push the Somali warm current, which is part of the equatorial current, which in I turn pushes a surface layer of water causing water mass density difference and then upwelling process is enhanced as in Fig. 4:

The consequences of the process are:

TEMPERATURE, exactly sea water, is the first to be affected as relatively cold water moves from beneath to sea surface instead of the surface layer pushed by Somali current causing water mass density difference and, then, upwelling average temperature is changed (Fig. 5 and Table (1. The circulation is strongly dependent on the density contrast between cold, denser water in the bottom, and the warmer, less dense surface water. Sea circulation patterns may therefore change quickly, reaching to changes in the weather and heating regime above. Temperature at Imran (Extreme west of Southern Yemen Coast) is between 22-24°. Upwelling process effect is obvious eastward as temperature is lower. This is shown in Fig. (5). Also temperature changes to 14°-16°C at depth between 200-400 meter. When effects of both SW winds and upwelling coincide, there is a sharp temperature drop to <17° near to the coast. The direct result of this is a synoptic disturbance of evaporation process in the area.

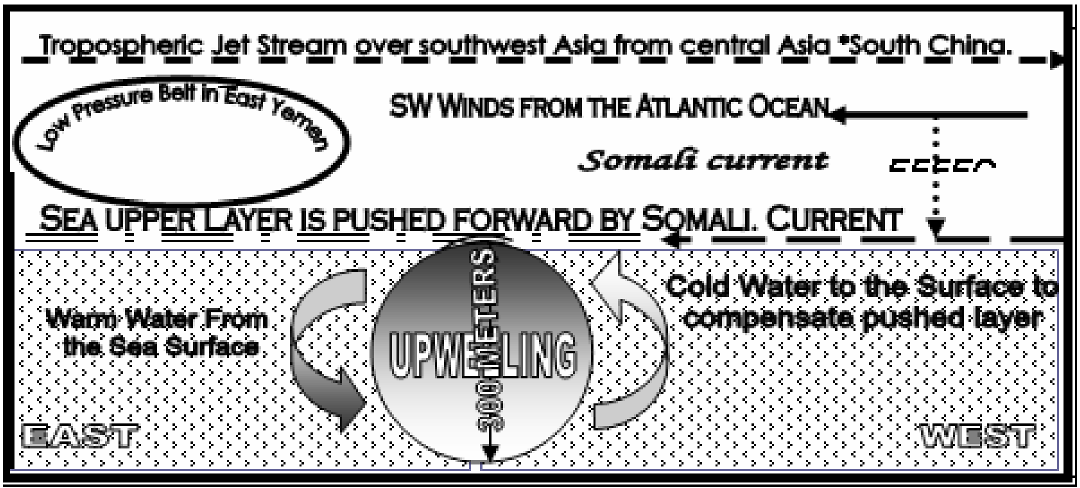


Fig. 4: A Portrayal Representation of the Upwelling Process
Source: Fieldwork Data, 1998

Table (1): Changes Brought by Upwelling to Seawater Temperature

| Depth (Meter) | Temperature |
|---|---|
| 1000 | 8° |
| 900 | 9° |
| 800 | 10° |
| 700 | 11° |
| 600 | 12° |
| 500 | 13° |
| 400 | 14° |
| 300 | 15° |
| 200 | 16° |
| 100 | 17° |
| 50 | 18° |
| 30 | 19° |
| 0-29 | 20-24° |

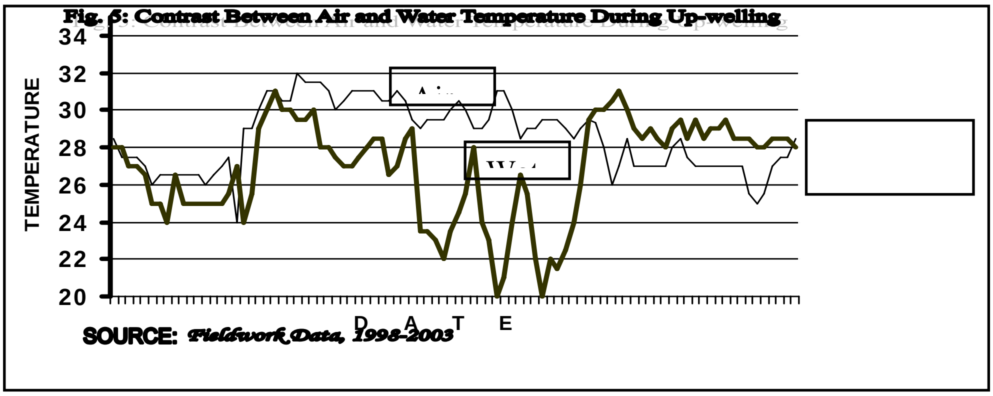



Fig. 5: Contrast Between Air and Water Temperature During Up-welling

Source: Field Data (1998-2003) and other Different Sources,

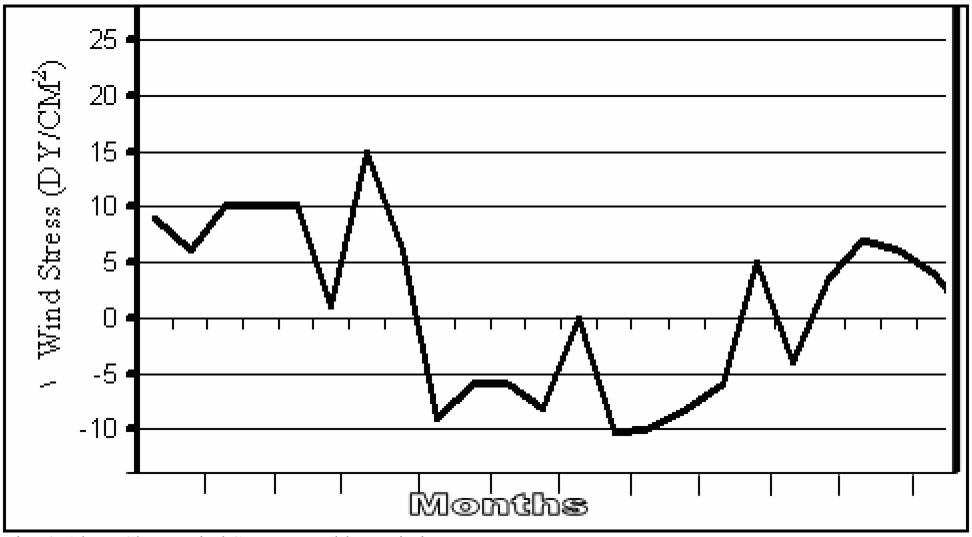



Fig. 6: Along Shore Wind Stress Monthly Variation
Source: Aden Airport Met. Station, different Years

**Wind Direction & Intensity**

The two concepts of Monsoon and seasonal winds are widely mixed and confused in Yemen. Monsoon refers to a type of wind that reverse its direction between summer and winter. But it is commonly known when the Arabs first use this term, they tend to refer to that type of wind that blows to India in summer and reverse its direction in winter. One famous conceptualization of Monsoon is by a German Geographer, H. Flohn, who in 1950 referred to the Monsoon as a type of wind that diverted its direction according to atmospheric instability, i.e., pressure system. The influence of upwelling on winds at the coast stems from its influence on temperature. There is clear evidence that there is a relationship between temperature and wind intensity (Fig. 6).

Also, upwelling affects wind direction in the region. The Monsoon winds blow parallel to the coast causing no rain on the coast and its adjacent areas. (Fig. 7). On the other hand, the seasonal winds originating in south Atlantic across Africa to the western high lands of Yemen, where they get rid of all its humidity in a form of orographic rainfall. Then, these winds become very dry over southern and eastern parts of Yemen. Such a dryness is also attributed to upwelling reducing sea water temperature, disturbing sea's surface water evaporation process and preventing winds from being humid to cause any coastal rainfall in the region.

**Fig.7: Hypothetical Representation of the Jet Stream and the Location of the ITCZ with the Prevailing Seasonal Winds**

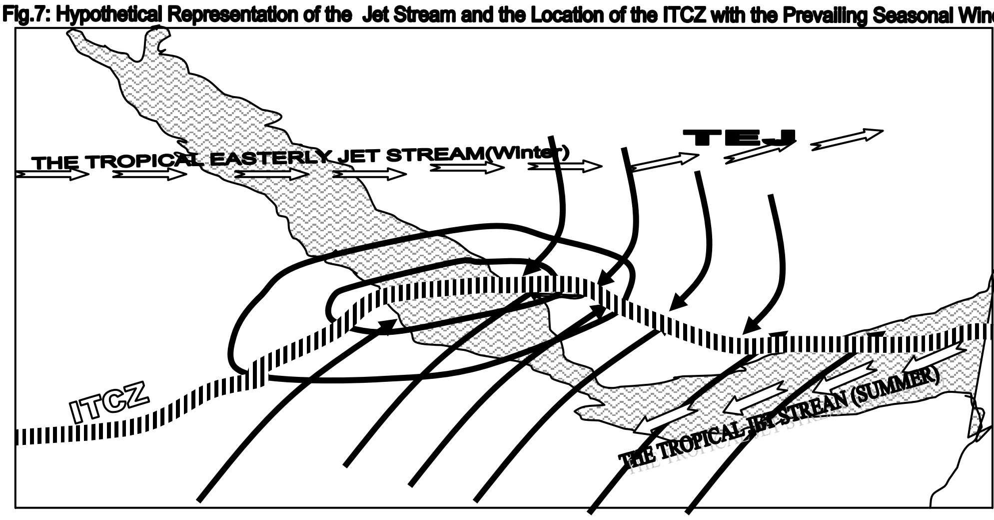
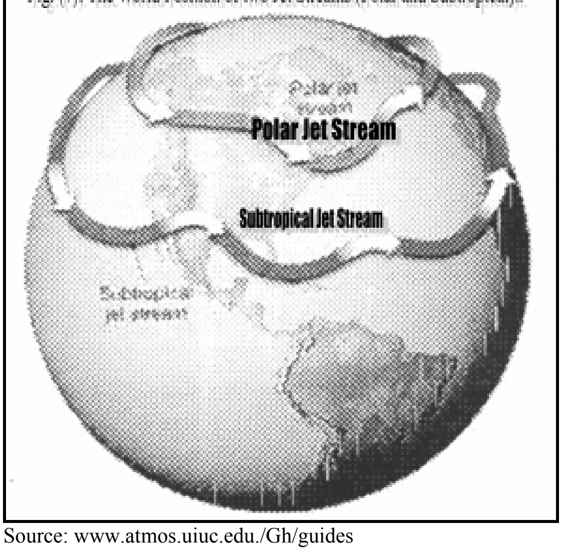



Fig. (7): The World Position of two Jet Streams (Polar and Subtropical)..




Source: www.atmos.uiuc.edu./Gh/guides

**The Tropical Easterly Jet Stream Acitivity:**

It is defined as "*a seasonal feature that exists during the northern hemisphere summer months. It is located in the upper troposphere, and it extends from the South China Sea, across southern Asia to northern Africa." (*Hulme and Tosdevin, 1988, p 181). At the beginning of June, the Tibet Plateau starts to heat due to sun radiation. As a consequence, the Tropopause gets up to make a steep gradient of air pressure and temperature towards the Equator. This is enough to create an easterly Jet Stream (TEJ) over Northern India through Arabia towards Africa. The TEJ is also "*produced as a result of the strong upper tropospheric anticyclone above the Tibetan Plateau*" (Hulme and Tosdevin, 1988, p 181). Generally, there are two main jet streams at polar latitudes, one in each hemisphere, and two minor subtropical streams closer to the equator. In the Northern Hemisphere the streams are most commonly found between latitudes 30°N and 70°N for the polar stream, and between latitude 20°N and 50°N for the subtropical stream. (*WWW.wikipedia.org*) There is also the Equatorial Easterly Jet occurs during the Northern summer between 10°N and 20°N. This last one is the concern of this research paper and it is recognized here as Tropical Easterly Jet Stream (TEJ). The wind speeds vary according to temperature gradient, averaging in summer between 55km/h and 400km/h. Associated with jet streams is a phenomenon known as Clear Air Turbulence (CAT), which is the result of massive disturbances of air, caused by vertical and horizontal windshear connected to the jet stream.

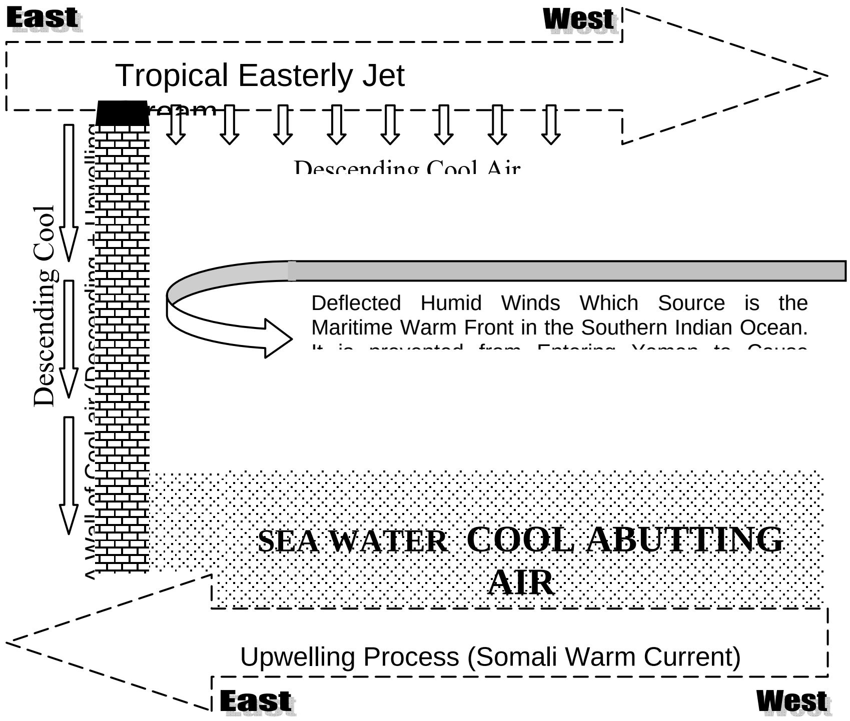
A strong TEJ is produced due to sharp surface temperature contrast. Its flow at upper troposphere. Depending on atmospheric conditions, air motions tend to enhance upward motion of air from the ground below. Rising air can lower the air pressure at the earth's surface. At another instance, depending on other factors, rising air cool due to adiabatic effect. The cool air tends to sink, which can increase the air's pressure at the ground surface. Then, now, the bilateral effect with the upwelling (Walling) is found: A wall of local high pressure (1016 mb) is formed along the coast (Fig. 9).

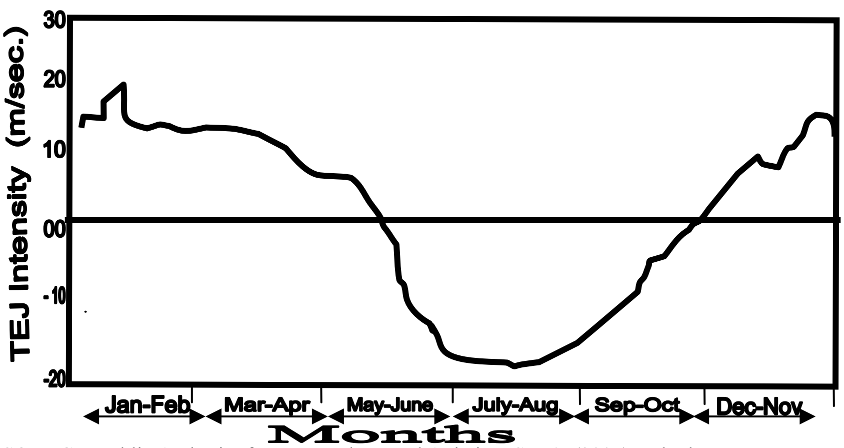
**The Tej Influence on Aridity of Southern Yemen:**

The TEJ is related rainfall (aridity) of southern Yemen in three way:

1. through its juxtaposition with Inter-tropical convergence Zone (ITCZ) (Fig 3).
2. through waves in its flow (Fig.9).
3. through its implicit perturbation and agitation of the moisture supplied to the region. This is same effect of upwelling discussed above.
4. The bilateral effect with the upwelling *Walling* .

Fig. (9): The Cool Air Walling Process by both TEJ and Upwelling




SOURCE: Public Authority for Meteorology and Aviation, Sana'a (2005) and other sources.
Fig. 10: TEJ Intensity over Yemen

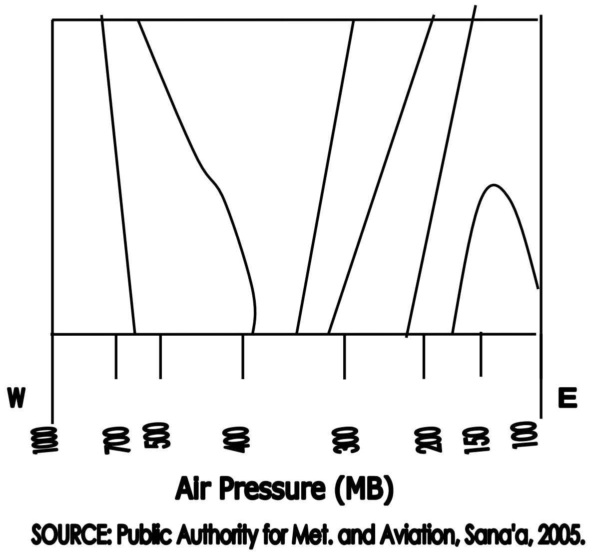



Fig. 11: Monthly Zonal Wind Over Southern Coast of Yemen

To understand well the negative effect of TEJ on rainfall of southern Yemen, one has to put in mind the (supposed) main cause of rainfall, i.e., the southwesterly winds which allow convective storms to develop. The ITCZ, which theoretically regulates rainfall in the region, attains its maximum northward extent, at the northern borders of Yemen, at the end of July/beginning of August making the peak of the rainy season in all Yemen, a part from the southern parts. At the same time, according to (Hulme and Tosdevin, 1988), the TEJ intensifies to a maximum in late July (Fig. 5). During Jul/August, the TEJ remains south of Tibet, and its extension west-ward enhances the formation of minor low pressure belts at a low altitude. This leads to intermingled periods of wet and dry weather conditions. Wet conditions are formed when westerly winds are effective. But this is not the case under the prevailing upwelling conditions. This phenomenon, through its process, retards normal humidity acquiring by the prevailing winds. In this way, it perturbs any natural cloud formation as an initial step for precipitation. Then, dry weather conditions are the dominant at any rate. Such an activity of the TEJ fade out during September-October when the north-easterly dry winds prevail. This coincidence of the existence of the TEJ at the peak of rainfall season, together with its climatic effects, is a clear evidence that TEJ affects negatively winds role in the study area. Therefore, the role of an upper tropospheric feature , i.e. the TEJ, synoptic feature is of importance in modulating surface rainfall over southern Yemen.

## RAINFALL

The effect of up-welling on rainfall is twofold:

**First: Direct Effect:** This is completed through:

- Negative effect of up-welling on the evaporation process.(Fig. 12).
- Controlling the wind ability in holding moisture from underneath sea surface.
- Indirect control of the ITCZ mobility.

- The bilateral effect with the TEJ (*Walling*) (diversion of humid winds away from Yemen –see Fig. 9).
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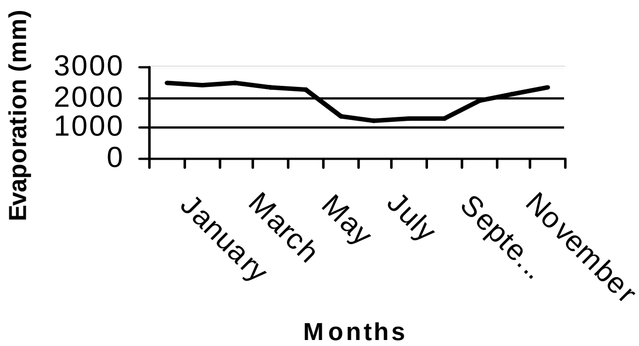
**Fig 12 Potential Evaporation (mm) From Sea Surface Water:**




**Source**: Public Authority for Met. and Aviation, Sana'a (2004)

This direct effect is reflected in the very diminutive amounts of rainfall along the coast and the adjacent areas (Table 2).

Table (2): Daily Rainfall Amounts (mm) in Selected Towns

| Town (Station) | Maximum | Average | Standard Deviation |
|---|---|---|---|
| Aden (Coastal Town) | 2.400 | 0.5083 | 84.365 |
| Al Mukalla (C. Town) | 11.60 | 1.5083 | 3.4939 |
| Al Ghaidha (Coastal Town) | 09.54 | 1.4181 | 2.9493 |
| Saiun | 14.50 | 1.4200 | 4.162 |
| Ta'zz | 149.20 | 71.733 | 64.22 |
| Ibb | 244.30 | 83.883 | 27.425 |

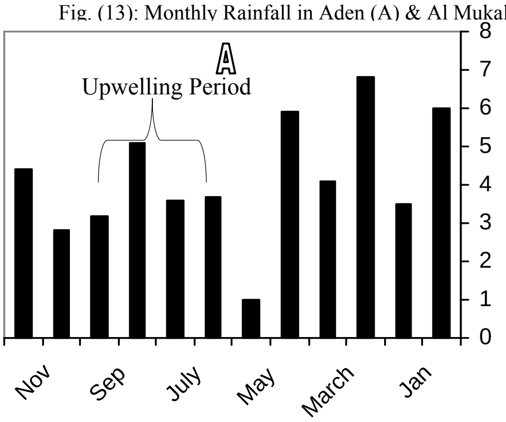
Source:

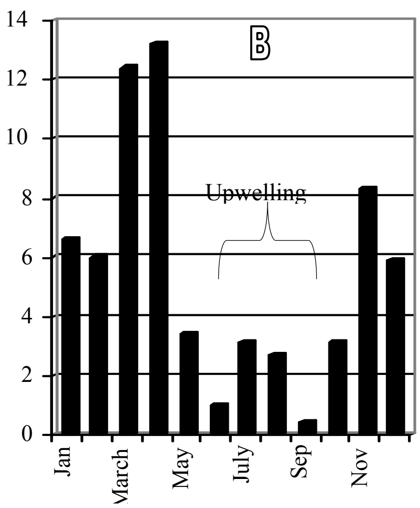
One can deduce from the Table that:

1. Due to the effect of both upwelling and TEJ, rainfall amounts in the study area are very low.
2. Height above sea level is not the only rainfall control. Although Hdeida is at a lower height (Tihama Depression) than both Aden and Al Mukalla, , it has higher average daily rainfall than both Aden and Al Mukalla, being 13.02 mm.
3. The direct distance between Al Ghaidha in Yemen and Salala in Oman is about only 200 km. The contrast between the two towns in average daily rainfall is very sharp. While it is only 1.4181 mm in Al Ghaidha, it is as much as 71.73 mm in Salala. The effect of upwelling is negligible at Salala due to the fact that the Somali Warm current (the main cause of upwelling in the area) is diverted by Ras Fartak (Cape Fartak) and the shape of the coast in the area (see Fig 2). The general

4. theory is that when an ocean current is diverted by a cape or by the shape of the coast, its nature changes (Emery, 1993). As the effect of upwelling faded out, the role of TEJ in walling effect is as consequence is nil at Salala.
5. The higher the standard deviation, the better indication of that there is a rainfall summit, and the opposite is true also.
6. Rainfall in July-September (upwelling period-the main rainy season of Yemen) is utterly lower in the coastal towns than the other two Winter and The Oceanic periods (Fig. 13).
7. The gradient of rainfall amounts shows increase towards both east and north away from direct upwelling effect on the coastal area.

Fig. (13): Monthly Rainfall in Aden (A) & Al Mukalla (B)(1984-2002)



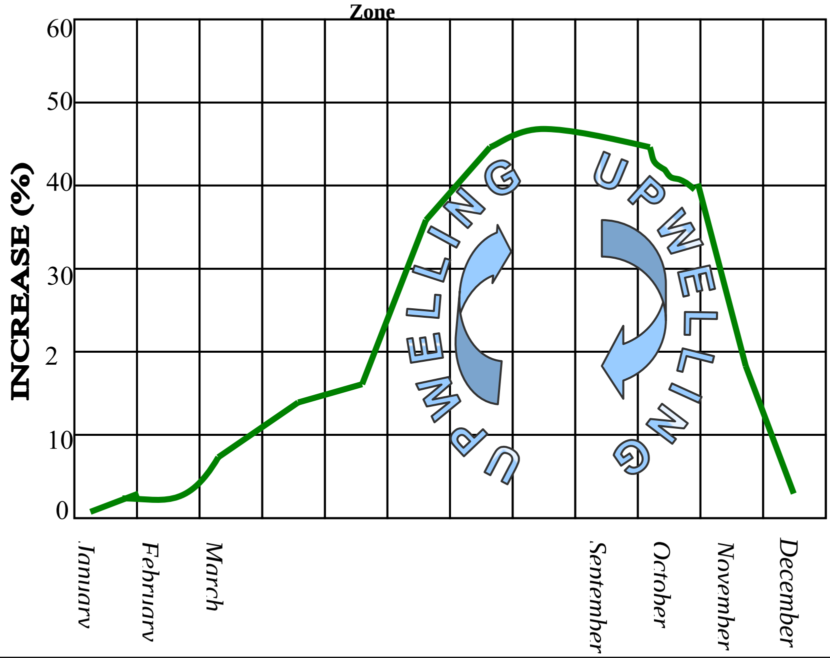




**Source**: Public Authority for Meteorology. . and

**Second Indirect Effect: Algae/Sea Weeds Effect**, In general, upwelling affects the growth of Algae and Sea Weeds which, in turn, affect rainfall in the area. is also affected by water upwelling. The clear effect of vertical water movement is that bottom materials are brought to the surface more than any other season, exactly phosphates $(PO_4)^{-3}$, Nitrates $(NO_3)^{-2}$, Silicates $(SiO_3)^{-2}$ and others. These are basic nutrients to the growth of seaweed (*Jahouri, 1999*). The lowering of water temperature also stimulates the growing season of these weeds. Fig.5 Shows availability of different species in different places of the study area.

Plankton has an important effect on water temperature. Water evaporates off the ocean whether or not life exists, so long as there is an ocean, but in many parts of the ocean's surface the evaporation process may be highly modified by marine plankton. For instance, some plankton emits dimethyl sulfide (DMS) which could be dissolved into $SO_2$ and other sulfur compounds. Another product of marine algae is a compound known as methyl iodine, which releases iodine, as well as Bromine compounds. Also when dim ethyl oxidized by OH, produces methane-sulfonic acid which when associated with aerosols particles helps to nucleate clouds. Clouds keep the algae and their surrounding water cool and control evaporation (Nisbet, 1991).

**Fig. 14**: **The Effect of Upwelling on Water Condensation in the Coastal Zone**




Source: *Fieldwork Data (2000--2005) and Other Various Sources.*

The same thing could be said about animal organisms. Fig. 15 Shows their availability during upwelling period –June to September. The role of marine animals has not yet been mentioned, as it is poorly understood, but there is obviously chain of life depending on the marine plankton, reaching right up to the great sharks and wheals. Disruption of the population of large animals could alter the population balance amongst the smaller animals and plankton and, conceivably, even change the cloud form. (Abu-Hilal, 1984 Bataher ,Ali Gumman, 1999, Khanbash, 1999 and other Different Sources).

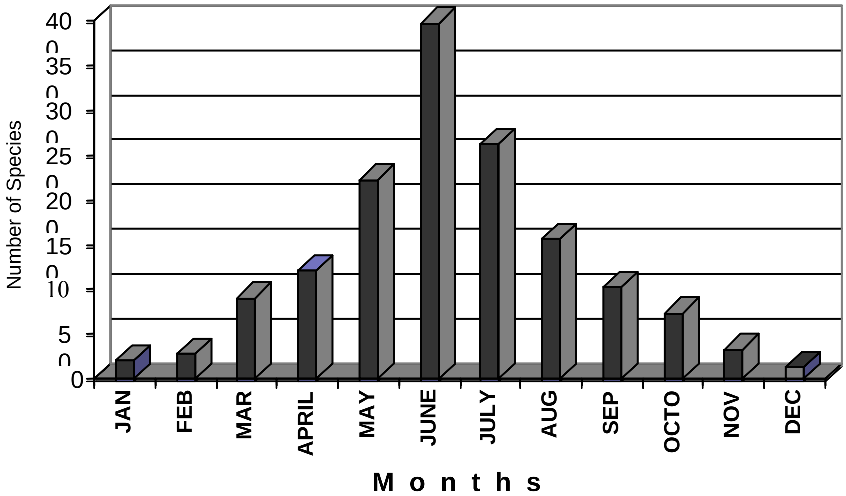
## Other Factors of Desert Formation

The present hyper aridity of the area is referred to Late Pleistocene (Table 3).

Table (3): Time-Stratigraphic Column of Quaternary of Southwest Rub'Al Khali of Yemen

| GEOLOGIC EPOCH | ABSOLUTE DATES (YR BP) | CLIMATE | REMARKS |
|---|---|---|---|
| LATE PLEISTOCENE | 36000 - 17000 | WET (PLUVIAL) | Lacustrine and re-worked alluvial sediments. |
| | 17000 - 9000 | HYPER-ARID | Aeolian sand, Dune Topography |

Source: Al-Sayari and Zötl, 1978, p. 257.



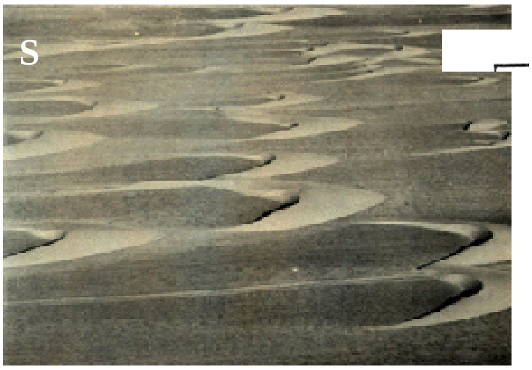

Source: Jahouri,Y.M. (1999):

Fig. 15: Animal Organisms Monthly Availability in the Arabian Sea`

Monsoon which is the main cause of wet climate in the area during 9000 to 6000 years BP, is now retarded by Upwelling/TEJ dual effect leading, consequently, to aridity prevalence in the study area. This is-with a little reservation- the view point of (Al-Sayari and Zötl, 1978, p. 262) stating that: "However, a northerly displacement of the south west monsoon in the Holocene resulted in a sub-pluvial phase in the Rub'Al Khali from about 9000 to 6000 years BP. Retreat of this wind regime at the end of this period to its approximate present location, where it sweeps only across the southern tip of the Arabian Peninsula, then resulted in a return of hyper-aridity which persists today. "

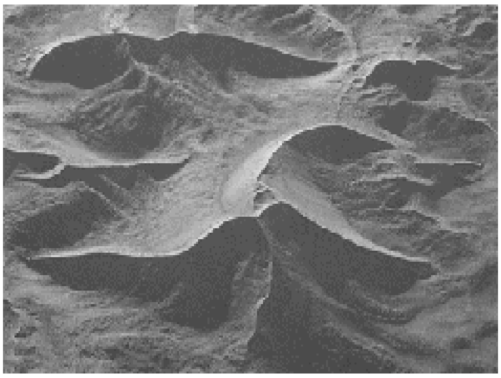
It is very important to refer to other evidence of desert formation process, apart from the dual effect of upwelling and TEJ phenomena. But desert studies still are hampered in Yemen by lack of accurate climatic data. Desert weather stations are lacking, and then, data from other sources do not reflect conditions from the desert, making data difficult to interpret and compare. The most reliable source, thus far, is the satellite imagery. Such a source allows only to assess geomorphologic phenomena through which one can justify the existence of such phenomena. Sand Dunes are bold features of deserts, and following are some types of dunes that could just give hints on desert formation process in Yemen. There are five basic types of dunes, the most important of which are: *crescentic*, *and*, *star*. Thus far, wind is thought as the main factor of dune formation, whether in Yemen or abroad. So, an existence of a sand dune indicates both velocity and direction of wind in any area:

Ripples and horns of this crescent dune indicate that the dune is moving right to left. Small crescentic dunes occur on the crests of these complex dome dunes of Yemen's/Saudi Arabia's Empty Quarter.




The most common dune form on Earth and on Mars is the *crescentic*. Crescent-shaped mounds generally are wider than long. The slip face is on the dune's concave side. These dunes form under winds that blow from one direction, and they also are known as barchans, or transverse dunes. Some types of crescentic dunes move faster over desert surfaces than any other type of dune. A group of dunes moved more than 100 meters per year between 1954 and 1959 in China's Ningxia Province; similar rates was recorded by the author in the northern Darfur/Kordofan Provinces of Sudan between 1973-1990. The largest crescentic dunes on Earth, with mean crest-to-crest widths of more than 3 kilometers.

These crescent dunes are migrating toward the left.



Star dunes, such as this, indicate the winds that formed them blew from many directions. Radially symmetrical, *star dunes* are pyramidal sand mounds with slipfaces on three or more arms that radiate from the high center of the mound. They tend to accumulate in areas with multidirectional wind regimes. Star dunes grow upward rather than laterally. They dominate some parts of Rub' Al Khali. The star dunes are up to 500 meters tall and may be the tallest dunes on Earth.

One can deduce the following facts:

1. Some dunes form under winds that blow from one direction, i.e. *crescentic*. Such dunes move faster over desert surfaces than any other type of dune. In the case of Yemen, as shown above, they move from north towards south. My be they originally formed in Saudi Arabia and then pushed by the north/northeasterly dry winds.
2. Other dunes tend to accumulate in areas with multidirectional wind regimes. Star dunes grow upward rather than laterally. This could add at least two other wind systems as geomorphic agents in dune formation:
   - The monsoon south westerly winds which have gotten rid of humidity in Yemen western highs to below over eastern Yemen as dry wind.
   - The local wind below from the localized high pressure that formed due to the dual effect of upwelling and TEJ.
3. Another factor that helps the dual effect of upwelling and TEJ in the foundation of desert conditions in southern and eastern parts of Yemenis a multi-system wind aeolian activity.

4. Ahmed, Ghadiri Abdul-Bagi (2002), in his article on the geomorphology of Hadramout (in Arabic), confirmed the existence of undersurface drainage system, in addition to gravel-to-silt deposits in the area, to point a humid climate dominated the area during Pleistocene. This refutes the viewpoint that aridity in the area could be attributed to its location in the rain shadow of the Western Heights of Yemen.

## Discussions

The influence of the upwelling processes during the South west Monsoon (June-August) on the Arabian Sea seems to be characterized by a distinct change of water temperature, salinity and the topography of the dissolved oxygen minimum layer. Such changes have greater effects on different oceanographic attributes of the study area, as well as on the marine ecosystems. The phenomenon itself is not a unique attribute of the area. It is rather found in different places of the world. Along the western coast of India, the intensity of upwelling was inferred from the vertical migration of ml/L isopleths. (Anonymous, 1980). Upwelling in the study area is not as strong as in Somalia where, due to the vertical movement of deeper water, sea surface temperatures drop down to 14°C (Warren et al, 1966). Variations in the intensity of wind and the orientation of the coastline are main factors determining the process. Also, it is well known that there are high upwelling indices during Southwest Monsoons over the whole Arabian Sea (Harish et al, 1990).

One upwelling effect is lowering the sea level. During the process, very cold dense water occupies the continental shelf, and due the change in the height of sea surface through isostatic adjustment, the sea level appears lower. From October onwards (end of upwelling process), due to pile up of water along the coast, the sea level appears to be high and results in sinking. Therefore, the period of upwelling coincides with the period during which the sea level is very low (Fig. 15), and the period of higher sea level coincides with the sinking process.

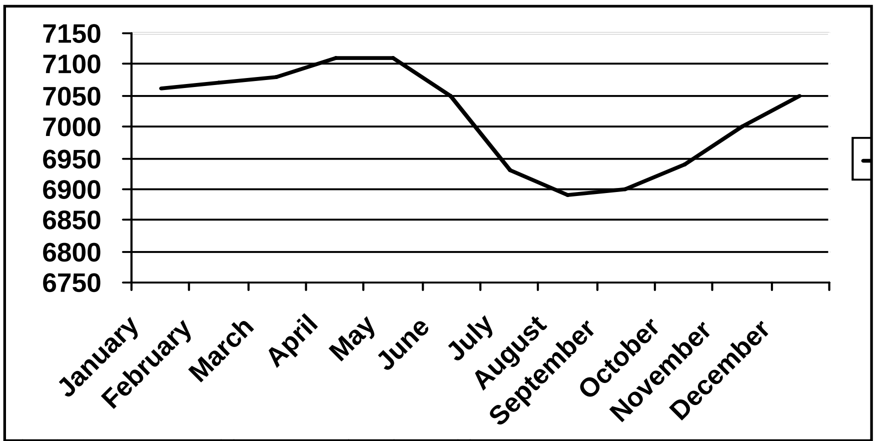



Fig. (16): Mean Monthly Sea Level of the Arabian (M –1999-2003)

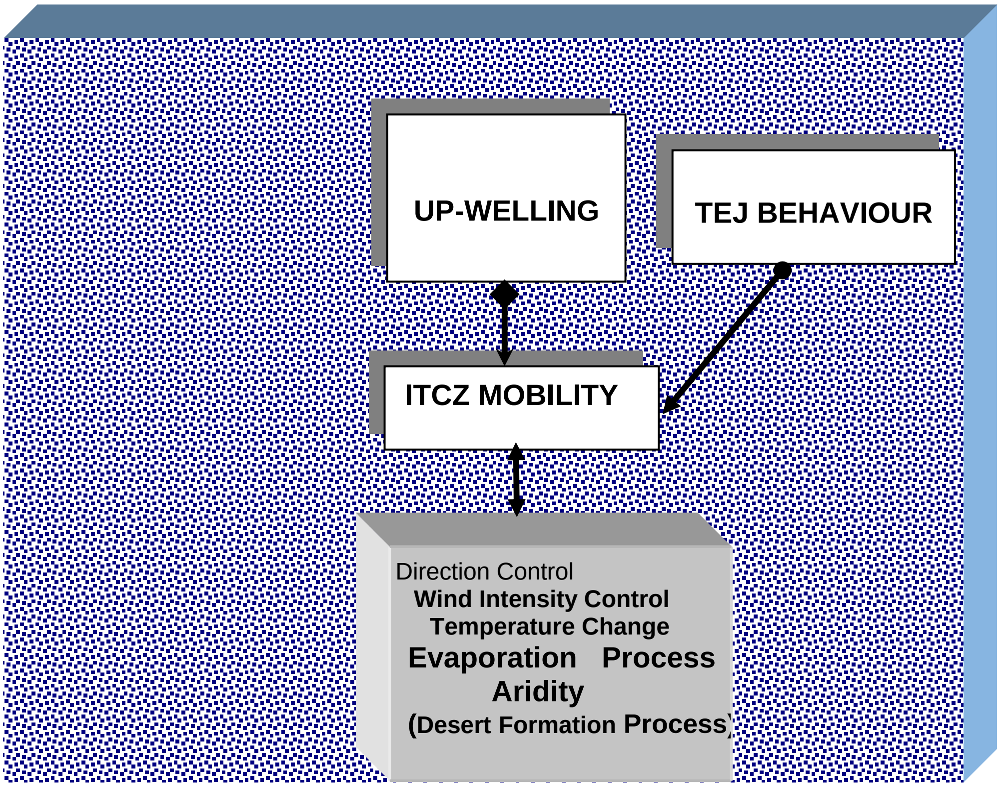



Fig. (17): The Effect of and TEJ Upwelling on Aridity
Source: Fieldwork Data (2004), & others

Aridity is one of the most important events to be related to the upwelling processes. The Arabian Sea is highly affected due to these processes. Actually, upwelling areas in different parts of the world are famous for their hinterland aridity as in north-west Africa, the Peruvian coast, south west America (California) and others (Abu Bakr, et al, 1999).

The effect of upwelling on reducing evaporation process, according to field observation, could be demystified through the following accretions:

- Vertical and horizontal incongruity of water temperature.
- Anomaly of both water density and salinity.
- Wind speed and Direction and the consequent wave formation.
- Vertical balance water activity.
- Earth rotation and its effect on water vertical and horizontal movements could also be added.

## Conclusions

Upwelling and TEJ are two salient phenomena that characterizes the Arabian Sea, Yemen. Upwelling is –at least- partially caused and animated in intensity by the South West Monsoon that dominates the area during the period July-end of September. The Somali warm sea current is directly responsible. It carries the upper layer of the sea obliging lower cold water to come the surface causing various oceanographic changes. Among these changes are the surface water temperature, wind direction control. TEJ also imposes different oceanographic effects that work to diminish rainfall amounts in the study area. Such a changes, in turn, affects all the environmental conditions of the area and are highly connected with both upwelling and TEJ intensity and incidence.

## Research Salient Results

♦ The two phenomena of upwelling and TEJ in the study area are a part of two processes in different parts of the world

♦ Upshot of the two processes in causing aridity in the study area are multiple: The most important of them are the physical consequences that pertain to the same effect of cold currents in continents western coasts. This is due to temperature variability, vertically and horizontally; wind movements: and others.

♦ The seasonal winds originating in south Atlantic across Africa to the western high lands of Yemen, where they get rid of all its humidity in a form of orographic rainfall. Then, these winds become very dry over southern and eastern parts of Yemen causing geomorphic effects.

♦ The free exchange of water between Gulf of Aden and adjacent seas has a clear effect on temperature changes. This fact is observed through temperature change from east to west, as it reaches its maximum of 25.18°C in January.

♦ Upwelling divides the sea in the study area into three main parts, which are the coastal zone; the Surf Zone; and the Oceanic Zone. Each zone is part of the whole process that lead to aridity.

♦ There is a close relationship between structure of clouds and the activity of the marine algae below. The role of marine animals has not yet been mentioned, as it is poorly understood, but there is obviously chain of life depending on the marine plankton, reaching right up to the great sharks and wheals. Disruption of the population of large animals could alter the population balance amongst the smaller animals and plankton and, conceivably, even change the cloud form.

♦ Plankton has an important effect on water temperature. Water evaporates off the ocean whether or not life exists, so long as there is an ocean, but in many parts of the ocean's surface the evaporation process may be highly modified by marine plankton. It associated with aerosols particles helps to nucleate clouds. Clouds keep the algae and their surrounding water cool and control evaporation.

♦ The TEJ is related to rainfall (aridity) of southern Yemen in three way:

1. through its juxtaposition with Inter-tropical convergence Zone (ITCZ).
2. through waves in its flow.
3. through its implicit perturbation and agitation of the moisture supplied to the region. This is same effect of upwelling discussed above.

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# الأثر المزدوج لظاهرتي التقلب المائي البحري و التيار المداري النفاث في عملية تكون الصحراء في جنوب و شرق اليمن

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إن كلا من ظاهرة التقلب المائي البحري (ابويلينغ) و التيار المداري الشرقي النفاث يعملان معا في التسبب في ظاهرة القحط التي تسود المناطق الجنوبية و الشرقية من الجمهورية اليمنية: فمن جهتها تتسبب ظاهرة التقلب المائي البحري في إعاقة العمليات الطبيعية التي تُحْدِث التساقط في منطقة الدراسة. يحدث ذلك من خلال التغيرات الفيزيائية و الكيميائية و الحيوية الكثيرة التي تحدثها الظاهرة في ماء البحر. و من أبرز من ما تحدثه هذه الظاهرة هو خفض درجة حرارة الماء السطحي للبحر مما يقلل من جهة من فرص تحميل الرياح التي مصدرها الجبهة المدارية الدافئة في المحيط الأطلسي بالرطوبة اللازمة لإحداث التساقط، وخلق منطقة ضغط جوي مرتفع محلي يصد هذه الرياح الرطبة التي مصدرها الجبهة الدافئة في جنوب المحيط الهندي و يحول مسارها بعيدا عن السواحل الجنوبية و الشرقية –من جهة أخرى– و هذا سببٌ آخر لقلة التساقط في منطقة الدراسة.

و من جهته يعمل التيار المداري الشرقي النفاث على إحداث تغيرات فيزيائية تتعلق خصوصا بدرجة الحرارة في طبقة التربوسفير و هبوط الهواء البارد إلى أسفل مما يمنع أو يعيق العمليات الطبيعية التي تُحْدِث التساقط في منطقة الدراسة. فتزامن قمة نشاط هذا التيار مع قمة نشاط الرياح الموسمية و التي مصدرها كلٌ من المحيطين الهندي و الأطلسي يحد من عمل هذين النوعين من الرياح في عملية التساقط بما يؤدي إلى وجود ظاهرة القحط في منطقة الدراسة. كما أن تزامن نشاط التيار المداري الشرقي النفاث مع وقت حدوث ظاهرة التقلب المائي البحري يجعلهما يعملان معا على خلق حاجز من الهواء البارد (ضغط جوي محلي مرتفع بمقدار 1016 ملليبار) يمتد من أعلى طبقة التروبوسفير و حتى سطح الحر و يقف سدا منيعا أمام ولوج الرياح الموسمية الرطبة إلى داخل البر اليمني لإحداث التساقط المطري.

و لإثبات كل ذلك، يحاول البحث من خلال العمل الميداني المكثف أن يحدد الآلية التي بها تؤثر هاتان الظاهرتان على مناخ منطقة الدراسة و بالتالي خلق ظروف صحراوية، و ذلك من خلال معرفة:

- التأثير الفيزيائي الذي يتصل بدرجة الحرارة البحرية و الهواء الجوي فوقها.
- التأثير على حركة الرياح و الرطوبة.
- التأثير على المناخ المحلي في منطقة السهل الساحلي و ما جاوره و خاصة على عملية و معدل سقوط الأمطار، و أثر ذلك في عملية خلق ظروف صحراوية في المنطقة.