A Study of Anomalous Wet and Dry Years in the Winter Precipitation of Pakistan and Potential Crop Yields Vulnerability

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Abstract: Pakistan experiences distinctively large rainfall variability on spatial as well as temporal scales. On spatial scale the rainfall variability is mainly caused by its peculiar topographic features encompassing from south to north of the country. On the other hand the temporal rainfall variability sometimes exceptionally large, does affect the climate of the country that in turn impacts the climate-dependent sectors like agriculture, hydroelectric power generation and ecology. In this study the 30-year winter season (December-March, DJFM) rainfall data of 35 meteorological sites of Pakistan have been analysed to identify the anomalous wet and dry years, their potential impact on crop yields across Pakistan and vulnerability of climate. The National Centre for Environmental Prediction (NCEP), US reanalysis data are used to investigate the association of the surface and upper air atmospheric circulation features responsible for anomalous wetness and dryness. This study may prove of some help for an improved winter rainfall prediction tool and better management of available water resources viz-a-viz optimal crop yields production.

Keywords: Winter rains, Anomalous wetness/ dryness, NCEP reanalysis, Agriculture yields.

1. INTRODUCTION

Precipitation and temperatures are the two best manifestation of climate of an area with rainfall variability being a crucial feature of climate. The changes in global rate and precipitation distribution may have a greater effect on human well-being and ecosystem dynamics than changes in temperature itself [1]. Climatic signal is said to originate mainly from winter precipitation and is robust over ecologically different sites. The rainfall variability occurs over a wide range of temporal and spatial scales and an understanding of such variability can be of considerable importance for improved risk management practices in agricultural and other industries [2]. Precipitation variability over a particular period across any area gives an insight to the climate and climatic change of that area.

Pakistan, exhibiting a markedly diversified climate, has mostly hot and dry climate in the south, temperate in northwest and arctic in the north. Summer temperature in the south rise over 50°C and winter temperature in the north fall below -20°C [3]. It experiences mainly two rainy seasons summer monsoon (July - September, JAS) and winter season (December - March, DJFM) [4-5]. Annual area - weighted rainfall of Pakistan is 238 mm. Of which summer contributes 140.9 mm (about 57%), winter share is 74.9 mm (about 30%) and 25.6 mm (13%) is contributed by the rest, like convective thunderstorms [3]. The crop yields in the rain-dependent areas have been typically less than half of those in areas with river-fed irrigation during deficient years [6]. The years 1987 and 1994 saw a drastic reduction of wheat crops principally due to a failed winter rainfall season [7]. The Thal (Punjab province) region's main winter crop grams is being adversely affected by shortening of winter and expansion of summer seasons [8]. During 1998-2002 the country faced a shortage of 26%-30% in wheat production due to a severe drought [9]. Similarly the rivers' discharge was noted to have been reduced by 25% due to 20%-30% less rainfall over the period 1998-2004 [10]. Another study revealed that the overall extent of negative impact of temperature was greater than the positive effect of rainfall on agriculture in the Potohar region of Pakistan [11]. Pakistan's two main crops wheat and maize are largely dependent on the winter (DJFM) and summer (monsoon, JAS) rainfall respectively. In rain-fed areas like Potohar Plateau it is the amount and frequency of rainfall coupled with its distribution on temporal and spatial scales which dictates the terms for maize crop. Excess or deficit rain badly affects the grain yield especially at early and reproductive stage of corn maize [12]. Erratic rains at the time of harvesting and threshing adversely affected the grain quality and to some extent lower the yield. Generally, wheat crop is vulnerable to many threats like diseases (rusts), aphid, fluctuation in temperature, drought spell and canal water non-availability [13]. BBC report "Climate-Asia" [14] too describes that erratic rainfall is damaging crops and reducing access to water for drinking and irrigation, while increases in

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pests and mosquitoes have an effect on both agriculture and the health of people and livestock. Rezaie *et al*., [15] confirmed that rainfall variability is critical for agricultural yields in Iran. If the pattern of precipitation from the time of planting onward is unknown, farmers are unable to tune their cropping systems to optimize resources. A study on Indian agriculture and climate change impacts demonstrated that changes in the temperature, solar radiation, and precipitation will have an effect on crop productivity and livestock agriculture [16]. Climate change will also have an economic impact on agriculture, including changes in farm profitability, prices, supply, demand, trade and regional comparative advantages [16].

The winter season (DJFM) precipitation in southwest Asia is brought about by eastward-propagating mid-latitude cyclones from the Mediterranean region [17]. These weather systems named western disturbances (WDs) are often observed as closed lows on mean-sea level chart or upper-level troughs over Iran, Afghanistan and Pakistan moving east/ northeast-wards. Developing basically over the Mediterranean and Atlantic seas the WDs pass between Latitude 30 °N and 60 °N so as to cause formation of the secondary lows over southeast Iran and south/ southwest Pakistan which by dragging in a warm moist air from the Gulf of Oman and north Arabian Sea cause precipitation across Pakistan.

Over the past few years an uneven and erratic rainfall occurrence is seen most common over Pakistan i.e. some years bringing largely excessive rains like last five consecutive flood years due to above normal JAS rainfall, and some years with largely deficient rains leading to drought episodes, e.g. 1998 – 2002 famous drought which had adversely affected whole southwest Asia with Pakistan suffered a shortage of 26%-30% in wheat production [9]. It is now well documented that the prolonged persistent drought of 1998-2002 was primly caused by the forcing in the Pacific and Indian Oceans, related to a combination of

1. anomalously cold SSTs in the eastern equatorial Pacific ocean leading to prolonged and protracted La Niña (temperatures below than normal),
2. an unusual above-normal warming in the eastern Indian / western Pacific oceans and
3. Indian Ocean precipitation extension, said to be inversely linked to south west Asia winter rainfall, inhabiting the main centre of cyclonic activity [18-20].

The anomalous wet and dry episodes are not actually the stand-alone events rather resulted by some remote atmospheric and oceanic forcing. Various researches have been carried out to investigate the wet/dry episodes' occurrence and their association with NCEP/NCAR (National Centre of Environmental Prediction/National Centre for Atmospheric Research) re-analysis data [21-23 and many others not quoted here]. Hence the present study too used the NCEP/ NCAR re-analysis data [24] to investigate about the atmospheric features association with anomalous wet and dry episodes.

With this backdrop it seems imperative to discern the anomalously wet and dry years in Pakistan winter rains, diagnose about the forcing behind them and potential linkage to crops vulnerability. We use 30-year seasonal rainfall data of 35 data sites obtained from the PMD, identify the wet and dry years, investigate about the atmospheric forcing responsible and see whether and how much crops yield is affected with anomalous wetness and dryness. Figure **1** shows the location of data sites used in the study. The detail of data sites climate is given in the Annexure. This paper is structured into 5 sections with data and methodology covered in section 2, results in section 3, discussion in section 4 and conclusion in section 5.

2. DATA AND METHODOLOGY

The monthly rainfall datasets of 35 data sites for 30-year period (1976-2005) have been obtained from the climate data processing centre (CDPC) of Pakistan Meteorological Department (PMD). The 35 stations well spread over Pakistan represent the whole country reasonably well. The data used are a quality-controlled data by the PMD's climate data processing section which regularly publishes and broadcasts it. The 30-year time span is selected because it conforms to the World Meteorological Organization (WMO) criteria that a 30-year time characterizes the climate of a particular region. The monthly total rainfall is aggregated over four months, December through March, to obtain the seasonal total rainfall for each station and then averaged for whole Pakistan. The wettest and driest years are characterised by the two thresholds, 90^{th} and 10^{th} percentiles respectively. The wet (surplus) and dry (deficient) years are identified by finding out the positively and negatively anomalous years [16]. The ±1.0 anomalies have been chosen as these values

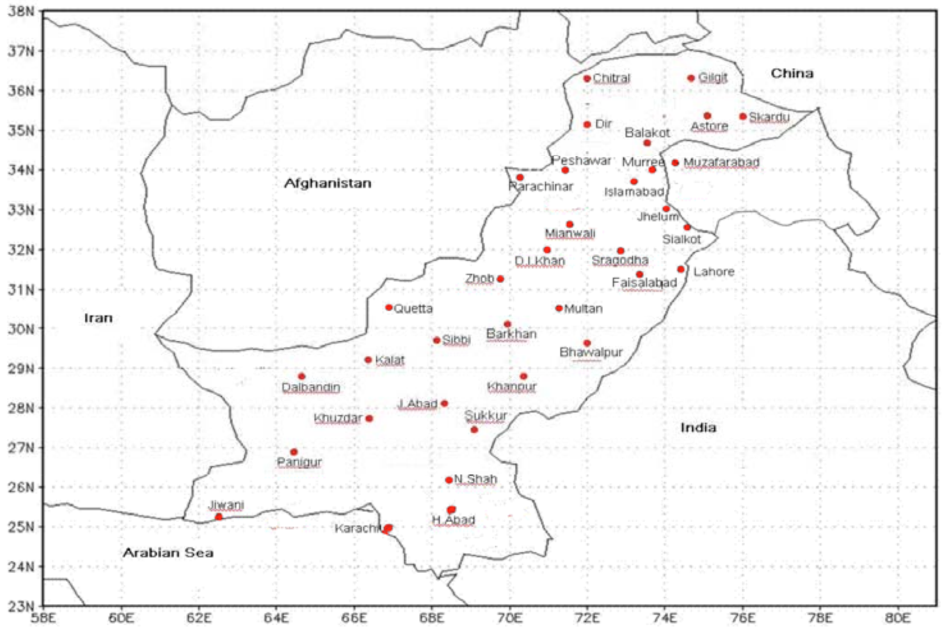

Figure 1: The data sites location across Pakistan.

account for 50% above (+1.0) or below normal (-1.0) rainfall. The surplus (with +1.0 and greater anomaly) and deficient years (-1.0 and less anomaly) are shown in Table **1**.

We extracted the composite anomalies of mean sea-level pressure and meridional and zonal winds at middle and upper atmospheric levels (Figures **3** and **4**) from the NOAA- ESRL (National Oceanic and Atmospheric Administration- Earth System Research Laboratory) website using the link http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl to identify the prevalence of weather patterns to find out the linkage among wet and dry spells and the associated circulation patterns over Pakistan and surrounding region. Given that a seasonal aggregate precipitation is actually resulted by combining effects of the atmospheric circulations at mean-sea-level, mid (500 mb) and upper-tropospheric (200 mb) levels; hence these levels of fields are selected for the present study.

3. RESULTS

By applying the 90th and 10th percentiles technique and standardised anomaly calculation to all 30-year seasonal total rainfall data we have identified the five wettest and driest years. The years with large anomaly of +1.0 (or greater) and -1.0 (or lesser) are given in Table **1**. The worth noting point is that there are three consecutive years in each category i.e. 1990-92, the wet (surplus) years and 1999-2002, the deficient (dry) years.

The graphical depiction given in Figure **2**, evidently shows that there were 16 positive anomalies, four consecutive years of 0.5 to 1.0 anomalies around early 80s, two of same magnitude in mid-80s, three of even greater magnitude 1.5 to 2 around early 90s followed by another large positive anomaly in the year 2005. While ten negative anomalous (indices of -1 to -1.7) years can be spotted with 1984-85 and 2000-02 being largely deficient years.

Table 1: Five Surplus (+1.0 and Greater Anomaly) and Deficient (-1.0 and Less Anomaly) Years

Surplus years	Anomaly standardised	Deficient years	Anomaly standardised
2004/05	2.2	2000/01	-1.7
1990/91	2.0	1984/85	-1.4
1991/92	1.4	1999/00	-1.2
1989/90	1.3	1976/77	-1.2
1980/81	1.0	2001/02	-1.1

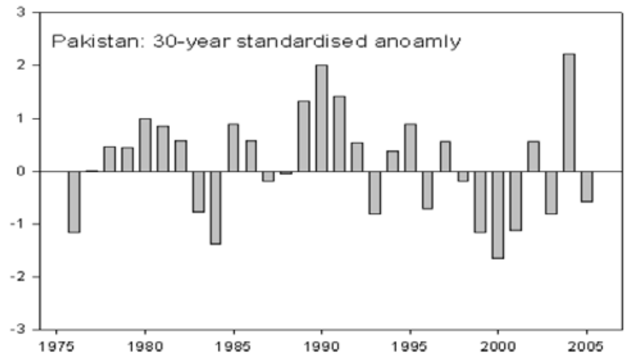

Figure 2: Pakistan winter season (DJFM) 30-year standardised rainfall indices.

From a meteorological point of view the abnormally wet and dry period across a region is actually a manifestation of prevalence of some particular atmospheric circulation features over there.

3.1. Wet Years' Anomalous Features

Figure **3**(**a-e**) exhibits the composite anomalies of sea level pressure (SLP), zonal and meridional wind (m/s) at 500 mb and 200 mb levels for identified wettest years. Figure **3a** depicts a significant negative anomaly of -0.5 to -1 mb spreading from east of the Caspian Sea down to southwest Afghanistan and then

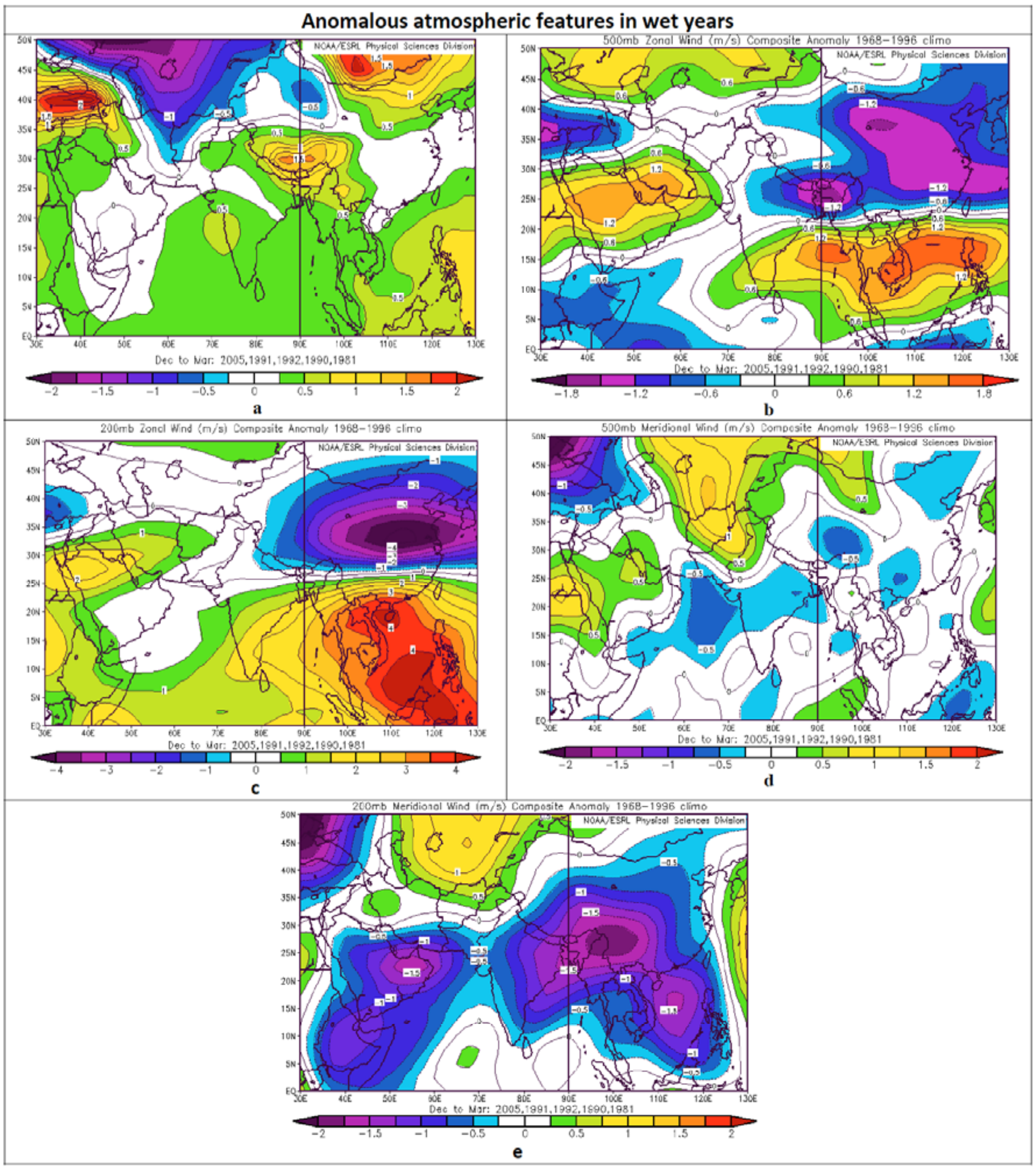

Figure 3: a: SLP (hPa) composite anomaly-wet. **b**: U(m/s) 500 mb composite anomaly-wet. **c**: U(m/s) 200 mb composite anomaly-wet. **d**: V(m/s) 500 mb composite anomaly-wet. **e**: V(m/s) 200 mb composite anomaly-wet.

northeast-wards to the Central Asian States. This feature is indicative of frequent passing of anomalously low-pressure systems over the area during wet years resulting in unusual wetness. Figure **3b** depicts a positive anomaly of 0.6-1.4 m/s in zonal winds flow at mid-tropospheric level (500 hPa) spreading over the North Arabian Sea, Arabian Gulf, most of Saudi Arabia and south Iran, which strongly suggests that a steep wind gradient was prevalent which caused a pronounced moisture transport from ocean in to southeast Iran and southwest Pakistan. Figure **3c** depicting the 200 mb zonal wind anomaly shows the persistence of positive anomaly of 1-2 m/s over north of Saudi Arabia extending up to Iran and to southwest Afghanistan, means that there existed an anomalous jet stream flowing from southwest carrying the moisture into Iran and south Afghanistan.

Considering the meridional (vertical) wind structure at 500 mb (Figure **3d**) we observe a marked positive anomalies of 0.5-1.0 m/s over most of Pakistan, the Persian Gulf and further down over south Red Sea and

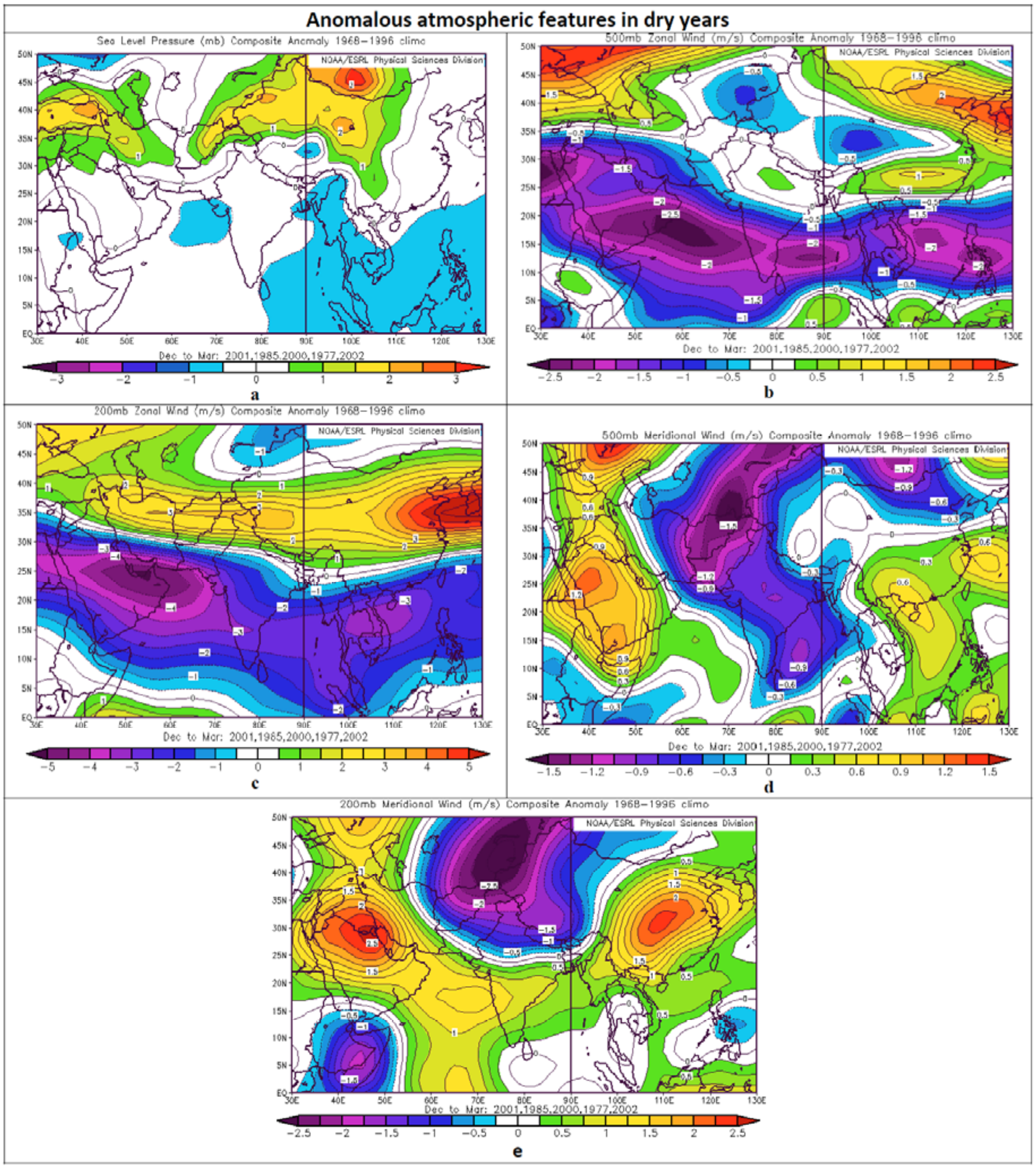

Figure 4: a: SLP (hPa) composite anomaly-dry. **b**: U(m/s) 500 mb composite anomaly-dry. **c**: U(m/s) 200 mb composite anomaly-dry. **d**: V(m/s) 500 mb composite anomaly-dry. **e**: V(m/s) 200 mb composite anomaly-dry.

east Africa implying that there was a strong southerly flow causing the moisture inflow from Gulf and formation of deep trough in mid-troposphere over Pakistan. At 200 mb the meridional wind with a positive anomaly of 0.5 to 1.0 m/s (Figure **3e**) over north/northwest Pakistan, Afghanistan and central Asia, which would have given rise to the jet stream.

These features at surface, mid and upper atmosphere indicate that during wet years there was more passage of low-pressure systems across Pakistan supported by strong horizontal and vertical wind gradients at mid and upper tropospheric levels which ultimately would have caused an enhanced moisture incursion from the North Arabian Sea and Gulf and hence resulting in abnormal wetness.

3.2. Dry Years' Anomalous Features

The anomalies' plots of the atmospheric fields for dry (or deficient) years are shown in Figure **4**(**a-e**). Figure **4a** shows a positive anomaly of 0.5 to 1 mb in SLP prevailing over northeast Afghanistan and northwest Pakistan with eastward extension which is a feature quite contrary to that observed in wet years' case (Figure **3a**). This means at mean-sea level there was no favourable condition for the formation of low-pressure systems. The zonal wind anomalies of -0.5 to -1.5 m/s at 500 mb and 200 mb (Figure **4b**, **c**) are observed spreading over a planetary scale from lat. 10°N to 26°N and long. 30 - 125°E, meaning there was absolutely no horizontal wind gradient which ultimately led to an abnormally stable atmosphere. The meridional wind anomalies at 500 mb (Figure **4d**) are observed with strong and significant negative anomalies of -0.6 to -1.2 m/s spreading over the entire Arabian Sea, most of Iran, Pakistan, Afghanistan, India and central Asian states. This is suggestive for prevalence of northerly flow and unusually high subsidence of the air, entirely opposite to what we observed in case of wet years. At 200 mb (Figure **4e**) the situation is materially no different with a strong negative anomaly of -1 to -2.5m/s over most Pakistan and extending northwards to Central Asia, while two positive anomalies of 2-2.5 m/s far too east over south China and in west over northeast Saudi Arabia to cause any effect over the study-area, Pakistan. These features contributed to the situation where at mean-sea level there was no passage of low-pressure systems across Pakistan and Afghanistan and upper-air flow was directed from the north instead of west/ southwest which led to unusual subsidence and hence the dryness.

4. DISCUSSION

The analysis of Pakistan 30-year winter rainfall data shows the 10 largely abnormal or anomalous years, i.e. five surplus (wet) years and five deficient (dry) years (Table **1**). This is an indication that Pakistan experiences a considerable inter-annual rainfall variability and the winter rainfall is greatly influenced by regional and global atmospheric parameters (Figures **3** and **4**). Various studies documented that the failed winter rainfall has resulted in a reduced wheat (a cash crop) and other winter crops production coupled with a reduced rivers discharge across Pakistan which ultimately affected the water supply for irrigation down the stream [7-10]. Likewise a study conducted on the climate change impact on agriculture has documented that 95 percent farmers in the arid region of northern Pakistan are of the view that temperature increase and rainfall decrease is the main cause in changing climate with rains have been dried up causing dramatic changes in the agriculture productions [11-13]. The results vindicate wheat crop high sensitivity to the changing climatic conditions and that a decreasing rainfall coupled with increasing temperature has alarming effects on wheat production.

For some areas in the west and southwest Pakistan the winter rain is more important as they receive their 40% to 80% rains during the DJFM season with no considerable monsoon rain, evident from the long term climatic average rainfall of individual data stations (Annexure), so its failure means an enhanced risk of drought-like situation there. Wintertime solid precipitation contributes to snow accumulation over Pakistan mountainous region in the north which feed the rivers Indus and Shyok basins contributing more than 25% of the inflow to Tarbela Dam [25] which is the main controlling structure for the Indus basin irrigation system and country's major power production unit. The inflow to another big reservoir and power generating unit 'Mangla Dam' comes through a river Jhelum whose basin located in the same terrain is also fed by winter snow and perennial ice during the summer season; vital for irrigation and hydropower production in the region [26].

The NCEP/NCAR reanalysis suggests that a persistence prevalence of the anomalous tropospheric pressure pattern at 200 hPa (4-year-averaged) spread over entire mid-latitudinal belt from west to east suppressed the cyclonic activity over the area. Resultantly the oceanic forcing which caused the change in temperatures, wind and atmospheric circulations led to unusual protracted drying.

5. CONCLUSION AND FUTURE PLAN

We can therefore conclude that a careful analysis of the past uneven episodes of anomalous wetness (dryness) with exploration of responsible atmospheric forcing can lead to a better climate elements' prediction and hence an improved assessment of potential impact on agriculture yields. Such attempt may prove helpful in better management of available water resources in the wake of excess (deficit) rainfall episodes. Future plan is to enhance this study by analysing such data over longer periods, say 60/ 90-year, and with considering more atmospheric circulation features like outgoing longwave radiation, OLR, surface air temperatures, moisture influx and sea surface temperatures (SSTs) etc. and also for the anomalous monsoon (summer, July-September, JAS) season over Pakistan.

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ANNEXURE

Information on WMO Index Number, elevation, location (Lat and Long), Mean winter rain, Mean minimum temperature and mean maximum temperature of the Meteorological stations used in study

No	Name of Station	WMO Index Number	Elevation a.s.l (m)	Lat. (° N)	Long. (°E)	Mean winter rain (mm)	Mean Temp. (T_{min}°C)	Mean Temp.(T_{max}°C)
1	Chitral	41506	1499	35° 51'	71° 50'	248.3	1.0	34.1
2	Gilgit	43516	1459	35° 55'	74° 20'	26.7	0.1	34.3
3	Astore	43520	2167	35° 22'	74° 54'	193.0	-4.6	25.4
4	Skardu	43517	2209	35° 18'	75° 41'	99.3	-4.2	29.5
5	Dir	41508	1369	35° 12'	71° 51'	616.9	-0.4	30.7
6	Balakot	41536	980	34° 23'	73° 21'	518.2	4.1	32.5
7	Peshawar	41530	359	34° 01'	71° 35'	170.4	6.6	37.0
8	Parachinar	41560	1725	33° 52'	70° 05'	270.6	0.7	26.5
9	Islamabad	41571	507	33° 37'	73° 06'	256.7	5.2	35.2
10	Murree	41573	2167	33° 55'	73° 23'	518.6	1.8	22.5
11	Muzaffarabad	43532	701	34° 22'	73° 29'	361.8	5.5	35.0
12	Jehlum	41598	232	32° 56'	73° 43'	174.7	7.7	36.8
13	Sialkot	41600	251	32° 30'	74° 32'	170.2	7.5	36.0
14	Lahore	41640	213	31° 33'	74° 20'	105.7	8.9	36.9
15	Sargodha	41594	187	32° 00'	72° 07'	21.0	6.9	----
16	Mianwali	41598	209	32° 35'	71° 32'	27.7	---	---
17	D.I.Khan	41624	173	31° 49'	70° 55'	62.7	5.9	38.6
18	Zhob	41620	1405	31° 21'	69° 28'	105.6	2.3	35.2
19	Quetta	41660	1600	30° 15'	66° 53'	191.2	-1.0	34.3
20	Barkhan	41685	1097	29° 53'	69° 43'	73.4	4.7	35.3
21	Sibbi	41697	133	29° 33'	67° 53'	44.8	9.0	42.6
22	Kalat	41696	2015	29° 02'	66° 35'	83.2	-1.8	-----
23	Dalbandin	41712	848	28° 53'	64° 24'	60.7	4.5	40.3
24	Khuzdar	41744	1231	27° 50'	66° 38'	88.5	5.9	36.0
25	Panjgur	41739	980	26° 58'	64° 06'	57.6	6.3	38.1
26	Faisalabad	41630	183	31° 26'	73° 06'	65.9	7.2	37.5
27	Multan	41675	122	30° 12'	71° 26'	43.1	7.8	39.4
28	Bhawalpur	41700	116	29° 24'	71° 47'	29.9	8.6	39.6
29	Khanpur	41718	87	28° 39'	70° 41'	18.7	7.4	39.8
30	Sukkur	41724	66	27° 42'	68° 54'	21.0	11.3	40.7
31	Jacobabad	41715	55	28° 18'	68° 28'	24.2	10.8	40.6
32	Nawabshah	41749	37	26° 15'	68° 22'	9.3	9.0	40.8
33	Hyderabad	41764	40	25° 23'	68° 25'	12.2	13.9	38.5
34	Karachi	41780	21	24° 54'	67° 08'	31.9	13.1	33.5
35	Jiwani	41756	56	25° 04'	61° 48'	90.9	15.8	32.6

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