A Study of Drought over Sindh (Pakistan) Using Standardized Precipitation Index (SPI) 1951 to 2010

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ABSTRACT

In the context of an effective communication between stakeholders, the Standardized Precipitation Index (SPI) is a powerful tool, requiring only rainfall data for its calculation, and delivering 5 major dimensions of drought: duration, intensity, severity, magnitude, and frequency. Furthermore, it is a multi-scalar index, providing an extremely helpful coverage of impacts on diverse time dimensions. The SPI was applied to precipitation datasets in Sindh, a region experiencing frequent drought events. The SPI's capacity to analyze historical records and compare different series is assessed, while its ability to monitor drought conditions, define its main features, and communicate its results to all stakeholders involved, is expected to create a wide acceptance of the Index. Sixty years (1951 to 2010) monthly precipitation data of nine (9) weather station of Sindh are used to calculate SPI values for different time scales; 3, 6, 9, 12, 24, 36 and 48 months. The time series plots of SPIs indicated that the time scales less than 12 months had enormous fluctuations so that identifying drought and wet periods were not so clear. However, plots of 36 month SPI and 48 month SPI obviously could identify drought and wet periods of the region clearly. The result makes clear that the duration, attenuation, intensity and magnitude for any particular month during our historical records are time scale dependent. Based on the above result it is recommend that the agriculturist use SPIs of 12 months or less and water resource managers apply 36 months SPI for Sindh region.

Key words: Drought, Standardized Precipitation Index, Z-Score, Multi-scale, Probability Density Function.

INTRODUCTION

Drought is a complex term that has various definitions, depending on individual perceptions e.g. in farmer's language "a shortage of rainfall or a long period of time without any rainfall", or a period of below average rainfall or a prolonged period of dryness that can cause damage to plants. It may be categorized into different types e.g. Meteorological, Hydrological, Agricultural and Socio-economic drought.

The glossary of Meteorology defines drought as a period of abnormally dry weather sufficiently prolonged for the lack of water to cause serious hydrological imbalance in the affected area, on the degree of dryness and the duration of dry spell (Huschke, R.E. ed., 1959)

Although, many erroneously consider it a rare and random event but drought is a normal, recurrent feature of climate. It can occur in virtually all climatic zones, with its characteristics varying significantly from one region to another. It is an insidious hazard of nature.

Drought can erupt in a matter of months, or it can gradually creep up on an unsuspecting society over several seasons. It goes unobserved by the public until impacts from the drought have already occurred. Drought has become a frequent phenomenon in Sindh, due to rise in pollution and climatic changes. Sindh is located in the western corner of South Asia, bordering the Balochistan plateau in the west. It is the third largest province of the country, stretching for about 579 km from north to south and 442 km (extreme) or 281 km (average) from east to west, covering an area of 140,915 square kilometres (54,408 sq mi) within Pakistani territory. With the Thar desert is in the east, Kirthar mountains in west, and Arabian Sea in the south, the central part is covered by the fertile Indus plain.

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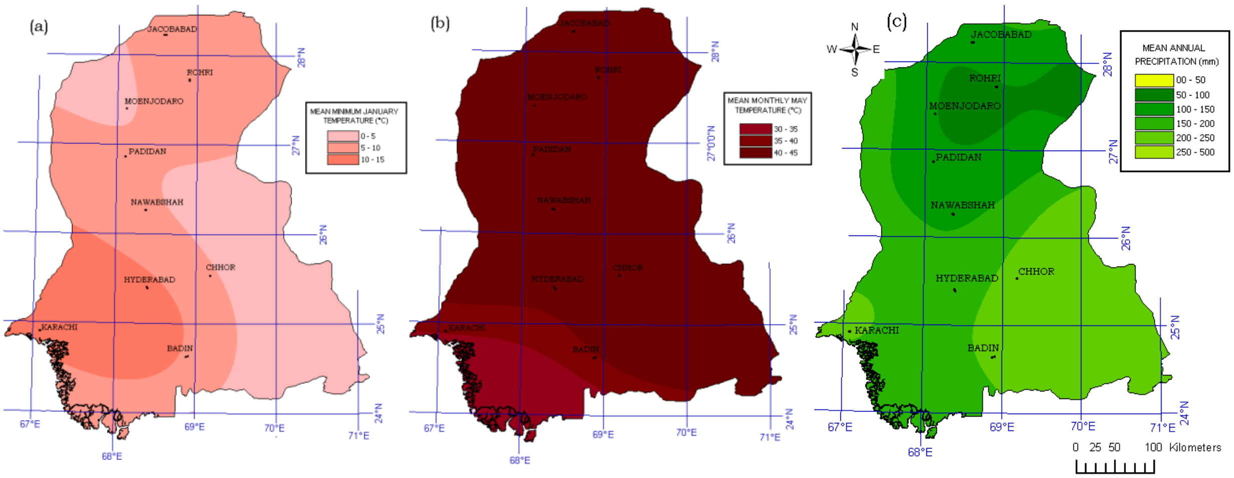

Figure 1: (a) Mean minimum January, and **(b)** mean maximum May temperature (°C), and **(c)** mean annual total precipitation (mm) of Sindh for the period 1951-2010

Dwelling in the semitropical area, the climate of Sindh is hot in summers i.e. during May and August and cold in winters i.e. during December and January. The mercury frequently rises above 46°C during the long summers (May – August) (Figure.1b), and falls below 2 °C during the short winters (December–January) (Figure.1a). The mean annual total precipitation (Figure.1.c) is about 150-180 mm, more than 70% of which is received during the monsoons (July and August). Scarcity of water is compensated by the inundation of the Indus twice a year, caused by the spring and summer melting of the Himalayan snow and by precipitation. These natural patterns have been somewhat modified by the construction of dams and barrages on the Indus River. Winds blow in west, southwesterly direction during mid-February until the end of September and northerly during the month of October to January.

Sindh is fractioned into three different climatic regions (Burton, 1992):

a. Siro (the northen/upper region, centred on Jacobabad),

b. Wicholo (the central/middle region, centred on Hyderabad), and;

c. Lar (the lower/southern region, south of Hyderabad).

The thermal equator passes through upper Sindh, where the air is generally very dry. Temperatures are generally lower in central Sindh than in upper Sindh but higher than that in lower Sindh. Dry hot days and cool nights are typical during the summer. Maximum temperature in Central Sindh typically reaches 43–44 °C. Lower Sindh has a damper and humid maritime climate affected by the southwestern winds in summer and northeastern winds in winter, with less precipitation than central Sindh. Maximum temperature in lower Sindh reaches about 35 to 38 °C. In the Kirthar range at on elevation 1,800 m (5,900 ft) and higher at Gorakh Hill and other peaks in Dadu district, temperatures near freezing have been recorded and brief snowfall is received in the winters.

The purpose of this study is to analyze the variability of drought historically in the province of Sindh, Pakistan in order to furnish drought mitigation planners and other users with information that will be helpful to review current drought in historical perspective.

METHODOLOGY

Experts in the Inter-Regional WMO Workshop on Indices and Early Warning Systems, 2009 has consensus that Standardized Precipitation Index (SPI) should be used to characterize meteorological droughts by all National Meteorological and Hydrological Services around the world (WMO Press Release No. 872 for use of the information media only)

SPI is a probability index for monitoring drought developed by McKee et al., (1993) by fitting a gamma probability distribution for a station frequency distribution of precipitation totals. This drought index was recently developed to detect drought and wet periods for different time scales in various regions of the world. Drought approaches have traditionally been discipline-specific, although its diffuse and complex nature calls for interdisciplinary and territorial methodologies, laying the grounds for a geographic approach. SPI allows to determine the rarity of drought on temporal resolution for any precipitation station.

The gamma distribution has been found to fit precipitation time series well by Thom (1958). The probability density function defined gamma distribution for x>0

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \quad \text{.......................... (1)}$$

where α is shape and β is scale parameter, x is precipitation and Γ(α) is gamma function and

$$\alpha = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \quad \text{........................... (2)}$$

$$\beta = \frac{\bar{x}}{\alpha} \quad \text{..................................... (3)}$$

$$A = \ln(\bar{x}) - \frac{\sum ln(x)}{n} \quad \text{........................... (4)}$$

and n is the number of observation.

For station in question, to find the cumulative probability of an observed precipitation event for the given month and time scale the resulting parameters are then used. x=0 is undefined in gamma function and precipitation may contains zeros. The cumulative probability H(x) is calculated by:

$$H(x) = q + (1-q)G(x) \quad \text{.......................... (5)}$$

Where q is probability of zero G(x) the cumulative probability of incomplete gamma function

The definition of drought proposed by McKee, et al. (1993) employing the Standardized Precipitation Index (SPI) is used to measure drought for time scales ranging from 3, 6,12, 24, 36 and 48 months. Therefore, computation of the SPI involves fitting a gamma probability density function to a given time series of monthly precipitation totals for a station. The resulting parameters are then used to find the probability of a particular precipitation event over a given time scale. This probability is then converted to the standard normal random variable Z, which is the SPI index value. Conceptually, the SPI for a given time scale is the difference of precipitation from the mean divided by the standard deviation. McKee et al developed the SPI in 1993 and originally calculated the SPI for 3, 6, 12, 24, 36 and 48 months time scales. Additionally, McKee et al. (1993), defines an event as drought when the SPI becomes -1.0 or less. The beginning of this drought is then defined as a period when the SPI first goes negative. The end of the drought does not occur until the SPI returns to positive. McKee et al (1993, 1995) defines drought intensity using the following categories, given in Table 1, Guttman (1999) uses the same categories in USA:

Table 1

SPI	Intensity	Time in Category (%)
3.00 to 2.00	extremely wet	02.3
1.99 to 1.50	very wet	04.4
1.49 to 1.00	moderate wet	09.2
-0.99 to 0.99	near normal	68.2
-1.00 to -1.49	moderate dry	09.2
-1.50 to -1.99	severe dry	04.4
-2.00 to -3.00	extremely dry	02.3

Because the SPI is standardized, these percentages are expected from a normal distribution of the SPI. The 2.3% of SPI values within the "Extreme Drought" category is a percentage that is typically expected for an "extreme" event (Wilhite, 1995). In contrast, the Palmer Index (Palmer, W.C. 1965) reaches its "extreme" category more than 10% of the time across portions of the central Great Plains. Many studies have identified the problems with spatial comparability and limitation of Palmer Index (Karl 1983, 1986), (Alley 1984), (Heddinghaus and Sabol, 1991), (Guttman et al. 1992) and (Wells et al. 2004). This standardization allows the SPI to determine the rarity of a current drought, as well as the probability of the precipitation necessary to end the current drought (McKee et al., 1993).

The SPI time scales reflect the impact of wet and dry spell on the availability of different water resources. Short scale precipitation anomalies affect soil moisture condition while long scale precipitation anomalies reflect impacts on stream flow, ground water and shortage in reservoir.

The SPI can be computed for different time scales, can provide early warning of drought, although it is not a forecasting tool, help assess drought severity, and is less complex than the Palmer, e.g., the drought in the every two to four years may be well observed by the 12 months SPI in Sindh. On the other hand, the 36 and 48 months SPI allow us to quantify long-term persistent droughts of the type that occurred in the 1974-75 and 2002-03. Shirvani, et.al., (2003) recommended upto 12-months SPIs for agriculturists and 36-months for water resource managers during European Geophysical Society (EGS) – American Geophysical Union (AGU) – European Union of Geosciences (EUG) Joint Assembly meeting held in Nice, France on 6 - 11 April 2003.

Anomalously wet and dry events may easily be determined. SPI requires long term data (i.e. 30 years or more). It can use to monitor drought at different time scales but cannot use to predict. The small time scale (e.g. 1, 3 etc. moths) extreme seasonal high or low precipitation amount misleads the result. Precipitation variability is much higher and is the only input climate parameter in SPI. The other climate parameters which cause water demand e.g. temperature, wind, solar radiation, evaporation etc. have very low variability therefore, do not account for.

The SPI is gaining increasing acceptance as a valuable tool for monitoring drought. It is currently being used by National Drought Monitoring Cell of Pakistan Meteorological Department (PMD), and many parts of the world e.g. National Drought Mitigation Center, the Western Regional Climate Center, as well as the Colorado Climate Center, etc.

DATA SET

Revisions of the monthly data set have been used, supplied by the Computerized Data Processing Centre (CDPC), PMD, Karachi to get the opportunity to investigate the occurrence of drought over Sindh province (Pakistan). This data set has been extensively quality controlled. For this study, the investigation period is from 1951 to 2010 while the nine stations of Sindh are Karachi, Hyderabad, Badin, Rohri, Moen-Jo-Daro, Jacobabad, Nawabshah, Padidan and Chhor, having minimal availability of missing data. The unit of precipitation is linear depth, usually in millimetres (volume/area), or kg m^{-2} (mass/area) for liquid precipitation (WMO, 2008). In this study, as per recommended by the Commission for Instruments and Methods of Observation at its eleventh session, 1994 (WMO, 2008), precipitation unit may also been used in kg m^{-2} i.e. (1 mm = 1 kg m^{-2}). The SPI for these nine stations of PMD has been calculated for 3, 6, 12, 24, 36 and 48 months time scale. Average SPI for the Sindh province has been calculated for each time scale.

ANALYSIS

12 and 36 months time scale SPI has been depicted in Figure.2a to 2i for Badin, Chhor, Hyderabad, Jacobabad, Karachi, Moenjodaro, Nawabshah, Padidan, and Rohri stations of Sindh. 6, 12, 24, and 36

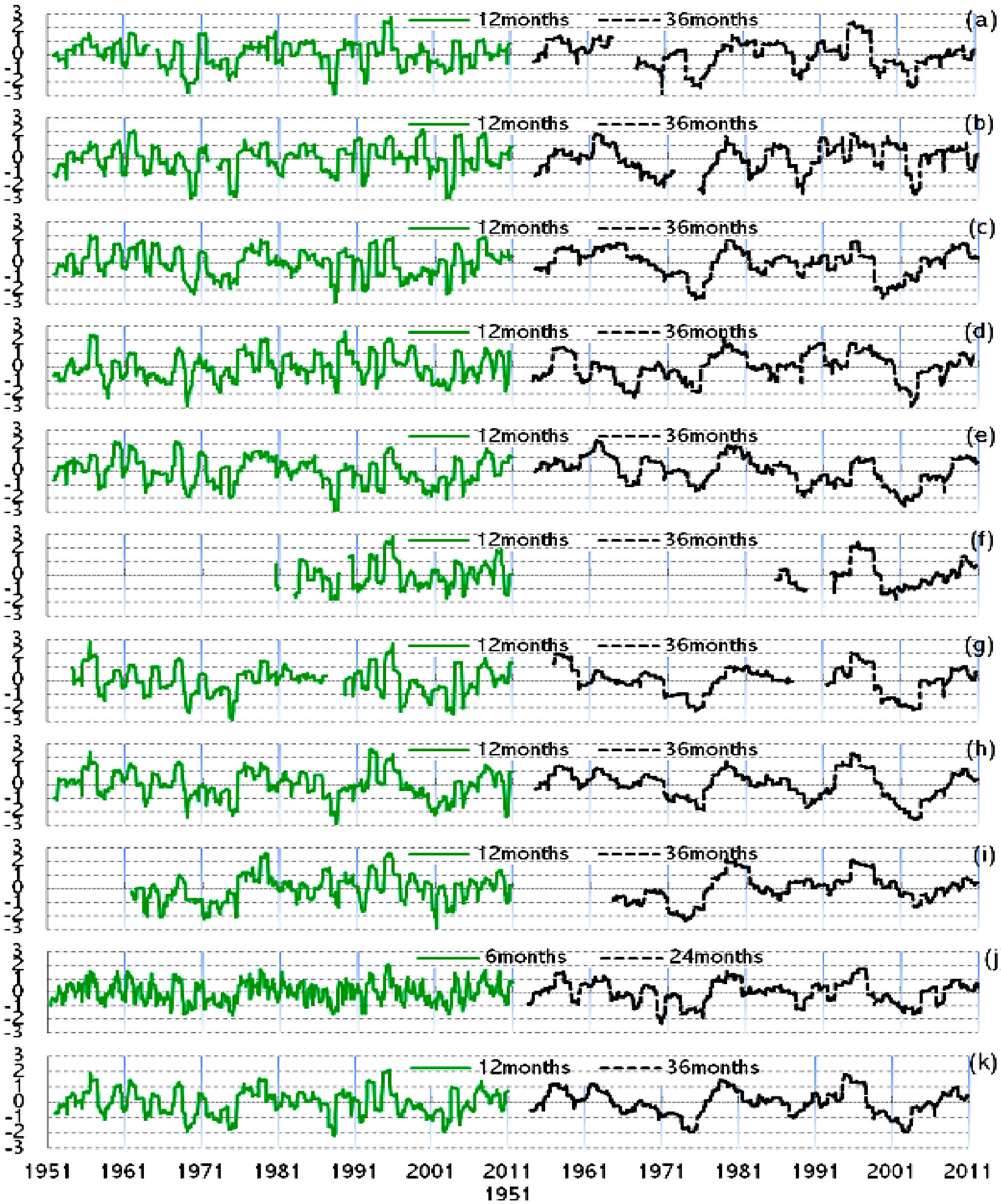

Figure 2: SPI (12 and 36 months time scale) for **(a)** Badin, **(b)** Chhor, **(c)** Hyderabad, **(d)** Jacobabad, (e) Karachi, **(f)** Moenjodaro, **(g)** Nawabshah, **(h)** Padidan, **(i)** Rohri, and **(j)** 6 and 24 months and **(k)** 24 and 36 months average time scale SPI for Sindh province

months Average time scale SPI for the Sindh province has been illustrated in Figure.2j and 2k. These Figures, portray that short term wet and dry spells cycle frequently occur in every 2 to 4 years at almost all stations of Sindh in 12 month time scale. Another 20 to 25 years cycle may also been witnessed in 36-months time scale. This 2 to 4 years small frequency of wet and dry spells become more prominent in Figures.2.b and 2.c and can easily be identified in these figures. The years which are identified as dry are 1957, 1963, 1968, 1972 and 1987, then after a long gap of 14 years, it appears again in 1987, 1991, 1996, 2001, and 2003. 12 and 24 months SPI (Figures.1.j and 1.k) indicates sustained drought during the period from the end of 1959 to the mid of 1973, and then 1988 and 2002. The same Figure. described the long term drought more elaborately. Two intense spells of drought in 1974 and 2002 become further cogent and grow to be strongly projected.

The average 36 month SPI time series shows the sustained and intense droughts in mid 1975 with its peak value (-2.01) another intense period of drought is also observed from in the early 2000s with its peak value (-1.99) in the year 2002. However, the average 48-month SPI time series gives a clear indication of the sustained and intense droughts from 1973 to 1975 with its peak value (-2.01) in the year 1975. Another intense period of drought has also been observed from 2002 to 2003 with their peak value (-2.09) in the year 2003.

The station wise detailed study indicates that moderate to severe drought is commonly observed at different time scale. In 12-months time scale moderate droughts have been observed 9, 8, 3, 13, 10, 5, 10, 7 and 5 times at Badin, Chhor, Hyderabad, Jacobabad, Karachi, Moenjdaro, Nawabshah, Padidan and Rohri respectively. Severe drought has been identified at Badin, Chhor, Hyderabad, Jacobabad, Karachi, Moenjodaro, Nawab, Padidan and Rohri at 1, 3, 6, 6, 8, 5, 1, 5 and 4 times respectively. Extreme droughts have been identified in 1969 and during 2001-02 at almost all stations except Karachi. Four stations experienced it during 1974-75 while few experinced in 1987-88, 1991-92 and 2010. Chhor observed peak value -2.7, Hyderabad -2.3, Jacobabad -2.4, Karachi -2.6, Nawabshah -2.4 while Rohri -2.2. It also reveals that during the years 1972 to 1975 and 1999 to 2003 most of the stations indicate moderate to extreme drought with peak values in 1975 and 2003 respectively. The station wise analysis also revealed that the drought intensity increases spatially from north to south or from Ciro (upper) to Lar (lower) region.

Similarly various peaks of wet period have also been observed during the study period but are considered irrelevant for the present study. The other time scales have not been illustrated but analyzed for study purpose. 3 and 6 months SPI had been reflected considerable rainfall variability in it. 48-months SPI had pointed the most drought hazardous year, its peak value some time mislead the intensity of drought.

Figure.3 shows long term mean annual precipitation of Sindh. As depicted in the graph, frequency of low precipitation is higher. Sindh received highest precipitation once in the time series in the 1994. One third of the time series records between 200-400 (mm or kg m^{-2}) ranges otherwise it is below 200 (mm or kg m^{-2}), which indicates permanent arid feature.

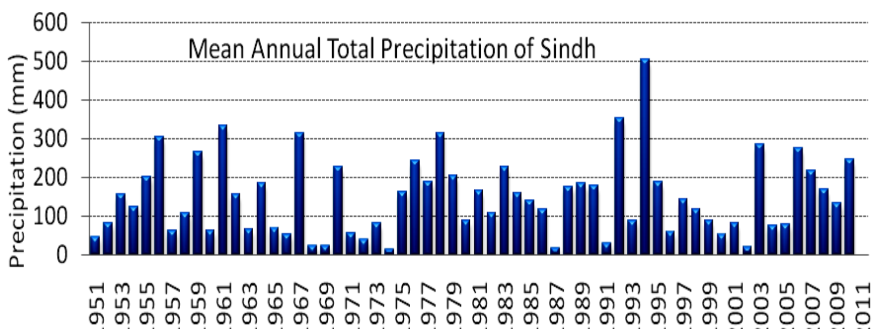

Figure 3: Total annual Precipitation of Sindh from 1951 through 2010

CONCLUSION

Sindh has arid climate, hence most vulnerable to drought hazard risk. SPIs time scale of 3, 6, 12, 24, 36 and 48 months have been analyzed. The time series of the average 3 and 6 months SPI for Sindh revealed that short term mild droughts are common at the stations in the study throughout the period of record. Fluctuations in 12 months SPI series have clearly identified short term wet and dry periods. However, 24, 36 and 48 months time scale SPI were noticeably perceived as dry and wet spells. The study reveals that short term wet and dry spell may easily be demarcated by small time scale average SPI analysis and long term by large scale from 24 to 48 months SPI for the province as a whole. The duration, attenuation and intensity for any particular month have been found to be time scale dependent. The study verified that long term drought of during 1974-76 and early 1999-2002 had a severe in nature at majority of the stations of Sindh. Since the time scale from sowing to harvesting of cash/food crops or vegetable is not more than 12 months span in any case, therefore, based on results, it is recommended that agriculturist and related stake holder may utilize 3, 6 and/or 12 months SPI while, water resource managers may apply 24, 36, 48 months SPI for water consumption, estimations and future planning in Sindh region getting the help from this past fifty year analysis.

Every drought event/spell ends when SPI becomes positive. Short time scales SPI anomalies reflect the soil moisture condition and long term time scale reflect streamflow, groundwater recharge and reservoir storage. Based on historical long term time series data, analyst can tell the impact of these anomalies on aforementioned domains. The duration of drought event/spell may be obtained by counting the months from the beginning to ending of negative SPI values and magnitude by positive summing the SPI values of all months within drought event/spell.

ACKNOWLEDGEMENT

Special thanks to Mr. Musleh-ud-din, ex-Director, IMG for precious suggestions and guidelines in the preparation of the manuscript. The cooperation of Mr. Abdul Rashid has been acknowledged. Authors are also thankful to the team of CDPC and IMG for their unbound help and support.

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