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RESEARCH ARTICLE

Statistical Trend Analysis of Climate Change Parameters in the Coastal Belt of Gulf of Kachchh, Gujarat, India

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ABSTRACT: The coastal belt along the Gulf of Kachchh is home to several seaports, oil import, refining facilities, power plants, and military bases. All of them are vulnerable to the fallouts of climate change, such as sea-level rise, air and sea surface temperature, storms, and flooding. A changing climate and intense human activities severely stress the coastal environments.

This paper attempts to statistically analyze the historical measurements of air temperature, sea surface temperature, sea-level rise, rainfall, and major storm events and arrive at the changes that occurred in the past using a linear regression trend line. The observed past changes are then compared with the future predictions of the same parameters as given by The Intergovernmental Panel on Climate Change.

Historical Measurements of air temperature show an increase of +0.006˚C/year, and future air temperature increase is in the range of +0.014-0.048˚C/year. It is pertinent to note that the observed air temperature rise in the past is lower than the predicted rise in the coming century.

Historical seawater temperature measurements show an increase of +0.014˚C/year; the predicted growth is +0.02˚C/year.

Rainfall historical measurements have shown an increase of +0.9 mm/year for Saurashtra and +0.2 mm/year for Kachchh. The future increase predicted is +0.5 mm/year as per the distribution of precipitation in global climate scenarios RCP2.6 and RCP8.5.

Storm events have increased over the past several decades. However, it is uncertain whether these storm changes exceed the levels expected from natural causes.

Sea level rise has been of the order of +1.8 mm/year and is predicted to rise to +1.7 mm/year.

The projections are supported by the trends in the observations, except for the air temperature, which is higher than found in the observations. For the other parameters, the observations and predictions are reasonably consistent.

KEYWORDS: Earth and Environmental Science, Climate Science, Climate change, sea-level rise, air temperature, sea water temperature.

Introduction

Weather refers to short-term atmospheric conditions, while climate is the weather of a specific region averaged over a long period of time.

'Climate change' can be taken as a change in the statistical properties of the climate system when considered over long periods of time (often 30 years)[1], regardless of cause.

Historical measurements on parameters such as air temperature, sea water temperature, rainfall, and storm events are collected from the Indian Meteorological Department (IMD),[2] at available stations in the Gulf of Kachchh area, and a linear regression line is used to analyze the annual variations.

The observed changes are not extrapolated for future predictions but serve as examples of climate change (climate change takes place over a timescale of 30 years). Hence, a linear regression trend line is taken to show climate change.

The observed past changes are compared with IPCC, 2014.[3] The Intergovernmental Panel on Climate Change (IPCC) analyzes and predicts climate change. Their studies are used directly or are downscaled to give more precise answers on a regional (e.g., India) or local scale (e.g., Gujarat state or the Gulf of Kachchh). Predictive climate change is based on long-term measurements and numerical models combined with different scenarios for future consumption of fossil fuels and the release of greenhouse gases. These studies do not end up with an exact description of the future climate; instead, a range of scenarios is produced.

Climate of Gulf of Kachchh:

Gujarat falls partly in the tropical and partly in the sub-tropical zone. Important large-scale geographical features for the climate in Gujarat are:

- The Indian continent to the east with its continental climate and the Himalayan mountains to the northeast; and
- The warm and salty Arabian Sea to the west.

The climate in the Gulf of Kachchh and its catchment area is arid to semi-arid. At this moment, the precipitation is below the potential evapotranspiration. The warm and dry climate creates a harsh environment with only limited water resources, e.g., drinking and irrigation.

The weather in Gujarat can be divided into four seasons (several names are used for the different seasons):

- The winter season, or NE monsoon, from November through February.
- The summer season, or pre-monsoon, from March through May.
- The monsoon season, or SW monsoon, or wet period, is from June through September; and
- The autumn season, or post-monsoon, in October.

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The monthly mean air temperature varies between 21°C in January and 30°C in June. The dominating winds and the rainfall change significantly with the seasons (Table 1 and Figure 1):

- During the winter, cooling of the continent and mountains causes weak NE winds that bring dry air from the inland continent to the area, and the rainfall is limited.
- During the monsoon, the heating of the continent and mountains causes stronger SW winds that bring more humid air from the Arabian Sea to the area, and the rainfall is significant (most of the annual rainfall falls during the monsoon).

Table 1: Wind speed and direction at the Gulf of Kachchh for three seasons.[4]

Season	Wind speed (m/s)	Wind Direction
NE monsoon	3.5	NW & E & NE (337°)
Pre-monsoon	4.5	WNW (292°)
SW monsoon	6.5	SW & W (247°)

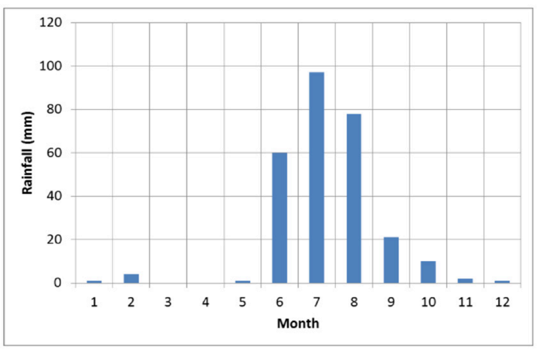

Figure 1: Monthly mean rainfall at Dwarka station in the Gulf of Kachchi.[5]

The potential evaporation exceeds the rainfall in Gujarat. For the Gulf itself, the evaporation, rainfall, and river inflow can be expressed in cm/year as follows,[6]

- - 100 cm/year from evaporation.
- + 42 cm/year from rainfall, and
- + 2 cm/year from rivers.

If it were not for the opening towards the Arabian Sea, the water level in the Gulf would fall 66 cm every year until the Gulf dried out. This water loss causes the salinity inside the Gulf to be higher than outside in the Arabian Sea. The warm and dry climate in the area, combined with the high salinity inside the Gulf, provides suitable conditions for salt production. A significant part of India's salt production occurs in the salt pans in the Gulf of Kachchh.

The north Indian Ocean accounts for 7% of global tropical cyclones.[7] More cyclones occur in the Bay of Bengal than in the Arabian Sea; the ratio of their respective frequencies is about 4:1.8 But the Arabian Sea can occasionally produce intense tropical cyclones. An example was Gonu in June 2007; this is the strongest recorded tropical cyclone in the sea. The cyclone tracks recorded from 1990 to 2021 by the India Meteorological Department (IMD, India) are given in Figure 2. Cyclones with landfall in the Gulf cause strong winds and heavy rain in the Gulf and its watershed area, storm surge, and high waves along the coast.

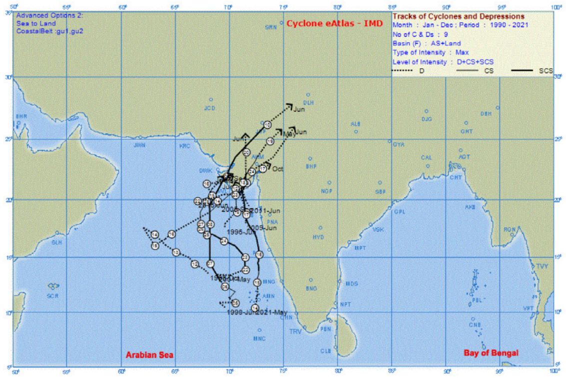

Figure 2: Cyclonic tracks in Gujarat Coast in the Arabian Sea from 1990 to 2021 as sourced from IMD.[2]

The trend in climate change parameters- historical data analysis:

Air Temperature:

The annual mean temperature in the southern Gulf (Saurashtra) and northern Gulf (Kachchh) for 100 years from 1901 to 2001 was procured from Indian Meteorological Department. The air temperature in the area has increased over the last hundred years (Figure 3 and Figure 4). The annual mean temperatures at both locations show an increasing long-term trend and an inter-annual variation. The inter-annual variation is bigger than the increase over the 100 years. The annual temperature increase in the Gulf of Kachchh area is found to be +0.0057°C/year as determined from the annual mean values for Saurashtra and Kachchh.

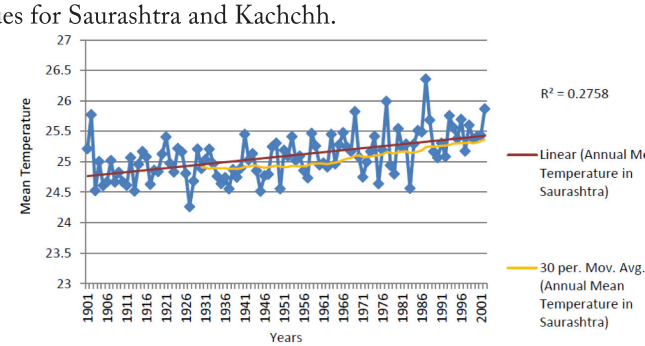

Figure 3: Annual mean temperature in the southern Gulf (Saurashtra) from 1901 to 2001 based on data and analyses from IMD.[2]

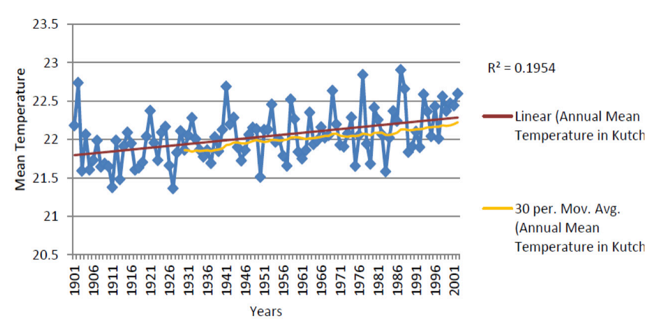

Figure 4: Annual mean temperature in the northern Gulf (Kachchh) from 1901 to 2001 based on data and analyses from IMD.[2]

Sea Water Temperature:

Long-term measurements from the Gulf of Kachchh are unavailable but have been made in the Arabian Sea. How ever, there should be a good correlation between the changes observed in the Arabian Sea and the changes in the Gulf of Kachchh itself. Indirect (more uncertain) measurements and observations of coral bleaching along the western coastline of India and in the Gulf of Kachchh indicate that sea temperatures have increased.[9] Figure 6 shows summer sea surface temperature by ocean basins, and the North Indian Ocean clearly shows an increasing trend line.

The yearly mean sea surface temperature at one location in the Arabian Sea from 1880 to 2012 (Figure 5) shows no significant long-term trend in the temperature. Still, a trend has been observed over the last 30 years, where the temperature increased by about 0.85°C.

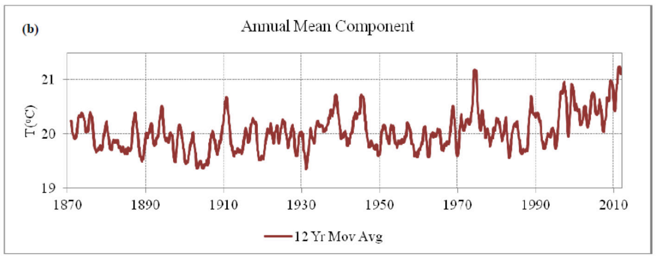

Figure 5: Yearly mean sea surface temperature at a location in the Arabian Sea from 1870 to 2012.[10]

An analysis of measurements from different ocean basins shows that the summer surface temperature in North India (NIO) ocean basin has increased by about 0.5°C (or 0.014°C/year) from the early seventies to the early zeros (Figure 6).

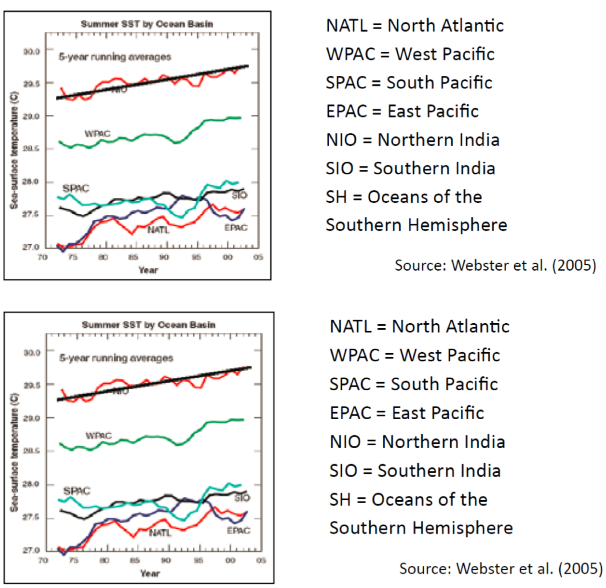

Figure 6: Summer sea surface temperature by ocean basin.[11]

Rainfall:

The annual rainfall in the area has not changed significantly over the last century (Figure 7 and Figure 8). The yearly rainfall shows a limited long-term trend but on the background of a considerable inter-annual variation. Even so, reading the numbers, however uncertain, the increase is found to be:

For the southern Gulf (Saurashtra): An increase from 1,160 mm to 1,250 mm (or an average of 0.9 mm/year); and

For the northern Gulf (Kachchh): An increase from 330 mm to 350 mm (or an average of 0.2 mm/year).

Cyclones bring much rainfall, so years with high rainfall are often years with cyclones. The number of intense rainfalls during the monsoon season has also increased in recent years, which increases the number of rainfed floods. There has also been an increase in droughts during the dry season.

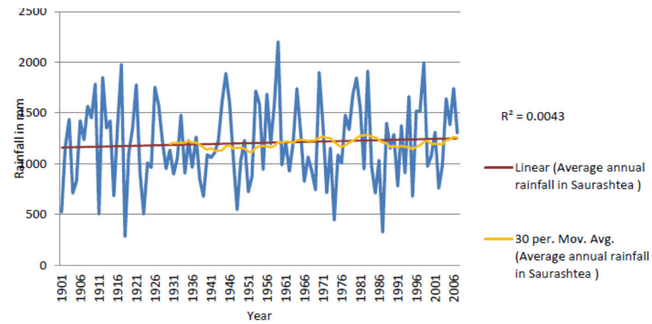

Figure 7: Annual rainfall in the southern Gulf (Saurashtra) from 1901 to 2001 based on data and analyses from IMD.[2]

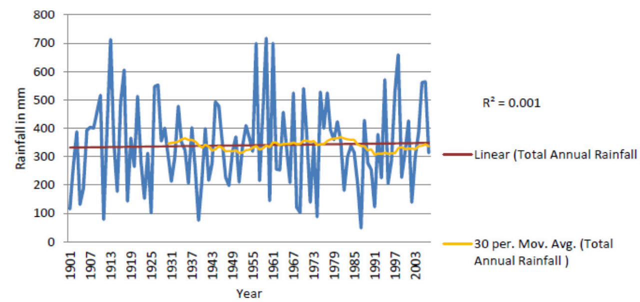

Figure 8: Annual rainfall in the northern Gulf (Kachchh) from 1901 to 2001 based on data and analyses from IMD.[2]

Sea Level:

Analyses of long-time series of water levels show that the sea level is rising along the Indian coastline (Table 2). Measured sea levels are relative to the land level; hence, they need to be corrected for tectonic land level rise. The measurements show that the average relative sea level rise is 0.85 mm/year (relative to land level), and the average absolute sea level rise is 1.28 mm/year.

Table 2: Trends of sea level rise (SLR) and land level rise (LLR) along the Indian coastline and nearby locations.[12]

Station	Period	Rel. SLR (mm/year)	LLR (mm/year)	Abs. SLR (mm/year)
Karachi	1916-1992	0.61 +/- 0.32	0.45	1.06
Mumbai	1878-1993	0.77 +/- 0.08	0.43	1.20
Kochi	1939-2003	1.31 +/- 0.23	0.44	1.75
Vishakhapatnam	1937-2000	0.70 +/- 0.28	0.39	1.09
Average	NA	0.85	0.43	1.28

According to Figure 9, the absolute sea level rise in the Indian Ocean outside the Gulf of Kachchh is about 2.2 mm/year. Since the continent's rise is about 0.4 mm/year, the relative sea level rise is about +1.8 mm/year.

NOAA satellite data show an absolute global sea level rise of 6 cm over the 20 years (or 3.0 mm/year) between 1993 and 2013.13 In other words, the change at the mouth of the Gulf of Kachchh appears to be about 70% (2.2 mm/year / 3.0 mm/year) of the absolute global change in this period.

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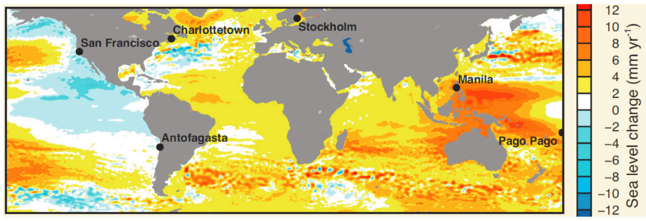

Figure 9: Map of rates of change in sea surface height (geocentric sea level) from 1993–2012 from satellite altimetry.[14]

Cyclones:

Forty cyclones hit the Gujarat coastline from 1893 to 2010.[2] More severe cyclones (88-117 km/h) have occurred in recent years and are assumed to be caused by the increasing sea temperatures. The cyclone wind speeds were analyzed to get an objective, however uncertain, a measure of the increase (Figure 10). Based on the trend line, the average cyclone wind speed was 66 m/s in 1893 and increased to 72 m/s in 2010.

The increase in wind speed is about 9% (0.05 m/s/year or 0.08 %/year). In this connection, it is important to note that the small increase in wind speed corresponds to an increase in cyclone-related impacts such as storm surges and rainfall-induced floods.

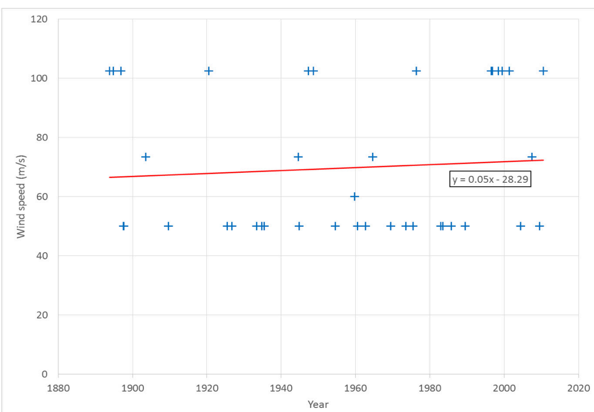

Figure 10: Cyclone wind speed (mean wind from the intensity) sourced from IMD.[2]

Future Prediction of Climate Change:

Anthropogenic greenhouse gas (GHG) emissions are mainly driven by population size, economic activity, lifestyle, energy use, land use patterns, technology, and climate policy. In the Representative Concentration Pathways (RCPs),[3] (which are used for making projections based on these factors) describes four 21st-century pathways of GHG emissions and atmospheric concentrations, air pollutant emissions, and land use. The RCPs include:

- One stringent mitigation scenario (RCP2.6). It is representative of a scenario that aims to keep warming likely below 2˚C above pre-industrial temperatures.
- Two intermediate scenarios (RCP4.5 and RCP6.0), and
- One scenario with very high GHG emissions (RCP8.5).

Scenarios without additional efforts to constrain emissions ('baseline scenarios') lead to pathways ranging between RCP6.0 (lower bound) and RCP8.5 (upper bound).

Air Temperature:

Figure 11 below shows different predictions of global temperatures. The increase of global mean surface temperature by the end of the 21st century (2081–2100) relative to 1986–2005 is likely to be:

- 0.3˚C to 1.7˚C under RCP2.6 (+0.003 to +0.017˚C/year).
- 1.1˚C to 2.6˚C under RCP4.5 (+0.011 to +0.026˚C/year).
- 1.4˚C to 3.1˚C under RCP6.0 (+0.014 to +0.031˚C/year), and
- 2.6˚C to 4.8˚C under RCP8.5 (+0.026 to +0.048˚C/year).

It is noted that the different climate scenarios are fairly similar within the first 30-50 years and follow the existing trend, but the differences between the scenarios increase after the first 30-50 years.

In the Gulf of Kachchh area, the temperature is projected to increase by about 1˚C (or +0.01˚C/year) in RCP2.[6] and by about 4˚C (or +0.04˚C/year) in RCP8.5 (which is seen to be central values in the global values), see the figure below.

It is predicted that the temperature in the western coastal zones in India from the 1970s to the 2030s will increase by 1.7-1.8˚C.[15] It corresponds to a rate of +0.0292˚C/year. It corresponds to a value in the high range for RCP6.0 and a value in the low range for RCP8.5 and is slightly less than predicted for the Gulf of Kachchh in the RCP8.5 scenario as it should be.

The two studies agree on the predicted temperature increase in the Gulf of Kachchh area (it is noted that the predicted rates are significantly higher than the observed temperature rate of only about +0.006˚C/year).

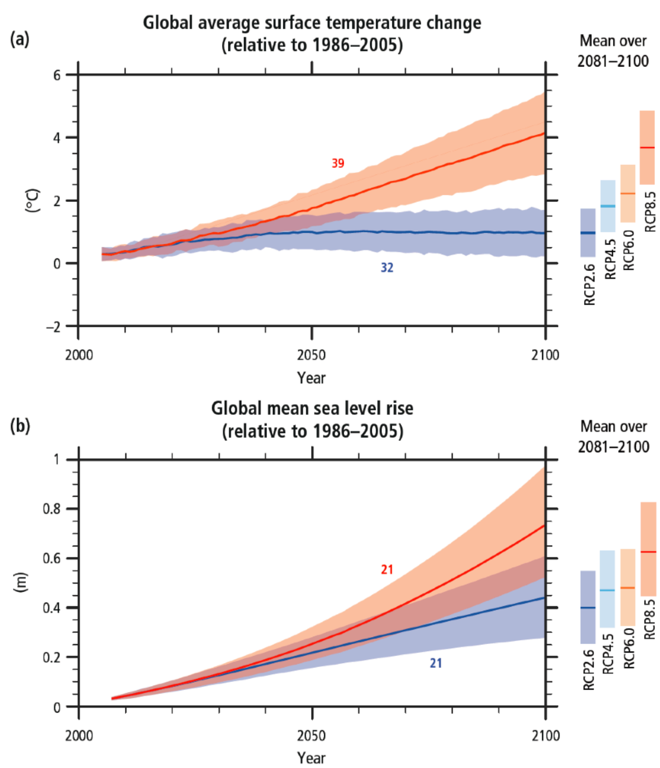

Figure 11: The development of (a) surface temperature; and (b) seal level rise; in the global climate scenarios.[3]

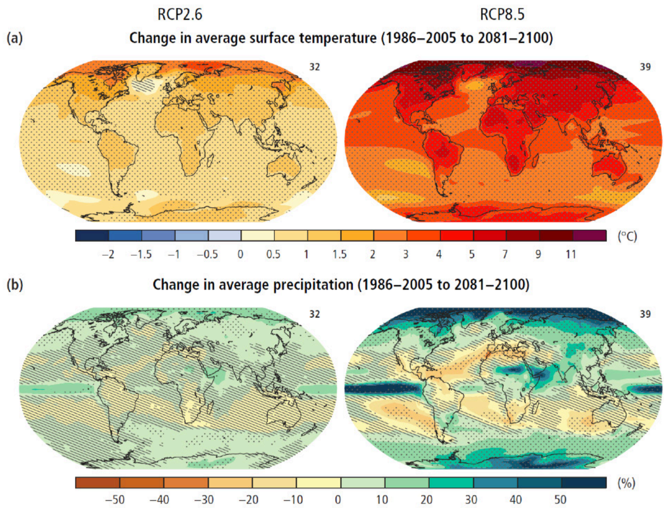

Figure 12: The distribution of a) surface temperature; and b) precipitation; in global climate scenarios RCP2.6 and RCP8.5.[3]

Sea Temperature:

The global ocean will continue to warm during the 21st century (IPCC, 2014)[3] and the strongest ocean warming is projected for the surface in tropical and Northern Hemisphere subtropical regions. Estimates of ocean warming in the top one hundred meters are about 0.6˚C (RCP2.6) to 2.0˚C (RCP8.5) by the end of the 21st century (the 2.0˚C corresponds to a rate of 0.020˚C/year) (Figure 12).

The analysis of historical data showed a trend of +0.014˚C/year, close to the rate found in RCP8.5.

Rainfall:

Scenario RCP8.5 provides an estimate on the higher side for climate change. For the Gulf of Kachchh, the increase corresponds to about +0.7 mm/year (Figure 12).

It is predicted that the rainfall in the western coastal zones of India will increase by 6-8% from the 1970s to the 2030s.[15] This corresponds to a rate of about +0.4 mm/year. Based on the trend of the observations, it is expected that the annual rainfall will increase by 0.9 mm/year for Saurashtra and by +0.2 mm/year for Kachchh (average is +0.55 mm/year). Rates from measurements and predictions match reasonably.

The increase in evaporation is expected to be less than the increase in rainfall, but the annual variation will differ. The monsoon season will probably get wetter, while the three other seasons will get dryer, which can impact, for example, the natural terrestrial vegetation.

Sea Level:

When evaluating the impact of sea level rise on the Gulf of Kachchh, the relative to land change is essential. When the water levels determined in climate models are considered, they should be corrected by the land level rise (0.4 mm/year).

Figure 11 above shows different projections. The increase of global sea level by the end of the 21st century (2081–2100) relative to 1986–2005 is likely to be:

- +0.40 m (0.26-0.55 m) under RCP2.6 (+2.2 to +5.1 mm/year relative to land);
- +0.47 m (0.32-0.63 m) under RCP4.5 (+2.8 to +5.9 mm/year relative to land);
- +0.48 m (0.33-0.63 m) under RCP6.0 (+2.9 to +5.9 mm/year relative to land); and
- +0.63 m (0.45-0.82 m) under RCP8.5 (+4.1 to +7.8 mm/year relative to land).

It is noted that the different climate scenarios are fairly similar within the first 30-50 years and follow the existing trend, but the differences between the scenarios increase after the first 30-50 years.

Historical measurements show a relative sea level rise outside the Gulf of Kachchh of 1.8 mm/year in the last 20 years; see Figure 9 above. A central estimate for the predicted relative global water level rise is assumed to be +5.2 mm/year. It is the mean value for RCP6.0 and RCP8.5. If the sea level rise at the Gulf of Kachchh is estimated to be a factor of 0.37 of the global change, it should be +1.7 mm/year, or close to the same rate as found in the analyses of recent measurements.

Cyclones:

The increasing sea temperatures are expected to increase the intensity of cyclones globally by 2-11% by the year 2100, or about 0.02-0.11 %/per year.[16] For the most intense cyclones, the precipitation is expected to increase by around 20% within 100 km of the storm center.

The analysis of information for cyclones close to the Gulf of Kachchh shows an increase in intensity of 0.05 m/s/year (or 0.08 %/year), which is in the range of the global prediction.

The average cyclone wind speed in 2000 was 71.9 m/s (from the linear trendline). Based on the estimated increase in intensity, the average wind speed in the year 2100 will be 76.9 m/s (from the linear trendline), and the intensity should be multiplied by 1.07. The impact of the storm surge will be more than the wind speed itself.

Results and Discussion

The comparison of the future predictions and the observed changes in historical data for climate change parameters is summarized in Table 3. The projections are supported by the trends in the observations, except for the air temperature, which is higher than found in the observations. In the other parameters, the observations and predictions are reasonably coherent.

Table 3: Summary of climate change projections

Parameter	Observed	Predicted	Comments
Air temperature	+0.006°C/year	+0.014°C/year to +0.048°C/year	The observed air temperature rise in the past is markedly lower than the predicted one in the coming century, and influenced by some uncertainty.
Sea water temperature	About +0.014°C/year	About +0.02°C/year	Supported by historical observations and predictions.
Relative sea level rise	+1.8 mm/year	About +1.7 mm/year	Supported by historical observations and predictions.
Cyclone wind speeds	0.05 m/s/year Or about +0.08 %/year	+0.02 %/year to +0.11 %/year	Supported by historical observations and predictions.
Rainfall	+0.9 mm/year for Saurashtra +0.2 mm/year for Kachchh	About 0.5 mm/year	Supported by historical observations and predictions.

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Conclusions

The historical measurements of climate change parameters such as air temperature, sea surface temperature, sea-level rise, rainfall, and major storms events are collected at available stations in the coastal belt of the Gulf of Kachch, Gujarat, India, and are analyzed statistically to determine the changes occurred in the past using linear regression trend line. The observed past changes are then compared with the future predictions of the same parameters as given by The Intergovernmental Panel on Climate Change, IPCC (2014). The projections are supported by the trends in the observations, except for the air temperature, which is higher than found in the observations. In the other parameters, the observations and predictions are reasonably coherent.

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