Global warming and tropical cyclones in the Arabian Sea and the Gulf of Oman

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Abstract

An increase in the frequency and intensity of tropical cyclones (TCs) under global warming is global concern. To probe this relationship, regions of where TCs are strong but rare are particularly important. Within this context, the Arabian Sea (AS) and the Gulf of Oman (GO) constitute excellent case-study examples. TCs in the AS and GO are rare phenomena but during the last two decades three strong events (Gonu, Phet and Shaheen) have occurred, leading to a total of 6.07 billion USD in damages and 159 fatalities. In this study we use historical TC records, satellite data, atmospheric and oceanographic models to probe the link between TCs and global warming. The results demonstrate that global warming has modified three important environmental parameters in the AS and GO: 1- there has been an increase in water temperature and density in the Persian Gulf (PG), 2- there has been a northward migration of the monsoon belt and an increase in upwelling on the Oman coast, 3- there has been an increase in heat advection and transfer by cyclonic/anticyclonic Mesoscale Eddy (ME) and geostrophic currents that are involved TC intensification. These processes have led to a shallow warm and high-salinity water plume from the PG to the AS, and an accumulation of the ME center between 16°N and 22°N. Warm geostrophic currents lead the TCs to the Mesoscale Eddy centers, favoring an increase in TC intensity at higher latitudes. As a result, strong TCs have made landfall on the Gulf of Oman and the Arabian Sea coasts. Our study suggests that the frequency of strong TCs will increase due to the effects of global warming. Education programs via international platforms such as the International Ocean Institute (IOI) and UNESCO are required for the countries at risk.

1. Introduction

Tropical cyclones (TCs) are amongst the most devastating natural hazards worldwide. They have led to considerable economic and personal damages in densely populated coastal areas, including the degradation of industrial and fishery infrastructures (ports, desalination plants, petrochemical facility and etc.) and destructive winds and flashfloods on coastal plains (Wang and Oey 2008; Han et al. 2012; Sun et al. 2013; Mei et al., 2015; Zhang et al. 2016). According to the World Meteorological Organization, the world's deadliest tropical cyclone during last 50 years was Cyclone Bhola, formed in the south center of the Bay of Bengal and hit East Pakistan on the 12th -13th November 1970. Nearly half a million people were killed due to the large storm surge, overwhelmed tidal flats and low-lying islands in the Bay of Bengal. The Orissa super cyclone in 1999 and Cyclone Nargis in 2008 caused around 238,000 deaths in Bangladesh and Myanmar (Singh et al., 2001).

TC genesis is controlled by four physical processes: atmospheric conditions (low-level cyclonic vorticity, less vertical wind shear, moisture at mid-tropospheric level), internal TC dynamics, Coriolis forces and underlying boundary conditions (Chen and Ding, 1979; Gray, 1979; Emanuel et al., 2004). The underlying boundary conditions, such as sea surface temperature (SST) and sufficiently mixed deep water are the most important factors to TC intensification (Jaimes et al., 2011; Yablonsky and Ginis, 2012; Yan et al., 2017; Lavender et al., 2018; Sun et al., 2019). The TC's energy source is heat transfer from the ocean surface; this heat is used to strengthen a cyclonic disturbance into an intense vortex. TC intensification is correlated with the 26.5°C isotherm depth and upper ocean heat content (Palmen, 1948; Williams, 2013; Shay and Brewster, 2010; Ackerman and Knox 2015).

TCs occur in the southwest Pacific, the northeast and northwest Pacific, the North Atlantic, the northern and southern Indian Ocean and Australian Sea basins (Gray, 1979). A recent study on the global distribution pattern of TCs for 1980–2018 demonstrated that the frequency of TCs has decreased over the southern Indian Ocean, the northeast of the Australian Sea and the northwest Pacific. Meanwhile, an increasing trend is observed in the Arabian Sea (AS), the northern Atlantic and central Pacific basins (Murakami et al., 2020). TCs are rare phenomena in the northern Indian Ocean (NIO). On average, just 7% of global TCs form in this basin (Neumann, 1993). The NIO basin is divided into the Bay of Bengal (BoB) and Arabian Sea (AS) basins. The number of TC events in the Bay of Bengal is four times greater than the Arabian Sea. Average TC frequency (Bay of Bengal/Arabian Sea) for the period 1982–2000 was 2.7 events/year and 1.6 events/year between 2001 and 2019. For the recent period, TC duration has significantly increased in the Arabian Sea. The increase in TC frequency and duration in the Arabian Sea has been concurrent with accelerating accumulated cyclone energy during the pre-monsoon (March–April–May) and post-monsoon (October-November) seasons. By contrast, no significant changes in TCs were observed in the Bay of Bengal (Deshpande et al., 2021; Bandyopadhyay et al., 2021).

The ocean mesoscale eddy is a significant ocean phenomenon that covers 20–30% of the ocean area (Cheng et al., 2014; Lumpkin, 2016). The mesoscale eddy (ME) circulation system has important effects on surface ocean water temperatures and also on subsurface layers, general circulation and regional climate (Macdonald & Wunsch, 1996; Dong et al., 2014; Zhang, et al., 2014; Yang et al., 2015). Mesoscale eddy energy transfer could have positive impacts on TC intensity (Sun et al., 2020). Strong eddy activity exists in the western basin of the Arabian Sea that is similar to eddy-rich regions in the global ocean (Scharffenberg & Stammer, 2010; Roullet et al., 2014). Eddy activities in the Arabian Sea exhibit strong seasonality that peaks during the summer monsoon season (Trott et al., 2018). Wind stress, the Somali current, the westerly propagating Rossby wave and background currents are all parameters that can further reinforce eddies in the region (Brandt et al., 2002; Trott et al., 2017).

Studies of global warming impacts on TC intensity, duration and tracks are important in the Gulf of Oman and the Arabian Sea because of their local and global economic importance. For instance, the Gulf of Oman is the only maritime entrance into the Persian Gulf (Fig. 1), a region which exports approximately 18.2 million barrels of oil per day. Several important cargo and fishery ports also exist on the Omani and Iranian coasts that are vital for the regional economy. The increasing number, intensity and duration of TC events in the Arabian Sea and the Gulf of Oman could accentuate maritime risks and economic damages.

The aim of this study is to evaluate the impacts of global warming on ocean-atmospheric parameters leading to the creation and migration of the most deadly and destructive TCs (Gonu, Phet and Shaheen) in the Arabian Sea and the Gulf of Oman, using satellite SST data and model reanalysis.

2. Data And Methods

2.1. TC tracts

In this study, we used the International Best Track Archive for Climate Stewardship (IBTrACS) dataset for the period 1860–2021 for the Arabian Sea basin. IBTrACS contains a time series of storm positions from forecasting agencies around the world. IBTrACS includes information on the location and intensity of TCs at 6-hour intervals (Knapp et al. 2010). The TC categories are classified according to the Saffir-Simpson Hurricane scale (SSHS). Tropical cyclone lifecycles were tracked using high-rate rectified SEVIRI IR10.8 µm Image of Meteosat-8 data available since September 2020.

2.2. Satellite and reanalysis data

Long-term SST changes were calculated using average SSTs at 20-year intervals for the period 1860–2021. The data were extracted from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) for the area 8-25.5N to 50-74E. The ICOADS data are provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA (http://www.esrl.noaa.gov/psd/). We also employed 0.25×0.25 degree daily Optimum Interpolation Sea Surface Temperature (OISST) based on AVHRR (Advanced Very High-Resolution Radiometer) for the SST anomaly changes before, during and after the Gonu, Phet and Shaheen tropical cyclone events. The OISST data derives from different platforms such as satellites, buoys, ships, and Argo floats to improve the accuracy and bias corrections (Reynolds et al., 2007; Huang et al., 2021).

Daily average data of the NCEP/NCAR reanalysis multi-pressure level model (Omega, geopotential height, U/V winds) with 2.5 degree × 2.5 degree resolution was employed for atmospheric instabilities before, during and after the studied TC events. In this study, we used vertical velocity, pressure gradient force, wind speed and direction for the 850 hPa and 500 hPa pressure levels. Furthermore, 10 m wind characteristics were calculated for the study intervals.

Horizontal surface currents data are based on the Ocean Surface Current Analysis Real-time (OSCAR) model that is developed by Earth Space Research (ESR). The 5-day resolution current velocity is estimated by surface vector wind, sea surface height and SST. The formulation of the model in 1/3 degree grids combines geostrophic, Ekman and Stommel shear dynamics and surface buoyancy gradient used for complementary terms.

Changes in salinity and temperature vertical profiles (0-150m) during the selected time intervals have been studied by Multi Observation Global Ocean ARMOR3D L4 analysis (Guinehut et al., 2012; Mulet et al., 2012) generated using the E.U. Copernicus Marine Service Information. The model has a spatial resolution of 1/4 degree down to 50 m depth.

The reanalyzed data are available in NetCDF4 format. The data was extracted and analyzed using ArcGIS pro ver. 2.5 and Origin pro 2021.

3. Results

3.1. Historical SST changes and TC frequency

We compared historical SST changes with TC frequency and intensity in the Arabian Sea for 1860–2021 (Fig. 2). For the period 1860–1880, only two events are recorded in the Arabian Sea. Lower SSTs are observed throughout the AS, Strait of Hormuz (SH) and Gulf of Adan (GA) between 1881 and 1900. The lowest SSTs are recorded along the Somali and Omani coasts, where cold-water upwelling occurs (< 25–26°C). Furthermore, along the Pakistani and Makran coasts (north of the Arabian Sea) SST reduction is observed due to increasing water discharge from the hinterland. Despite decreasing SST through the Arabian Sea, the frequency and length of TCs increased (from 0.1 to 1.4 and 0–5 respectively). The trend of SST reduction continued during the period 1901–1920 and TC frequency attained an average of 1.8 events/year (Fig. 3). Meanwhile warm SST areas in the Strait of Hormuz and the Gulf of Adan reached their minimum. During this period, no significant changes in TC length and landfall is observed. For the period 1921–1940, warm SST tongues penetrated from the southeast of the Arabian Sea and a north- and west-ward shift of warm water took place. Concurrently, SSTs increased in upwelling zones, in the Gulf of Adan and Strait of Hormuz basins. The frequency of TCs increased and landfall was steady. Furthermore, average TC length decreased. The penetration of warm SSTs through the Arabian Sea continued between 1941 and 1960. During this period, the cold water connection for the Somali, Omani and Pakistani coasts ceased and lower SSTs were restricted to upwelling zones and river discharge areas. TC frequency, length and landfalling events significantly increased. During the period 1961–1980, a new tongue of warm water (28.5–29°C) flowed from the southeast and west of the Arabian Sea and the Gulf of Adan, respectively. No significant SST changes were observed in the Strait of Hormuz. The frequency of TCs and the number of landfalling events increased considerably, while TC length decreased negligibly (Fig. 3).

The period 1980–2000 manifests increasing SSTs throughout the Arabian Sea basin. The westward migration of warm SST tongues is concurrent with rising SST in the Gulf of Adan which occurred during this period. Contemporaneously, increasing SST is observed along the Somali and Omani upwelling zones (Fig. 2). Furthermore, the low SST zone along the Pakistani coast attained its minimum. The frequency of TCs decreased dramatically (from 3.4 in 1960–1980 to 1.9 during the period 1980–2000), but TC length, landfall frequency and power all increased (Fig. 3). For the period 1860–1980, all TC categories did not exceed zero (according to the SSHS). TC events exceeding zero began during the period 1981–2000. The upward movement of warm water to the north during 2000–2021 was concurrent with increasing SST across all basins (Persian Gulf, Gulf of Adan and Strait of Hormuz). Cold water upwelling and water discharge declined along the Somali coast and the northern Arabian Sea, respectively. The upwelling area along the Omani coast reached its minimum and its SSTs attained 26-26.5°C. Average SST in the Arabian Sea during the period 2000–2021 (26–29°C) was favorable to TC genesis. As a result, the frequency of TCs increased and the number of strong TCs grew dramatically. Westward migration of TCs to the Gulf of Adan and the Srait of Hormuz increased considerably and landfall was the highest of the last 160 years. During this period, Gonu, Phet and Shaheen were the most important TCs in the Arabian Sea, causing severe economic and human damage.

3.2. Tropical cyclone Gonu

On the 31st May 2007, a monsoon surge produced an area of low-pressure omega at 0–8°N and 59–68°E and a high pressure zone extended north of AS (19-24N and 59-68E). Cyclone with 1492 gph at center developed at 11.6°N and 72.6°E in 850 hPa with a thick trough to the west (Fig. 4). Wind speed at this pressure level was < 5 ms^{-1}. Concurrently, a cyclonic system with a core of 5848 gph extended at 500 hPa (8.2°N and 67.5°) with 15 ms^{-1} wind speed. The tropical cyclone Gonu (TCG) started at 13.7°N and 71.6°E where several mesoscale eddies existed. The tropical cyclone Gonu tracked to the northeast (33 km) and tracked to the northwest through to the warm geostrophic current. The tracking speed of tropical cyclone Gonu increased on June 1st (283.4 km) when it aligned with the anticyclonic mesoscale eddy geostrophic current. Tropical cyclone Gonu speed decreased with growing TC power and wind speed. During first six hours of June 2nd (12:00 to 6:00 am), after tracking 74.8 km to the west, tropical cyclone Gonu's path changed to the north and tracked just 23 km during 18 hours. This reduction in speed occurred along the counter geostrophic warm current (Fig. 5). As a result, the power and wind intensity increased during tropical cyclone Gonu's low-speed tracking. Increasing surface wind speed and, subsequently, growing geostrophic current intensity to the southwest and west of the Arabian Sea took place with increasing tropical cyclone Gonu category (from − 1 to 1). As a result, the westward migration of cyclonic mesoscale eddy occurred from 67.37°E to 64.69°E (Fig. 5). After tracking 35 km to the northeast (12:00 am to 3:00 am) on June 3rd, tropical cyclone Gonu tracked 295 km to the northwest, along the strong geostrophic warm current. Tropical cyclone Gonu's category quickly increased from zero to three in less than 18 hours.

Between June 4th and 5th, the omega low-pressure cell shifted to the northeast and was located at 11.4°N and 61.3°E at both 850 and 500 hPa pressure levels. The tropical cyclone Gonu column was well developed at both pressure levels (Fig. 4). Horizontal wind speed and pressure were lower at the center of the 850 hPa cyclonic cores (1436 gpm) and 500 hPa (5808 gpm). By this time, tropical cyclone Gonu had tracked 627 km during 48 hours when it attained categories 4 and 5 through 18.5–21.5°N to 60.2–60.5°E. Concurrently, the surface wind speed reached 12 ms^{-1} in the west of the Arabian Sea. Increasing surface wind stress led to accelerating mesoscale eddy activities north and south of the Rasa al Had. To the south of Ras al Hadd, the size and current speed of the anticyclonic mesoscale eddy increased. The current speed attained 2 ms^{-1} west and north of the mesoscale eddy and SST anomaly increased 1.2°C through its geostrophic current. The warm water was transported to the northeast and east where a cyclonic mesoscale eddy was active through Gonu's path. Furthermore, the southeast migration of the anticyclonic mesoscale eddy to the north of Rasa al Had (60.7°E and 22–24°N) occurred. The speed and size of the mesoscale eddy's geostrophic current increased and several eddies were created in the Gulf of Oman (Fig. 5). Intensification of the mesoscale eddy led to decreasing SST in the Gulf of Oman. This different advection of two anticyclonic mesoscale eddies, north and south of Ras al Hadd, suggests variable water temperatures at mixed layers.

The vertical temperature and salinity profiles along Gonu's path show that the depth of the 26.5°C isotherm fell to 82.5 m at lower latitude (Fig. 6). With increasing latitude, the isotherm depth decreased and reached its minimum at 21–23°N (upwelling zone) and increased again when approaching the Persian Gulf. High-salinity water mass thickness increased through the Persian Gulf with an interruption in the upwelling zone. Three hotspot areas (30-32.1°C) are observed along TCG's track. The first one is located at 14–15°N with low salinity, the second and third are located at 16–21°N and 23–25°N with higher salinity. These temperature anomalies result from the mesoscale eddy activities and the Persian Gulf water discharge at lower and higher latitudes, respectively. The accumulation of high salinity (36.63 to 37 PSU) and warm water (29–31°C) was observed between 0–40 meters at 17–21°N (Fig. 6). In this area, Gonu attained its maximum category.

During tropical cyclone Gonu, the warm and high-salinity water stratification was removed due to the increasing water circulation and upwelling. Upwelling freshwater at 21–23°N led to a decrease in the depth of the Persian Gulf water plume into the Arabian Sea. As a result, warm and highly-saline water accumulated at lower depths. This link is clearly observed in salinity and temperature profiles during and after Gonu. The image shows that with increasing fresh and cold water upwelling to the north of Ras al Hadd, the depth of the high-salinity water mass shifted upwards and the Gulf's water plume was at lower depths. At the same time, the anticyclonic mesoscale eddy transferred warm/cold water to the surface via geostrophic currents.

SST in the Gulf of Oman decreased dramatically when Gonu entered the basin. The SST reduction took place due to an increase in upwelling of cold water and the anticyclonic mesoscale eddy in the northern Ras al Hadd. This SST reduction had negative effects on the cyclone power and tracking speed. Gonu entered the Gulf of Oman at category 3, travelling 353 km over 2 days it reached landfall on the Iranian coast (Jask) at category − 3. In the Gulf of Oman, Gonu increased cold water input into the Persian Gulf and SST reduction occurred along the northern part of the Persian Gulf's central basin. Concurrently, outflowing warm and high-salinity water was accelerated through the Srait of Hormuz (below the surface current). This effect is observed on salt and temperature profiles at 23 to 25.5° N (Fig. 6). Furthermore, high SSTs are still observed in the center of the anticyclonic ME at Ras al Hadd, but its geostrophic current temperature decreased during impacts of upwelled cold water. The north eastward migration of the cold geostrophic current led to decreasing SST in the northern Arabian Sea.

3.2. Tropical cyclone Phet

The monsoon surge that occurred at the end of May led to an increase in intensity of the mesoscale eddies through the Arabian Sea. Warm SST was concentrated in the center of the Arabian Sea due to temperature advection and concentration through the geostrophic currents. A low-pressure system developed over the Arabian Sea with a trough to the west, on the 31st May 2010. Meanwhile, low pressure omega extended to 10°N and 64°E at 850 hPa and the southeast of the Arabian Sea at 500 hPa with cyclonic winds (Fig. 7). Tropical cyclone Phet (TCP) began at 14.4°N and 65°E with category − 3 over warm cyclonic ME geostrophic currents. Phet attained TC category zero on May 31st due to the tracking over warm geostrophic currents with the same direction (Fig. 8). On June 1st, Phet category attained 1 and it tracked 256 km during 24 hours. The omega moved north and northwest at 500 and 850 hPa pressure levels, respectively, and the cyclonic system was well defined at both pressure levels on June 2nd. The anticyclonic mesoscale eddy intensity south of Ras al Hadd increased due to monsoon surface wind stresses. With the northwestward migration of Phet and intensification of the mesoscale eddy, heat advection from the mixing layer increased. Phet's category increased suddenly from 1 to 4 during 6 hours in 17.5–18°N and 59.8–61.2°E when it reached the anticyclonic mesoscale eddy. Furthermore, Phet's speed decreased and it tracked 131 km during 18 hours as a category 4 TC. On June 3rd, Phet's path changed to the north when the category was 4. The shift in path of Phet resulted from the strong geostrophic current to the west of the mesoscale eddy (Fig. 8). When Phet left the mesoscale eddy, the TC category decreased and tracking speed increased.

Phet made landfall in Oman at category 2 on June 4th and continued its path to the north. The TCP tracking path changed to the northeast over the Gulf of Oman when the omega low pressure lay to the northeast of the Arabian Sea (Pakistan). On June 5th, Phet tracked to the southeast along the northern Ras al Hadd of the cold core anticyclonic mesoscale eddy and it tracked 300 km during 24 hours. Phet moved 410 km to the northwest and made a second landfall over Pakistan on June 6th .

The most important feature of Phet was that it attained a high TC category over a short period of time. The temperature profile before the onset of Phet demonstrates that the 26.5°C isotherm depth was 70–80 m and it decreased towards higher latitudes. Shallow warm water masses (30.43–32.15°C) were created at 14.5 to 19°N due to the ME temperature advection. The salinity profile suggests a shallow (0-40m) accumulation of high-salinity and warm water mass between 14 and 15.5°N (Fig. 9). This accumulation was the result of the impacts of monsoon and cold water upwelling on the shallow-water plume of the Persian Gulf. Phet's power increased gradually as it moved across warm and low-salinity water masses (14-15.5°N). Phet's TC category increased dramatically when it reached warm and high-salinity water between 17°N to 19°N. With intensification, the anticyclonic mesoscale eddy south of the Ras al Hadd and upwelling freshwater, a low-salinity warm water mass was created at 19.5–20.5°N (Fig. 9). This pushed Phet's path to the north and the TC category decreased with the lower salinity levels. With the northward migration of Phet, the depth of high-salinity water influx increased (decreasing SST in the north of the Persian Gulf) at 21-23.5°N that shows rising water exchange in the Persian Gulf and a decrease in the connection to the Arabian Sea due to the upwelling. Salinity and temperature decreased when Phet reached the Gulf of Oman and the northern Arabian Sea. This suggests that the eastward migration of the TC decreased the current intensity towards the Persian Gulf. As a result, the SST increased in the eastern part of the Gulf.

3.3. Tropical cyclone Shaheen

Gulab and Shaheen were two related tropical cyclones that occurred during the post-monsoon cyclone season in the northern Arabian Sea. Gulab cyclone was generated in the Bay of Bengal between the 24th and 25th September 2021 and reached the Arabian Sea on the 29th September. On 30th September, a low-pressure omega developed at 22.5°N and 68°E and a depression was created at 850 hPa (Fig. 10). The speed of the Gulab cyclone track decreased and convection increased over the warm SSTs of the

Arabian Sea. On October 1st, convection increased at the storm center and the tracking path changed to the northwest though the dual core cyclonic mesoscale eddy warm geostrophic current. The tropical cyclone Shaheen (TCS) was generated when it crossed over the mesoscale eddy warm core. Therefore, the category attained one and the cyclone eye was developed (Fig. 11). After tracking 200 km to the northwest, Shaheen changed its path and moved 75 km to the west on October 2nd. Shaheen's track speed increased concurrently with an increase in distance to the ME core and deviated to the northwest. The TCS category and tracking speed increased when it reached the northern Ras al Hadd cyclonic mesoscale eddy (Fig. 12). Shaheen shifted north through the mesoscale eddy geostrophic current and attained category 2. After tracking 102 km, the Shaheen started tracking southwest when it approached the mesoscale eddy's core. At the center of the mesoscale eddy, Shaheen shifted to the west and tracked 75 km as a category 2 system on October 3rd. The path of the TCS again changed to the southeast under the influence of the mesoscale eddy's geostrophic current direction (Fig. 12). Contemporaneously, the category decreased with increasing distance from the mesoscale eddy and rising SST anomalies. Finally, Shaheen made landfall over northern Oman coast with a category 1 strength, making it the only cyclone to make landfall there since 1860.

During the summer monsoon season, several eddy cells formed over the Arabian Sea, especially at Ras al Hadd and in the northern Arabian Sea. These single eddy cells merged and formed dual-core eddies due to the increasing intensity of the geostrophic current. As a result, three important mesoscale eddies were created in the northwest (a dual-core mesoscale eddy to the south of Ras al Hadd) and north (dual core cyclonic mesoscale eddy) of the Arabian Sea and the Gulf of Oman (cyclonic mesoscale eddy; Fig. 12).

Cold water upwelling during the monsoon season led to an increasing shallow warm and high-salinity water plume into the Arabian Sea. The salinity and temperature profile suggests that increasing output density from the Persian Gulf impeded cold and fresh water from reaching the surface. Instead, a low-depth water plume occurred (Fig. 13). Accelerating mesoscale eddy intensity led to the transfer and accumulation of heat through geostrophic currents. As a result, the cyclonic mesoscale eddy in the Gulf of Oman led to the upwelling of warm water through northern Oman and its transfer to the east. Meanwhile, northeastern geostrophic currents result from a dual core anticyclonic mesoscale eddy south of Ras al Hadd and increased warm water transfer to the northern Arabian Sea. This transfer of warm water led to increasing SSTs in the northern Arabian Sea (e.g. 26.5°C at a depth of 16 to 40 m).

The lowest isotherm depth was observed at 59°E to 60°E (Gulf of Oman) where cold water upwelling decreased the depth of the Persian Gulf warm and saline output. Concurrently, an amplification of the intensity of the dual-core cyclonic mesoscale eddy in this area led to the accumulation of warm water at 62–63°N. The heat transition from the lower latitude led to an accumulation of low salinity warm water from 63°E to 69°E. Approaching the Persian Gulf (58–62°E), salinity increased at lower depths (Fig. 13). Shaheen's category evolved from – 1 to 0 when the system moved over warm and low salinity waters. The TC strength increased considerably when Shaheen reached the cyclonic mesoscale eddy and warm geostrophic currents with higher salinity. With decreasing cold-water upwelling during and after Shaheen, the depth of the warm and high-salinity water plume depth at lower longitudes increased. As a result, SSTs decreased in the northern cyclonic mesoscale eddy in the Gulf of Oman but high SSTs were observed south of it. The higher SST was observed at Ras al Hadd where warm water advection occurred through the anticyclonic mesoscale eddy geostrophic current.

4. Discussion

Between 1860 and 1920 a decrease in SSTs is observed in the Arabian Sea, the Persian Gulf and the Gulf of Adan that is correlated with a reduction in SSTs at the global scale (Fig). Low SSTs to the west and the southwest of the Arabian Sea (Somalia and Oman) resulted from low salinity and cold water upwelling under the influence of summer monsoon winds and strong Somali currents (Morrison, 1997; Joseph & Freeland, 2005). Furthermore, water discharge form large rivers reduced SSTs in the northeast of the Arabian Sea. An increase in the frequency of TCs is concurrent with an increase in SSTs and suggests the role of ocean dynamics in the creation and distribution patterns of TC categories lower than 0. Global warming effects have direct impacts on the poleward shift of monsoon low level jet surface wind stress (Swapna et al. 2014; Roxy et al. 2016; Aneesh and Sijikumar, 2016) and an increase in SSTs in the western basins. Increasing SST in the Persian Gulf and the Gulf of Adan increased the heat budget to the west of the Arabian Sea. Heat exchanges were promoted between coastal and ambient waters (de Marez et al., 2019), therefore, eastward heat transport with a large temperature gradient occurred due to the zonal Ekman transport (Trott et al., 2017). Furthermore, warm and high-salinity water formed in the Persian Gulf sinks at the subsurface and spread over a large portion of the Arabian Sea (Morrison, 1997; Kumar & Prasad, 1999; Rochford, 1964). The depth of the high-salinity water in the Arabian Sea was controlled by cold water upwelling and SSTs in the Persian Gulf. The depth of the water plume decreased with increasing SST in the Persian Gulf (increasing evaporation and salinity) and cold-water upwelling on the Omani coast.

Penetration of warm and low-salinity water from the northern equator led to an increase in the frequency of TCs in the Arabian Sea between 1961 and 1980. Average TC power has increased since 1981 when the poleward migration of the jet axis increased and wind stress forces increased in the west of the Arabian Sea (Pratik et al., 2018). The migration of the monsoon axis to the north led to a strengthening of the wind stress and increasing upwelling on the Omani coast compared to Somalia (Varela et al., 2015). As a result, the low SST was limited to the Omani coast and attained minima from 2001–2020. Synchronously, marine productivity decreased in the western Arabian Sea (Roxy et al., 2016). Upwelling on the Omani coast decreased the depth of the warm and high-salinity water plume into the Arabian Sea. Therefore, a shallow high-salinity water mass accumulated at lower latitudes in the western Arabian Sea.

The mesoscale eddy plays an important role in heat advection from lower warm layers. Peaks in eddy activity occur during the summer monsoon season (Trott et al., 2018) when SSTs in the Persian Gulf and the Gulf of Adan are at their maximum. Mesoscale eddies affect the flux of heat and salt (Zhan et al., 2020), transferring warmer water along geostrophic currents. During the summer monsoon, the intensity of anticyclonic mesoscale eddies to the south of Ras al Hadd increases with accentuated surface wind stress, dipole current and upwelling on the Omani coast. Heat advection increases in the mesoscale eddy center and warm water moves, via geostrophic currents, to the east and north of the Arabian Sea. Concurrently, a shallow mass of high-saline water (0-30m) accumulates between 16°N and 22°N due to cold-water upwelling at Ras al Hadd. Mesoscale activities increase water column temperature at lower latitudes. The studied TCs (Gonu, Phet, Shaheen) were created around cyclonic mesoscale eddies where omega pressure was minimum. TC tracking paths and speeds were controlled by geostrophic warm currents. The TC categories increased slowly when tracking over warm and low-salinity water and rapid intensification occurred when TC centers reached the warm mesoscale eddy core or warm high-salinity water. Sea surface cooling reduced high-saline water stratification and the heat flux zone at the center of the mesoscale eddy that favored rapid TC intensification (Balaguru et al., 2020; Sun et al., 2020).The TCs tracking speed decreased when the TCs attained their maximum category at the mesoscale eddy core and TC paths changed through the mesoscale eddy current direction.

TCs in the Gulf of Oman are rare phenomena and just two events, Gonu and Shaheen, have affected the area since 1860. The strong tropical cyclones were created in the AS after a monsoon surge when warm and high-salinity water moved to lower depths. Increasing mesoscale eddy intensity in the Arabian Sea guided TC paths to the eddy centers or high-salinity water mass via warm geostrophic currents. Shallow plumes occurred when an unusual peak of SST in the Persian Gulf increased the density of outflowing water through the Strait of Hormuz. Warm water with higher density moved over the cold and fresh water in the upwelling zone. Therefore, SST increased in upwelling zones. With the northward migration of TCs, the intensity of upwelling increased along the Omani coast. Southeastward migration of the anticyclonic mesoscale eddy in northern Ras al Hadd led to decreasing SSTs in the Gulf of Oman. As a result, the water plume from the PG decreased, subsequently, the SST south of Ras al Hadd's mesoscale eddy decreased. Low SST in the Gulf of Oman changed the TCs path east (Phet) or decreased TC intensity (Gonu).

The most important feature of Shaheen was its track path. During the summer of 2021, the Persian Gulf's SST attained its maximum since 1860 (Fig. 14) and upwelling along the Omani coast increased salinity and temperature at a depth of 0–20 m in the Gulf of Oman. During the summer monsoon season, the northwestward migration of the cyclonic ME occurred at Ras al Hadd and over the Gulf of Oman. Interaction of Ekamn pumping and cold water upwelling at Ras al Hadd led to warm water upwelling on the northern Omani coast. Therefore, accumulation of warm water with low salinity occurred north of the AS due to the MEs geostrophic currents. Meanwhile, SST increased in the Gulf of Oman following the upwelling of cold water and the intensification of the cyclonic mesoscale eddy. Shaheen's category increased when it tracked over warm geostrophic currents and the eye was created when the Shaheen's center crossed over the cyclonic mesoscale eddy core in the northern Arabian Sea. The present high-salinity water mass at the cyclonic mesoscale eddy led to increasing TC intensity and decreasing speed tracks. Consequently, the TC track path changed due to the ME geostrophic current. Finally, Shaheen made landfall at category 1 on the northern Omani coast and led to severe damage.

The results of this study demonstrate how global warming could increase TC frequency and categories in the Arabian Sea. The frequency of TCs have increased more in the Arabian Sea than in the Bay of Bengal during the period 1982–2019 (Deshpande et al., 2021). This trend is correlated with an increase in SSTs in the Persian Gulf and upwelling along the Omani coast following the northward shift of the monsoon low-level jet. According to the analytical model, upwelling along the Omani coast will increase in the next century (Praveen et al., 2016). As a result, the frequency of strong and landfalling TCs in the Arabian Sea will increase. The results of this will help to shed light on the reasons for an increase in the frequency of Arabian Sea TCs with respect to the Bay of Bengal. Also, these results could help to predict the TC path and their category for future events in the Arabian Sea. TCs constitute a new phenomenon for the people and governments of Iran, Pakistan and Oman, therefore, instructional programs via international platforms such as UNESCO and the International Ocean Institute (IOI) are required to understand the risks of TCs in order to decrease fatalities.

Conclusion

TCs in the Arabian Sea are mediated by several parameters such as sea surface temperatures (SST), ocean currents, mesoscale eddy (ME) activity, the position of the monsoon low-level jet axis and dipole currents. During the last 161 years, the frequency of TCs has increased in the Arabian Sea. The frequency of TCs has increased due to the penetration of the warm-water tongue from the northern equator to the southeast of the Arabian Sea. TC power has increased due to an increase in SSTs in the Persian Gulf since 1981.

Global warming has led to an increase in SSTs in the Persian Gulf and the poleward migration of the summer monsoon wind axis. Higher evaporation in the southern Persian Gulf has increased the density and temperature of output water via the Strait of Hormuz. The warm and highly saline water sinks to the subsurface and spreads over a large portion of the Arabian Sea. Increasing upwelling along the Omani coast and an anticyclonic intensification of the mesoscale eddy south of Ras al Hadd are two important effects of summer monsoon wind stress on the western Arabian Sea.

Cold-water upwelling on the Omani has decreased the depth of the warm and high-salinity plume in the Arabian Sea when a peak of warm SST occurred in the Persian Gulf. The high-density water moved over the cold upwelled water and shallow high-salinity water accumulated at 16°N and 22°N. Heat advection over the water mass has created geostrophic warm water currents through the Arabian Sea and the water temperature profile has increased in the mesoscale eddy core.

The tropical cyclones Gonu, Phet and Shaheen were the most destructive tropical cyclones (TC) in the Arabian S since 1860. They formed over warm core cyclonic mesoscale eddies when vertical vorticity increased. The TCs tracks and speed were controlled by low salinity warm geostrophic currents. Meanwhile, TCs have steadily become more powerful with increasing geostrophic current temperatures through to the mesoscale eddy core. TC intensity increased suddenly when it reached the center of the mesoscale eddy with the warm core and high-salinity water. With increasing intensity, the speed track decreased and the TC path was redirected due to the eddy's geostrophic current. The TCs intensity decreased concurrently with increased distance from the mesoscale eddy core. The mesoscale eddy position and direction at Ras al Hadd played important roles in increasing the intensity of TCs and directing them to the Gulf of Oman.

The northward migration of Gonu and Phet led to increased upwelling on the Oman sea coast, concurrently, increasing intensity of the anticyclonic mesoscale eddy in northern Ras al Hadd decreased SSTs in the Gulf of Oman. As a result, the TCs category and direction changed over the Gulf of Oman. Therefore Shaheen intensity increased over the Gulf of Oman and made landfall at category 1 on the northern Omani coast.

The frequency of strong TCs will increase in the next century due to global warming effects in the Arabian Sea and the Gulf of Oman. Therefore mitigation plans via international platforms such as UNESCO and the IOI are necessary for at risk countries such as Iran, Oman and Pakistan to reduce infrastructural damage and the loss of human life caused by TC events.

Declarations

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Data availability

All data is publicly available.

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Figures

Figure 1

Regional map of the study area and track of the studied TCs

Figure 2

Historical SST changes and TC events in the study area

Figure 3

TC frequency, length, landfall and category during the studied time intervals

Figure 6

Salinity and temperature profiles along Gonu’s track before, during and after the TC event

Figure 7

Meteorological variables (omega, wind speed and geopotential height) before, during and after tropical cyclone Phet

Figure 8

Surface wind speed and direction, SST and current direction at 15 m water depth before, during and after tropical cyclone Phet

Figure 9

Salinity and temperature profiles along the Phet’s tracking path before, during and after the TC event

Figure 10

Meteorological variables (omega, wind speed and geopotential height) before, during and after tropical cyclone Shaheen

Figure 11

Meteosat-8 images of the life cycle of TCS

Figure 12

Surface wind speed and direction, SST and current direction at 15 m water depth before, during and after tropical cyclone Shaheen

Figure 13

Salinity and temperature profiles along the TCS track before, during and after the TC event

Figure 14

Mean SST changes in the Persian Gulf, the Gulf of Adan, the Arabian Sea and global temperature anomaly (https://www.ncdc.noaa.gov)