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Overview of Wind Climatology for the Gulf of Oman and the Northern Arabian Sea

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Abstract Wind data from three different Atmospheric models, including National Center for Environmental Prediction (NCEP), Climate Forecast Reanalysis System (CFSR), and European Center for Medium Range Weather Forecasting (ECMWF) were used to summarize the wind climate over the Gulf of Oman and the northern Arabian Sea. General circulation pattern over this region is significantly affected by summer and winter monsoons driven by land-sea latent heat difference. Winter monsoon occurs from November to April and is associated with northeasterly winds with average speeds of < 5 m/s, summer monsoon of July-September causes energetic and persistent southerly and southwesterly winds with average speed of 15 m/s. This persistent wind regime during summer contributes significantly to ocean circulation and biogeochemical processes in the northern Arabian Sea and the Gulf of Oman. Rest of the months are considered as either post-monsoon (October) or pre-monsoon (May and June) with a transition phase and less persistent wind pattern. Annual wind data analysis of the Gulf of Oman and the northern Arabian Sea shows that predominant wind direction in the Gulf of Oman is westerly to northwesterly, while for the northern Arabian Sea southwesterly is the most frequent wind direction.

Keywords Gulf of Oman, Arabian Sea, Monsoon, Coastal upwelling, Shamal wind

1. Introduction

Seasonal Wind pattern over the Gulf of Oman and the northern Arabian Sea is the main driving force for its unique circulation pattern, wave dynamics, and the associated biogeochemical cycles. Although tropical cyclones are an occasional feature of the northern Indian Ocean, they rarely enter the northern Arabian Sea and the Gulf of Oman ([1]). The dominant climatology of the region is driven by the monsoon which is a seasonally reversing wind event during summer and winter. Summer monsoon is dominant during July to September with a persistent direction of southwesterly, while the northeasterly winter monsoon occurs from November to April ([2]). The rest of the years is categorized as the post-monsoon occurring right after the summer monsoon (October) and pre-southwest monsoon including months between winter and summer monsoons (May and June) ([3]).

Summer monsoon spawns the most energetic wave regime in the Arabian Sea and the Gulf of Oman ([4]). Recent studies revealed that waves generated during the monsoon season form a bimodal frequency spectrum over the northern Gulf of Oman ([5]). Monsoon climate also substantially contribute to the regional circulation and oceanic heat/salt transport in the northern Arabian Sea and the Gulf of Oman ([6]). The summer monsoon season drives the Ras al Hadd Jet (RHJ) which is a persistent seasonal current along the coast of Oman with substantial effects on the transport of biogeochemical substances and redistributing nutrients across the water column ([7]). The distinct direction of the summer monsoon from the southwest, which is almost parallel to the Oman coastline in the northern Arabian Sea, produces a strong coastal upwelling system that highly contributes to bringing the nutrient-rich deep water to the surface and supporting phytoplankton blooms. This makes the coastal and offshore water of Oman one of the most productive coasts in the world ([8, 16-18]). Phytoplankton bloom has also been reported in the aftermath of southwest monsoon along the Iranian coasts of the Gulf of Oman ([9]). Even in the coastal bays of the Gulf of Oman onset of summer monsoon contributes to the enhanced fisheries. Rabbaniha et al. (2014) [10] reported that fish larva diversity and abundance in the Gowatr Bay on the northern coast of the Gulf of Oman significantly increases during the post-monsoon time.

Regarding the unique nature of wind climatology over the Arabian Sea and the Gulf of Oman, understanding of its seasonal and spatial variability is a pre-requisite for any study aiming to address the hydrodynamics and transport phenomena in the region. The present paper uses long-term data from different atmospheric models to summarize wind

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characteristics over these two regions and address its associated temporal variations.

2. Study Area and Data

The area of Study comprises the Arabian Sea and the Gulf of Oman (Figure 1). The Persian Gulf is also included due to the significant impact of atmospheric pressure variations over this water body on the wind pattern of the Gulf of Oman especially during the spreading of winter "Shamal" wind.

Wind velocity components and surface pressure data from three different sources including NCEP [11], CFSR [12], and ECMWF [13] are used to address the temporal and spatial variations of wind regime over the study area.

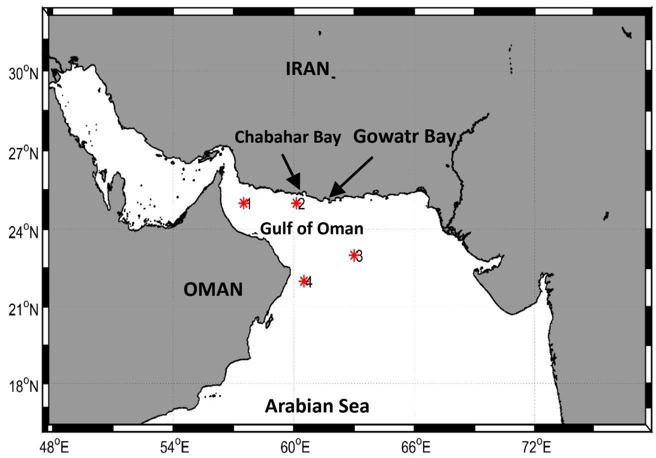

Figure 1. Geographical extent of the study area including the Arabian Sea, the Gulf of Oman, and the Persian Gulf. Locations of selected ECMWF model grid points for presenting time series of wind data over the Gulf of Oman and the Arabian Sea are shown with asterisks

3. Seasonal Variations: A General Overview

As mentioned in Section 1, wind climatology for the region can be classified into four seasons, including winter monsoon, pre-southwest monsoon, summer monsoon, and a short post-monsoon period between the summer and winter monsoon. During the summer months of July to September, the intense temperature difference between land and ocean due to the contrasting sensible heat results in low surface atmospheric pressure over a large part of the Asian continent bounding the Indian Ocean and centers in Tibet and northern India [2]. Over the Indian Ocean, this sensible heat difference enhances a high pressure system at about 30 degrees south. These high and low pressure systems with large spatial pressure gradient stimulate strong northward airflow. The airflow causes persistent southwesterly surface winds over the Arabian Sea with speed of about 15 m/s ([14]). Locations of these low and high pressure systems are reversed during late autumn and winter. The low pressure system is persistent over the ocean, while the center of the high pressure system moves over the continental landmass on the north of the Indian Ocean. The ensuing seaward pressure gradient contributes to northerly to northeasterly winds as winter monsoon. The wind regime associated with winter monsoon; however, is much weaker than the summer monsoon (about 5 m/s).

The pre-southwest monsoon and post-monsoon months are transition periods with weak or still developing low/high pressure systems with a smaller spatial gradient that are not strong enough to support steady northward or southward air flow. The examine of average atmospheric pressure at the sea surface for different months supports the above statements, see Figure 2. Archived pressure data are obtained from the NCEP/NCAR reanalysis model (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surface.html).

Surface atmospheric pressure distribution for the region is presented for different months representing the four distinct patterns of atmospheric pressure and wind over the study area. Winter and summer monsoons are represented by January and July, while the pre- and post-monsoon periods are represented by April and October. Monthly averages provided for 2002 are consistent with other data sets discussed in the paper. During January 2002, a high pressure system with a mean sea level pressure of about 1000-1025 mbar was dominant along northern and southern coasts of the Gulf of Oman and extended almost parallel to the coastline to the east. This high pressure system covered the eastern tip of the Arabian Peninsula and extended westward over the Persian Gulf. The system migrated to offshore of the Iranian and Oman coasts during April 2002. During this month, the average pressure over the eastern tip of Arabian Peninsula decreased to 975 mbar as a result of increasing temperature during the spring and smaller latent heat of land compared to water.

Average pressure map during July 2002 is a classic case for the onset of southwest monsoon [2, 3, 6]. A high pressure system (1000 mbar) was fully developed over the northern Arabian Sea and off the coasts of Gulf of Oman. A low pressure system with a surface atmospheric pressure of 950-975 mbar was developed over the Indian subcontinent. The large spatial gradient between the oceanic and continental surface atmospheric pressure caused a consistent and energetic southwesterly wind in the northern Indian Ocean and the Arabian Sea (see Figure 3).

The average surface pressure at the west of the Gulf of Oman was 975 mbar as a result of large latent heat over the Iranian and Oman coast in the north and south of the Gulf of Oman. This low pressure front extended westward over the Persian Gulf and significantly weakened the persistent "Shamal wind" and its effect on the east of Gulf of Oman. October is the transition month between the summer and winter monsoon. This month is characterized by the gradual migration of high pressure front of 1000 mbar toward the land in the northern Gulf of Oman and re-development of a high pressure system over the Persian Gulf. At the tip of Arabian Peninsula, a low pressure system is still dominant as a result of higher continental temperature during this transition month.

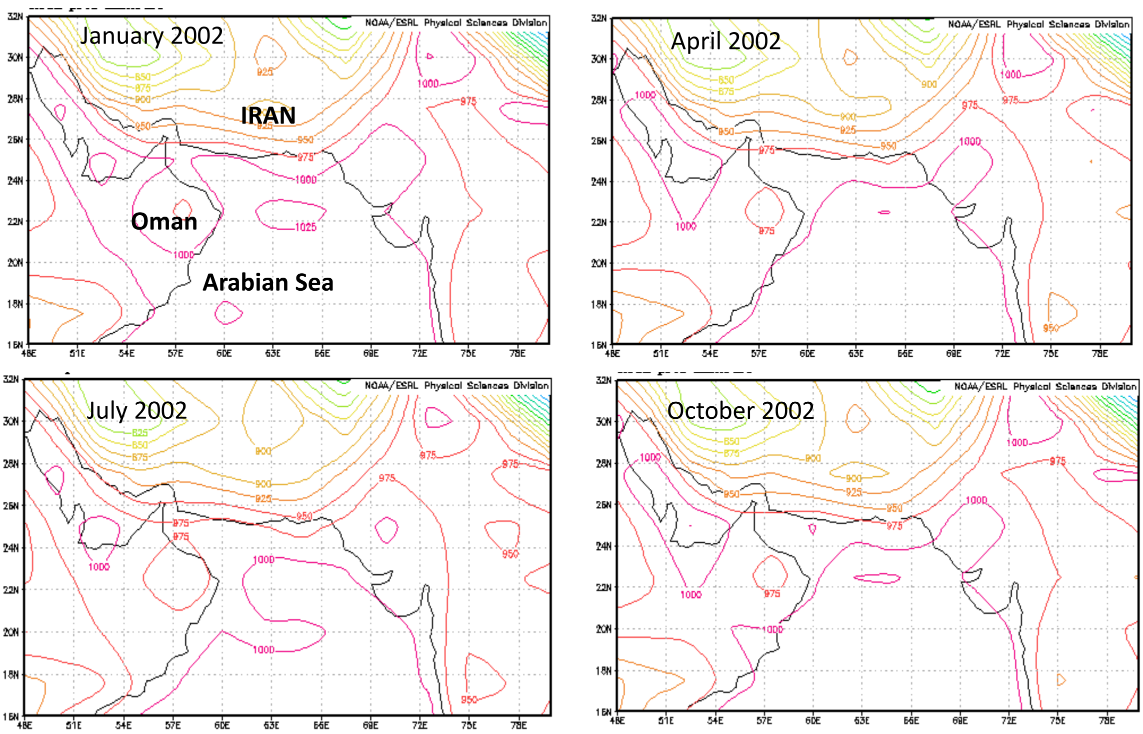

Figure 2. Monthly-averaged surface atmospheric pressure during four representative months over the Arabian Sea, the Gulf of Oman, and the Persian Gulf and surrounding lands. Data were obtained from NCEP/NCAR reanalysis for 2002

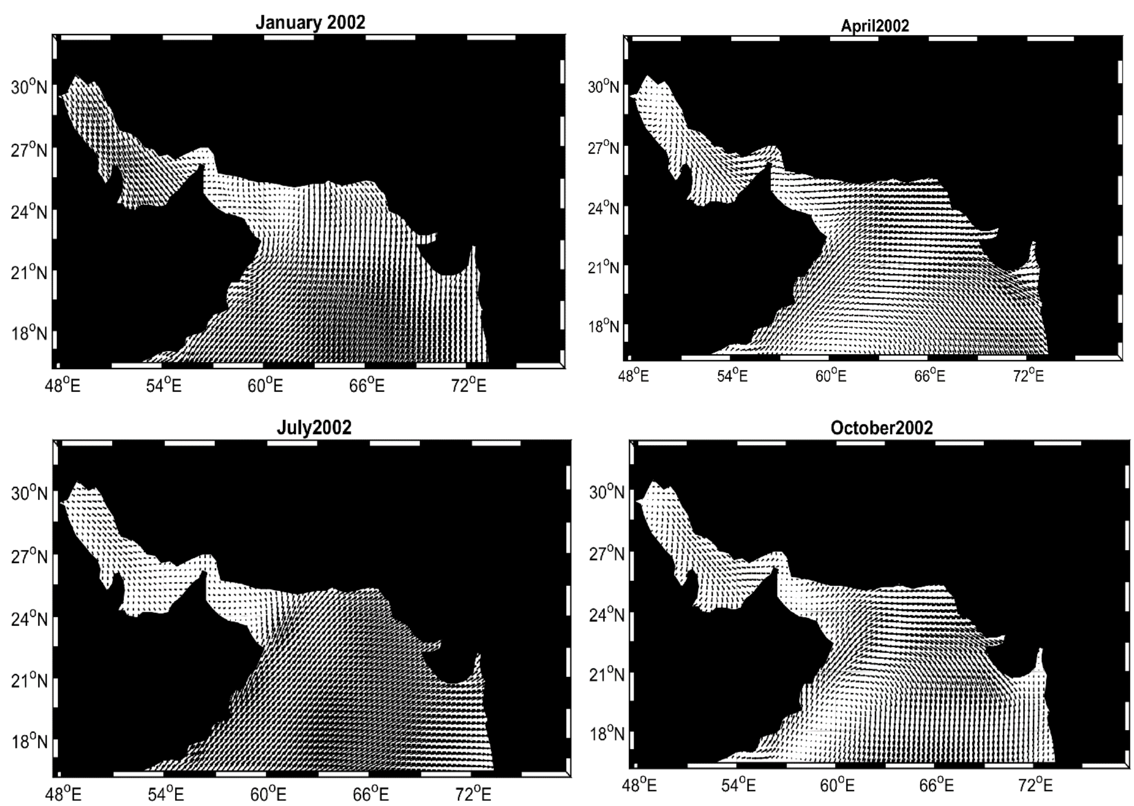

Figure 3. Monthly-averaged wind vectors over the Arabian Sea, the Gulf of Oman, and the Persian Gulf. Wind data were obtained from CFSR model for 2002. Vectors in all panels have the same scaling, so wind intensity can be compared between different months. Quantitative values of wind speeds can be found in Figure 4

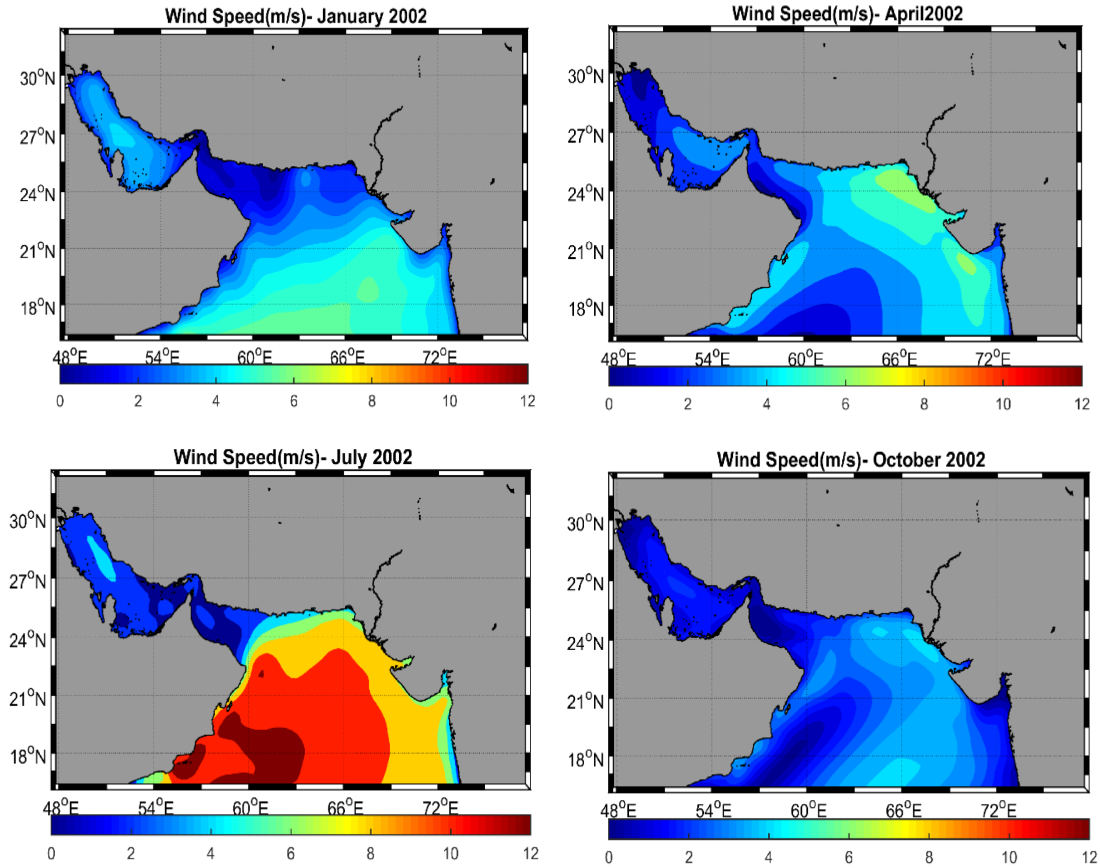

Figure 4. Monthly-averaged wind speed over the Arabian Sea, the Gulf of Oman, and the Persian Gulf for four months representing different wind patterns. Wind data were obtained from CFSR model for 2002

Seasonal wind regime for the study area, resulting from reversing surface pressure system, are provided in Figures 3 and 4. Wind velocity data were obtained from the CFSR (NCEP Climate Forecast System Reanalysis) model database [12] and were averaged for each of the four months presented in Figure 2. A consistent high pressure system existing over the landmass on the north of the Gulf of Oman in January 2002 produced a predominant northerly wind field over the east of the Gulf of Oman with speed up to 3 m/s and a more intense northeasterly wind field over the Arabian Sea with an average speed of 6-7 m/s. This is a classic example of winter monsoon [2, 3, 6]. Over the west of the Gulf of Oman, weak northwesterly winds were dominant as a result of "Shamal" wind blowing in the Persian Gulf. During the pre-southwesterly monsoon month of April relatively weak southwesterly winds are dominant over the northern Arabian Sea with an average wind speed of 3-5 m/s. Winds change direction to westerly off the tip of Arabian Peninsula as a result of "Shamal" wind spreading over the west of the Gulf of Oman. The west of the Gulf of Oman during this month is significantly affected by "Shamal" wind from the Persian Gulf which is still strong during this month. Average wind field during July 2002 clearly shows the prevalence of summer monsoon. Wind field over the entire northern Arabian Sea and the east of the Gulf of Oman is characterized by intense southwesterly winds with speed of 8-12 m/s or larger (Figure 4). Higher wind speeds are observed in the Arabian Sea, and wind speed decreases when approaching the northern coasts of the Gulf of Oman (Figures 3 and 4). The Gulf of Oman, especially its western parts experience a relatively calm period with the easterly wind with an average speed of 2-3 m/s. The post-monsoon month of October shows the weakest wind field over the study area compared to other three months (Figures 3 and 4). Although remnants of southwesterly winds over the northern Arabian Sea are still observed, their area of influence is limited to the Oman coastal area with wind speed declined to 4-6 m/s. During this month, the lowest averaged wind speeds (less than 2 m/s) are observed in the Gulf of Oman amongst all four months.

4. Comparing and Contrasting Wind Climate over the Gulf of Oman and the Northern Arabian Sea

As discussed above, wind climate of the northern Arabian Sea and the Gulf of Oman generally follows four different seasonal patterns (winter monsoon, pre-monsoon, summer monsoon, and post-monsoon). In this section, more detailed characteristics of winds over these regions are presented by examining timeseries of wind speed and direction and long-term wind roses at four locations over the Gulf of Oman and the northern Arabian Sea. Timeseries of wind speed and direction were obtained from ECMWF-ERA40 (Allahdadi et al., 2004) database (see Figure 1 for the location of points).

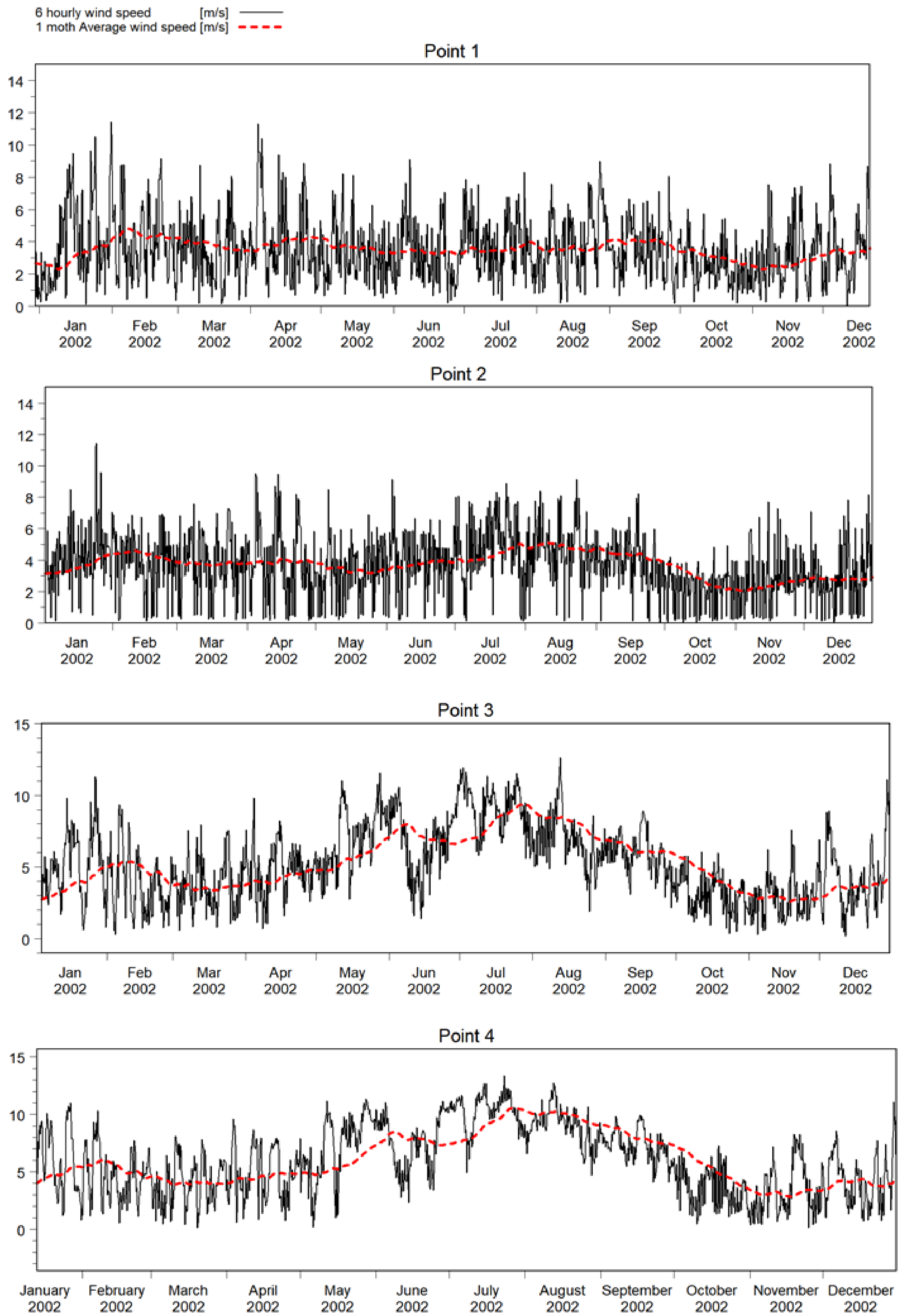

Figure 5. Timeseries of simulated wind speed from four locations shown in Figure 1 in 2002 (data were obtained from ECMWF-ERA40 model)

Timeseries of wind speed extracted from these locations for the year of 2002 shows a significant difference in seasonal variations of wind regime in the Gulf of Oman compared to the northern Arabian Sea (Figure 5). For the location on the west of the Gulf of Oman (Point1) almost no significant seasonal changes in wind speed are observed. At this location, the one-month averaged wind speed (the dashed line) is almost straight showing the wind speed of 4 m/s with slight increases in wind speed during February and September. Point 2, located almost off the Chabahar Bay in the eastern part of the Gulf of Oman, shows stronger seasonal signals. During the summer monsoon (July-September) the monthly-averaged wind speed increases from 5 m/s to about 5.5-6 m/s. Similar to P1, at this location there is a slight increase in the monthly-averaged wind speed during late January and early February due to the winter monsoon outbreak. The summer monsoon signal is very strong at P3 and 4, which are located in the northern Arabian Sea. The monthly-averaged wind speed increases from 5 m/s during the pre-monsoon season of April and May to 10-11 m/s during the summer monsoon months of July-September. Seasonal variability of wind field for these four locations are further examined by presenting wind vectors for two representative months during winter monsoon (January) and summer monsoon (July) (Figure 6 and 7).

During January at both locations in the Gulf of Oman (P1 and P2), different wind directions including northeasterly, northwesterly, and southeasterly are observed (Figure 6). Winds that are coming from the northern sector are due to the winter monsoon outbreak in the Gulf of Oman are not as persistent as the winds observed in the northern Arabian Sea. Both stations located in the northern Arabian Sea show steady northern winds for the second half of January that are associated with the winter monsoon. In July 2002, wind direction at P1 shows a combination of northwesterly and southeasterly winds with the occasional disorganized pattern. During the second half of this month, winds are mostly southeasterly that could be due to the summer monsoon winds over the northern Arabian Sea. Location P2 shows more consistent winds from the southern sector (southerly to southeasterly).

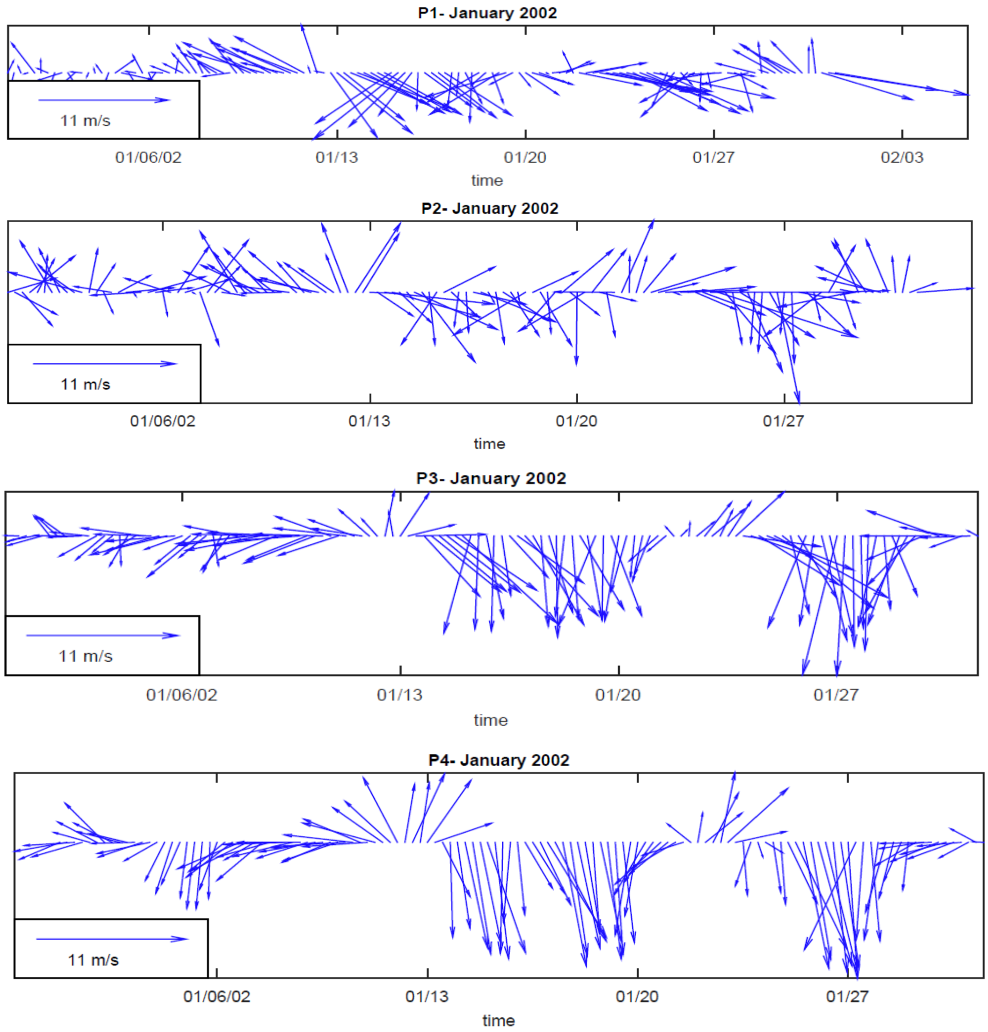

Figure 6. Time variations of wind vector at different points over the Gulf of Oman and the northern Arabian Sea (see Figure 1 for locations) during January 2002

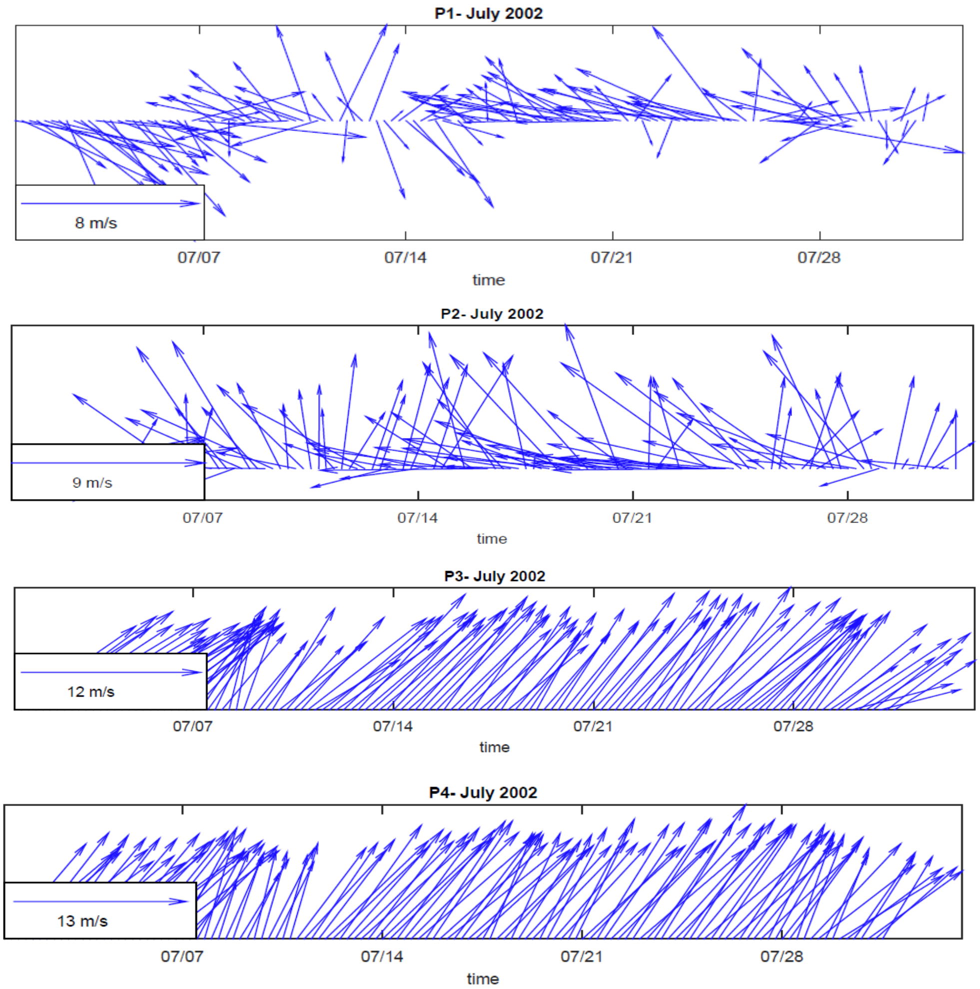

Figure 7. Time variations of wind vector at different points over the Gulf of Oman and the northern Arabian Sea (see Figure 1 for locations) during July 2002

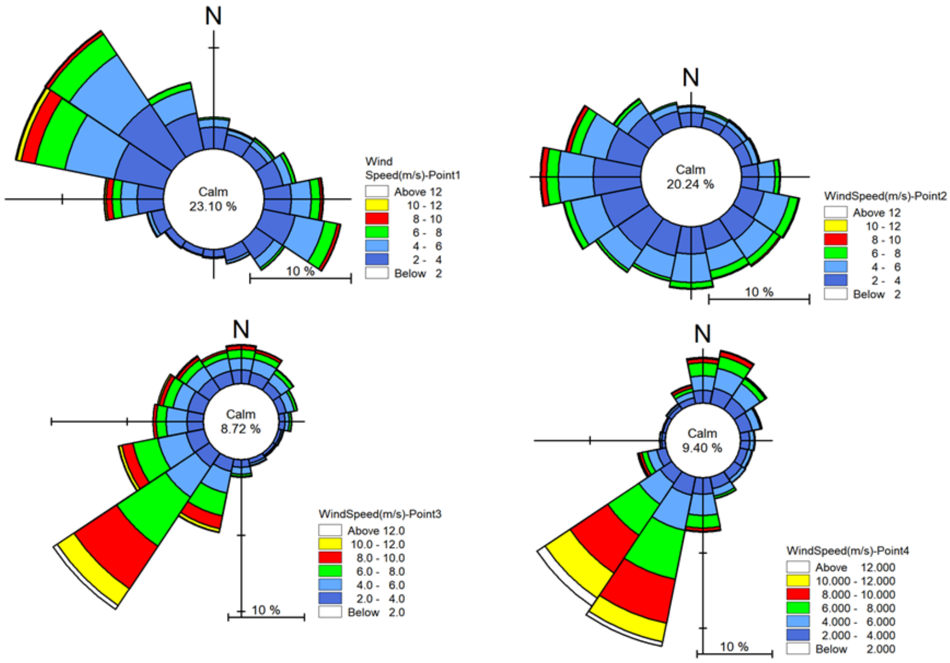

Figure 8. Wind roses at the location of P1-P4 based on 12-years data from ECMWF-ERA40

Wind vector in both stations in the Arabian Sea (P3 and P4) show steady southwesterly winds with wind speeds of 11 m/s or larger which is an example of the summer monsoon. Wind roses of simulated wind from ECMWF-ERA40 database for 1992-2003 at P1-P4 show significant differences between dominant wind directions in the Gulf of Oman with those of on the northern Arabian Sea (Figure 8). Predominant wind direction for station P1 on the west of the Gulf of Oman is northwest, while for P2 located east of the Gulf of Oman, the dominant direction is westerly. However, due to the influence of different atmospheric fronts over the Gulf of Oman, the frequency of occurrence for other directions are also significant. For P3 and P4, the frequency of occurrence for southwesterly winds is substantially larger than other directions which is consistent with Figures 3 and 7.

5. Summary and Conclusions

In this paper wind climatology over the Gulf of Oman and the northern Arabian Sea was investigated and summarized by examining modeling data of surface atmospheric pressure and wind velocity components. Former studies provided different seasonal patterns for the wind regime over this region, which is driven by shifting of high and low pressure systems over the ocean and landmass. During fall-winter time period (November-April) contrasting latent heat of water and land produces a high pressure system over the continental Asia and a low pressure system over the Arabian Sea and the northern Indian Ocean. This generates north to south air flow which is associated with northeasterly winds of the winter monsoon. From July to the end of September persistent and intense southwesterly wind are predominate over the Arabian Sea and eastern parts of the Gulf of Oman. During this season locations for centers of high and low pressure systems over land and ocean are reversed so that high pressure system moves over the ocean. This intense and persistent wind substantially contributes to the regional circulation, wave dynamics, and redistribution of biogeochemical substances over the Arabian Sea and the Gulf of Oman. Coastal and offshore upwelling induced by this wind, forms one of the most productive oceanic areas along and off the coasts of Oman in the northern Arabian Sea. Waves that are generated over the Arabian Sea by summer monsoon highly contribute to the wave dynamics of the northern Gulf of Oman by forming bimodal frequency spectra over this region in conjunction with local waves. During the pre-monsoon (May and June) and post-monsoon (October), winds are not as persistent as summer and winter monsoons and significantly decrease in speed. As time series of wind speed and direction at different locations demonstrated, summer monsoon has the minimum effect on wind regime along in the west of the Gulf of Oman and in the western part, a relatively weak effect is detected in comparison to locations in the northern Arabian Sea. Long-term wind roses show dominant wind directions of westerly-northwesterly and southeasterly for locations in the Gulf of Oman and the northern Arabian Sea respectively.

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