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Westward mountain-gap wind jets of the northern Red Sea as seen by QuikSCAT

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ABSTRACT

We analyse ten years of QuikSCAT satellite surface winds to statistically characterize the spatio-temporal variability of the westward mountain-gap wind jets over the northern Red Sea. These wind jets bring relatively cold and dry air from the Arabian Desert, increasing heat loss and evaporation over the region similar to cold-air outbreaks from mid and subpolar latitudes. QuikSCAT captures the spatial structure of the wind jets and agrees well with in situ observations from a heavily instrumented mooring in the northern Red Sea. The local linear correlations between QuikSCAT and in situ winds are 0.96 (speed) and 0.85 (direction). QuikSCAT also reveals that cross-axis winds such as the mountain-gap wind jets are a major component of the regional wind variability. The cross-axis wind pattern appears as the second (or third) mode in the four vector Empirical Orthogonal Function analyses we performed, explaining between 6% to 11% of the wind variance. Westward wind jets are typical in winter, especially in December and January, but with strong interannual variability. Several jets can occur simultaneously and cover a large latitudinal range of the northern Red Sea, which we call large-scale westward events. QuikSCAT recorded 18 large-scale events over ten years, with duration between 3 to 8 days and strengths varying from 3–4 to 9–10 m/s. These events cause large changes in the wind stress curl pattern, imposing a remarkable sequence of positive and negative curl along the Red Sea main axis, which might be a wind forcing mechanism for the oceanic mesoscale circulation.

1. Introduction

For about 10 years, the Seawinds/QuikSCAT satellite mission from NASA (National Aeronautics and Space Administration) provided an unprecedented view of the near-surface vector winds over the global oceans (e.g. Cornillon and Park, 2001; Chelton et al., 2004; Chelton et al., 2006; Ebuchi et al., 2002; Fu and Morrow, 2013; Hoffman and Leidner, 2005; Holbach and Bourassa, 2014; Kelly et al., 2001; O'Neill et al., 2005; O'Neill et al., 2010; Risien and Chelton, 2008). Notably, QuikSCAT captured persistent small-scale features in the wind stress curl and divergence fields in coastal regions where orography influences the near-surface winds such as the mountain-gap wind jets of Tehuantepec, Papagayo and Panama in the Pacific coast of Central America (Brennan and Cobb, 2010; Chelton et al., 2004; Holbach and Bourassa, 2014).

The fact that QuikSCAT captures orographic-associated features motivated us to examine this dataset to understand the largely unknown westward mountain-gap wind jets over the northern Red Sea (Jiang et al., 2009). The Red Sea, an Indian Ocean marginal sea, is surrounded by mountains on both sides of the basin (Fig. 1). These mountains constrain the prevailing winds to blow approximately along the Red Sea main axis (Fig. 2). But synoptic conditions can sometimes cause the winds to blow across the axis through the mountain-gaps from both sides of the basin.

Besides orography, the large-scale Indian monsoon system and the regional land-sea breeze govern the Red Sea wind variability (e.g., Churchill et al., 2014; Davis et al., 2015; Patzert, 1974; Sofianos and Johns, 2003; Steedman and Ashour, 1976). Sea breeze-like circulation is responsible for the largest part (about 80%) of the moisture transport between the Red Sea and the surrounding dry lands at least in the ERA-Interim dataset (Zolina et al., 2017). QuikSCAT, however, is unable to fully resolve the diurnal cycle associated with the Red Sea breezes because its sampling frequency is at best twice a day at each location (e.g., Gille et al., 2003); hence, this subject falls outside the scope of the present study.

Because of the monsoons, the Red Sea surface winds have a seasonally dependent spatial pattern (Clifford et al., 1997; Johns et al., 1999; Langodan et al., 2017; Patzert, 1974; Sofianos and Johns, 2003). Over the northern Red Sea (north of 20° N), the along-axis winds are predominantly southward all year-round, but in the southern basin they

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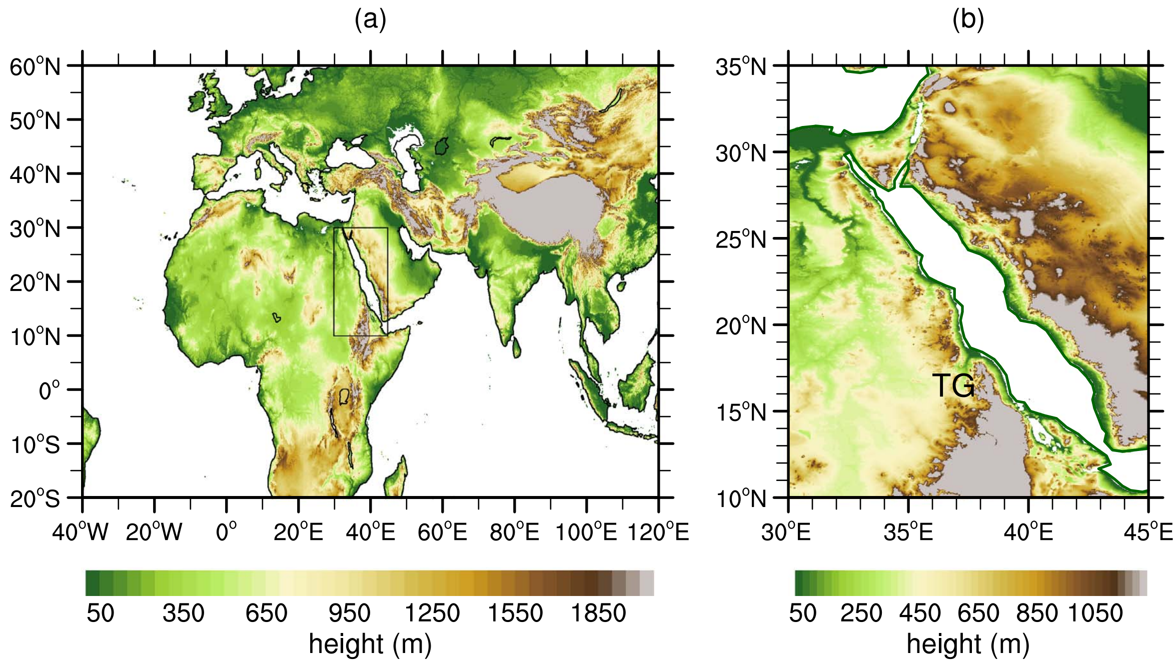

Fig. 1. Land elevation from the ETOPO2 Global Relief data (see Section 2.3 for a description about this dataset): (a) Large-scale view, including Africa, Europa and Asia. Black rectangle highlights the Red Sea (b) Land elevation surrounding the Red Sea. The colorbars in (a) and (b) have different ranges. TG stands for Tokar Gap. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

reverse seasonally due to the monsoonal regime (Fig. 2). Hence, during the summer monsoon (May–September), the climatological winds blow southward over the entire Red Sea (Fig. 2 e–i). In the winter monsoon (October–April), the winds in the northern and southern basins blow in opposite directions, forming a climatological convergence zone near 19° N (Fig. 2 l–m). Pedgley (1966a) defined the cloudy area with calm or light winds where the two opposite-blowing air-streams meet as the Red Sea Convergence Zone (RSCZ) (Fig. 3c). This definition has been used in several works since then (e.g., Langodan et al., 2015; Patzert, 1974; Ralston et al., 2013; Viswanadhapalli et al., 2017; Zolina et al., 2017).

The pioneer studies of Pedgley (1966a,b) were motivated by the fact that the RSCZ controls the northward migration of the Desert Locust swarms, a plague that periodically hits the bordering countries of the Red Sea as already described in the Old Testament of the Bible. Based on along-axis wind data from February 1964, Pedgley (1966a,b) inferred that the RSCZ migrates in a north-south direction, with its northward position reaching Jeddah at 21.28° N (Fig. 3a). The meridional migration of the RSCZ was later confirmed by Patzert (1974). In the QuikSCAT climatological winds, the RSCZ is better defined in November and December and located at about 19° N. Under the RSCZ, the northward and southward winds bend westward towards the Tokar Gap on the Sudanese coast (18° N–19° N, TG in Fig. 1b). The narrow band of westward winds between 18° N–19° N associated with the RSCZ seen in QuikSCAT also appear in model simulations and reanalysis products (e.g., Jiang et al., 2009; Viswanadhapalli et al., 2017). Johns et al. (1999) describe the RSCZ as the limit between the monsoon-dominated atmosphere in the south and the continental atmosphere in the north.

Despite the surface winds being predominantly along the main axis, several works describe the winds occasionally blowing in a cross-axis direction through mountain gaps on both sides of the Red Sea (e.g., Bower and Farrar, 2015; Clifford et al., 1997; Davis et al., 2015; Jiang et al., 2009; Zhai and Bower, 2013). These mountain-gap cross-axis winds have no clear signature in the climatological monthly means. In the central Red Sea, cross-axis winds occur in summer (hereafter boreal seasons), with winds blowing eastward through the Tokar Gap (Davis et al., 2015; Jiang et al., 2009; Zhai and Bower, 2013). Zhai and Bower (2013) found strong evidence that the Tokar Gap wind jet leads to the formation of oceanic dipole eddies between 18° N–20° N, similar to the effects of the Tehuantepec, Panama and Papagayo wind jets (e.g., McCreary et al., 1989; Chelton et al., 2000; Kessler, 2006). Numerical simulations using ROMS (Regional Ocean Modelling Systems) by Farley Nicholls et al. (2015) corroborate these findings.

Much less is understood about the cross-axis winds blowing through the mountain gaps in the northern Red Sea. Differently from the Tokar Gap wind jet, the northern Red Sea jets are predominantly westward, from Saudi Arabia to Africa, and occur in winter (Jiang et al., 2009; Bower and Farrar, 2015). These wintertime events are distinct from the narrow RSCZ-associated westward winds because the mountain-gap winds bring relatively cold dry air and dust from the desert and are formed by multiple jets extending over a large latitudinal range (Bower and Farrar, 2015; Jiang et al., 2009; Kalenderski et al., 2013). However, most of the knowledge about the westward wind jets is based on short-time numerical simulations using the Weather Research and Forecasting (WRF) model (e.g. Jiang et al., 2009; Kalenderski et al., 2013) and no statistics (e.g., frequency, duration) about them existed until the present study. The simulations are for periods of 60 days or less between December 2008 and January 2009, and focus on a single event on 14–15 January 2009. To the best of our knowledge no comprehensive study about the westward mountain-gap wind-jet events based on satellite observations has been realized to date.

During westward wind-jet events, relatively strong winds (up to 15 m/s) and cold dry air cause episodes of large oceanic heat loss (-700 to $-900\,W/m^2$) and high evaporation (>5 m/yr) in the northern Red Sea (Jiang et al., 2009; Bower and Farrar, 2015). Hence, the westward events resemble the severe cold-air outbreaks that occur in mid and subpolar latitudes such as over the Gulf Stream region (oceanic heat loss of about $1000\,W/m^2$) (e.g., Marshall et al., 2009), the Japan/East Sea ($>400\,W/m^2$) (e.g., Dorman et al., 2006) and the bora-winds in the Adriatic Sea ($700\,W/m^2$) (e.g., Lee et al., 2005, Poulain and Cushman-Roisin, 2001)

Because the westward events cause strong heat loss and evaporation, they may trigger surface water mass transformation that can lead to the formation of Red Sea Overflow Water (Bower and Farrar, 2015;