Variability of Vertical Wind Shear

Subjects: Environmental Sciences
Contributor: Atanasio Manhique

Vertical wind shear is caused by a wind of different speed or direction over a relatively short distance in the atmosphere.

Keywords: cyclogenesis ; vertical wind shear ; Mozambique Channel

1. Overview

This entry explores the relationship between vertical wind shear (VWS) and tropical cyclone (TC) genesis in the Mozambique Channel (MC) for the period 1979–2019. Additionally, SST, low-level relative vorticity, 700 hPa relative humidity and upper-level divergence were also analyzed for the peak cyclogenesis months to explore their relative contributions. The analyses were done using NCEP/NCAR Reanalysis-1 for the atmospheric fields, monthly Optimum Interpolation SST V2, and for the cyclogenesis the TC best track data from the La Reunion–Regional Specialized Meteorological and Joint Typhoon Warning Centre. A total of 43 TCs generated in the MC were observed for the analysed period. The maximum frequency of cyclogenesis in the MC was observed during January and February and the spatial location of maximum TC genesis was coincident with the minimum values of the VWS. The VWS showed significant correlations with TC intensity, particularly when considering the upper atmosphere (200–500 hPa) or the bulk (200–850 hPa) VWS. The mean composites of the cyclogenesis months over the MC of SST, relative humidity at 700 hPa, divergence at upper atmosphere, showed significant values. However, linear correlations between these factors vs. TC genesis frequency and intensity were not significant. Analyses of interannual correlations between VWS and Niño-3.4 (subtropical southwest Indian Ocean dipole-SIOD) showed statistically significant positive (negative) correlations at different lags, suggesting that La Niña and the positive phase of SIOD conditions are favorable to weaker VWS and thus to intensification of TCs in the Mozambique Channel. Thirteen landfall cases were observed with seven over the Madagascar west coast and six over the Mozambique coast. The landfall over the Madagascar (Mozambique) coast was associated with strengthened (weakened) VWS.

2. Tropical Cyclones

The process by which tropical cyclones (TCs) form and intensify, often referred to as tropical cyclogenesis, is strongly dependent on the existence of several environmental conditions. Gray [1] listed six basic conditions favoring TC genesis, namely: (i) sea surface temperature (SST) exceeding 26 °C, (ii) enhanced mid-troposphere (700 hPa) relative humidity, (iii) conditional instability, (iv) enhanced lower troposphere relative vorticity, (v) weak vertical environmental wind shear (VWS) and (vi) a displacement by at least 5° latitude away from the equator. Chan et al. [2] suggested that VWS is one of the main governing factors of both tropical cyclogenesis and tropical cyclone intensity. Moreover, some studies indicate that the uncertainties in forecasting the environmental wind shear values prevent the improvements in TC intensity forecast [3][4]. Over the tropical Pacific, some studies have indicated that VWS is a key environmental variable that determines the TCs development [5][6]. Jones et al. [7] considered the VWS a key predictor of seasonal TC activity. Although some literature has shown cases of cyclones intensifying under moderate to strong VWS (e.g., [8][9][10]), in general large values of VWS are considered to be detrimental to the formation as well as the intensification of TCs, due to the “ventilation” effect [1][11][12][13]. Chan et al. [2] have indicated that the reduction of ventilation above the boundary layer due to vertical alignment is crucial to accumulate the energy within the inner core region of a TC. Nolan and McGauley [6] studied the relationship between VWS and TC genesis events within the latitudes 20° S and 20° N from 1969 to 2008, and found that VWS values in the range of 1.25–5 m/s are the most favorable for TC genesis, although previous studies suggested VWS values between 5–10 m/s (e.g., [14]). Some studies also suggested that there is a VWS threshold value above which TCs may not develop, for example, a threshold value of 12.5 m/s was determined for the western North Pacific by Zehr [15].

The Southwest Indian Ocean (SWIO) is one of the major basins of TCs formation and intensification. TCs forming in this region account for about 14% of the global total, with an average of 12–13 TCs forming each year in the cyclone season running from November to April [16][17][18]. SWIO TCs, especially those forming in the Mozambique Channel (MC) have been poorly studied so far although they frequently impact island nations and countries on the mainland of southeastern Africa [19][20][21]. Leroux et al. [21] stated that over the cyclone seasons from 1999/2000 to 2015/16, on average, Mozambique was hit by tropical systems once per year and by TCs about once every 3 years, and that those numbers are even worse for Madagascar, which was hit twice per year by tropical systems and was hit once every 2 years by TCs. These countries are listed as the world's least developed, with high levels of vulnerability to climatic shocks. This study aims to contribute to the improvement of monitoring and seasonal forecast of TCs in the SWIO and thus to mitigation of the destructive impacts of TCs in the affected countries, which is one of the main objectives of the research project ReNovRisk-Cyclone [22].

Previous studies [23][24][25] have described several characteristics of the VWS and its association with tropical cyclone activity in the SWIO. Their results showed a band of weak VWS located near the Equator with a tendency to move (south–north) accompanying the displacement of the Inter-Tropical Convergence Zone (ITCZ) which is an important mechanism for tropical cyclogenesis. During the cyclone season in the SWIO, the ITCZ stretches across the MC between 15–20° S and the area of weak VWS along it can enhance the positive vorticity needed for tropical cyclogenesis in the region [18][26][27]. Matyas [28] indicated that given the displacement of the ITCZ in the MC during the cyclone season, TC formation frequency, location and environmental conditions by month. Ho et al. and Kuleshov et al. [17][25] suggested that during the cold phase of El Niño–Southern Oscillation (ENSO), there is a reduction of TC genesis in the western part of the South Indian Ocean (SIO, west of 75° E) and an increase in the eastern part (east of 75° E) as well as displacement of the area favorable for TC genesis further away from the equator and an inverted scenario is observed during the warm phase. The impact of VWS on TC genesis and intensification has been significantly explored globally, however, to our knowledge over the SWIO there are few studies, and none focusing on the MC. The MC has unique environmental conditions for TCs genesis, namely the presence of a summer trough which is associated with moist convection (e.g., [29]) the summer convergence zone, known as the South Indian Convergence Zone, which is associated with zonal wind convergence and moisture convergence [30] and the relative higher SST as compared to the same latitude east of Madagascar [18]. Moreover, the topography of Madagascar has a shielding effect, thus affecting the low-level circulation in the channel (e.g., [31]). Given these peculiarities, it is of interest to explore how the environmental factors contribute to the cyclogenesis in this region. The main objective of this study is to assess the relationship between the seasonal to interannual variability of the VWS and TC genesis frequency and intensity in the MC.

3. Discussion

Lower values of mean 200–850 hPa VWS over the SWIO are observed during the period December–February, with a distinct band (values below 6 m/s) extending across central South Indian Ocean towards southern Africa. In the MC, the mean position of this band is located between the latitudes 16−22° S. The region is also coincident with the highest cyclogenesis in the MC, above 40 TC formed in the period here considered. January to March monthly VWS anomalies maps, plotted together with TC genesis, show that most TCs are formed in regions of negative anomalies, although some developed to at least TC intensity in regions with positive monthly anomalies. However, it is important to note that the February mean VWS, over the region where all the cyclogenesis was observed, is within the values considered to be favorable for TC genesis (e.g., [5]). The region in the MC with maximum cyclogenesis events is coincident with the mean location of the center of the MC trough and the months (January and February) with highest events are also coincident with the period of the peak of strength of the trough. Barimalala et al. [29] indicate that the interannual variability in the MCT is associated with moist convection over the MC and is modulated by the location of the warm SST in the south Indian Ocean. These environmental conditions, as indicated in the introduction, are also important for cyclogenesis. Mean composite analyses of SST, relative humidity at 700 hPa and divergence at 200 hPa for January and February (with cyclogenesis) showed significant values, however, at the interannual timescale, no significant correlations were observed with TC genesis and TC maximum intensity. Statistically significant correlations were only observed between TC maximum intensity and VWS (200–850 hPa and 500–200 hPa) suggesting the influence of upper atmosphere vertical wind shear at interannual time scales in the development of TCs.

Correlation analyses of interannual variability of 200–850 hPa VWS (December –March) with Nino 3.4 (SIOD) index at different lags (SON, OND, NDJ, DJF and JFM), shown in Table 1, were significantly positive (negative). This suggests that high values of VWS are associated with El Niño, hence not favorable for TC intensification. Most of the 15 cases of TC that developed to at least TC intensity, developed under La Niña or neutral conditions (six under La Niña, six under neutral and three under El Niño conditions). It is noteworthy that four cases of the neutral condition were under the negative Niño-3.4 index. On the other hand, the negative correlation with the SIOD, suggests that warm SST over SWIO, linked to SIOD, is associated with weaker VWS over the MC. These results may indicate that both La Niña and positive SIOD are favorable to weaker VWS and to intensification of TC in the Mozambique Channel.

Analysis of composite anomalies of 200–850 hPa VWS for landfall events suggest that higher values over the MC are favorable to landfall over Madagascar west coast while weaker values are more favorable to landfall over the Mozambique coast. Composite analyses of low level geopotential height and wind suggest a significantly strengthened MC trough during landfall over the Madagascar west coast.

4. Conclusions

The cyclone activity in the MC has not been much studied, particularly the cyclogenesis, however, there is a significant number of cyclones making landfall or affecting Mozambique and Madagascar that are generated in the MC. The VWS over the SWIO is characterized by a band of minima magnitude, propagating southward and reaching its maxima southward position between January and February. Over the MC, the region of minima is associated with the highest number of cyclogenesis. A total of 43 cases of TC genesis were observed in the MC and 15 developed to at least Tropical Cyclone intensity. The VWS showed significant correlations with TC intensity, particularly when considering the upper atmosphere (200–500 hPa) or the bulk (200–850 hPa) VWS. The lower atmosphere VWS (500–850 hPa) did not show statistically significant correlation, a similar result was observed with the correlations between the TC genesis frequency and VWS. Analyses of interannual correlations of VWS and Niño-3.4 (SIOD) showed significant positive (negative) correlations at different lags suggesting that La Niña and positive phase of the SIOD conditions are favorable to weaker VWS and to intensification of TC in the Mozambique Channel. Thirteen landfall cases were observed with seven over the Madagascar west coast and six over the Mozambique coast. The landfall cases over the Madagascar (Mozambique) coast were associated with strengthened (weakened) VWS. The landfall events over Madagascar appear to also be associated with a significantly stronger MC trough.

References

1. Gray, W.M. Global view of the origin of tropical disturbances and storms. Mon. Weather Rev. 1968, 96, 669–700.
2. Chan, K.T.F.; Wang, D.; Zhang, Y.; Wanawong, W.; He, M.; Yu, X. Does strong vertical wind shear certainly lead to the weakening of a tropical cyclone? Environ. Res. Commun. 2019, 1, 1–13.
3. Emanuel, K.; DesAutels, C.; Holloway, C.; Korty, R. Environmental control of tropical cyclone intensity. J. Atmos. Sci. 2004, 61, 843–856.
4. Finocchio, P.M.; Majumdar, S.J. A Statistical Perspective on Wind Profiles and Vertical Wind Shear in Tropical Cyclone Environments of the Northern Hemisphere. Mon. Weather Rev. 2017, 145, 361–378.
5. Aiyyer, A.R.; Thorncroft, C. Climatology of Vertical Wind Shear over the Tropical Atlantic. J. Clim. 2006, 19, 2969–2983.
6. Nolan, D.S.; McGauley, M.G. Tropical cyclogenesis in wind shear: Climatological relationships and physical processes. In Cyclones: Formation, Triggers and Control; Nova Science Publishers, Inc.: New York, NY, USA, 2012; pp. 1–36.
7. Jones, J.J.; Bell, M.M.; Klotzbach, P.J. Tropical and Subtropical North Atlantic Vertical Wind Shear and Seasonal Tropical Cyclone Activity. J. Clim. 2020, 33, 5413–5426.
8. Molinari, J.; Vollaro, D. Rapid Intensification of a Sheared Tropical Storm. Mon. Weather Rev. 2010, 138, 3869–3885.
9. Montgomery, M.T.; Lussier, L.L., III; Moore, R.W.; Wang, Z. The genesis of Typhoon Nuri as observed during the Tropical Cyclone Structure 2008 (TCS-08) field experiment—Part 1: The role of the easterly wave critical layer. Atmos. Chem. Phys. 2010, 10, 9879–9900.
10. Rios-Berrios, R.; Torn, R.D.; Davis, C.A. An Ensemble Approach to Investigate Tropical Cyclone Intensification in Sheared Environments. Part II: Ophelia (2011). J. Atmos. Sci. 2016, 73, 1555–1575.
11. Mundell, D.B. Prediction of Tropical Cyclone Rapid Intensification Events. Master’s Thesis, Colorado State University, Fort Collins, CO, USA, 1990.
12. DeMaria, M. The effect of vertical shear on tropical cyclone intensity change. J. Atmos. Sci. 1996, 53, 2076–2087.
13. Zehr, R.M. Environmental vertical wind shear with Hurricane Bertha (1996). Weather Forecast. 2003, 18, 345–356.
14. Bracken, W.E.; Bosart, L.F. The role of Synoptic-Scale flow during tropical cyclogenesis over the North Atlantic Ocean. Mon. Weather Rev. 2000, 128, 353–376.

15. Zehr, R.M. Tropical Cyclogenesis in the Western North Pacific; NOAA Technical Report NESDIS 61; NOAA: St. Petersburg, FL, USA, 1992; p. 181.
16. Fink, H.A.; Speth, P. Tropical cyclones. Naturwissenschaften 1998, 85, 482–493.
17. Ho, C.-H.; Kim, J.-H.; Jeong, J.-H.; Kim, H.-S.; Chen, D. Variation of tropical cyclone activity in the South Indian Ocean: El Niño–Southern Oscillation and Madden-Julian Oscillation effects. J. Geophys. Res. 2006, 111, 1–9.
18. Mavume, A.F.; Rydberg, L.; Rouault, M.; Lutjeharms, J.R.E. Climatology and landfall of tropical cyclones in the SouthWest Indian Ocean. J. Mar. Sci. 2009, 8, 15–36.
19. Malherbe, J.; Engelbrecht, F.A.; Landman, W.A.; Engelbrecht, C.J. Tropical systems from the southwest Indian Ocean making landfall over the Limpopo River Basin, southern Africa: A historical perspective. Int. J. Climatol. 2012, 32, 1018–1032.
20. WMO. Global Guide to Tropical Cyclone Forecasting; Guard, C., Ed.; WMO: Geneva, Switzerland, 2017; p. 399. Available online: (accessed on 7 January 2020).
21. Leroux, M.-D.; Meister, J.; Mekies, D.; Dorla, A.-L. A Climatology of Southwest Indian Ocean Tropical Systems: Their Number, Tracks, Impacts, Sizes, Empirical Maximum Potential Intensity, and Intensity Changes. J. Appl. Meteorol. Climatol. 2018, 57, 1021–1041.
22. Bousquet, O.; Barruol, G.; Cordier, E.; Barthe, C.; Bielli, S.; Calmer, R.; Rindraharisaona, E.; Roberts, G.; Tulet, P.; Amelie, V.; et al. Impact of Tropical Cyclones on Inhabited Areas of the SWIO Basin at Present and Future Horizons. Part 1: Overview and Observing Component of the Research Project RENOVRISK-CYCLONE. Atmosphere 2021, 12, 544.
23. Chen, S.S.; Knaff, J.A.; Marks, F.D., Jr. Effects of Vertical Wind Shear and Storm Motion on Tropical Cyclone Rainfall Asymmetries Deduced from TRMM. Mon. Weather Rev. 2006, 134, 3190–3208.
24. Bessafi, M.; Wheeler, M.C. Modulation of South Indian Ocean Tropical Cyclones by the Madden–Julian Oscillation and Convectively Coupled Equatorial Waves. Mon. Weather Rev. 2006, 134, 638–656.
25. Kuleshov, Y.; Ming, F.C.; Qi, L.; Chouaibou, I.; Hoareau, C.; Roux, F. Tropical cyclone genesis in the Southern Hemisphere and its relationship with the ENSO. Ann. Geophys. 2009, 27, 2523–2538.
26. Jury, M.R.; Pathack, B. A study of climate and weather variability over the tropical Southwest Indian Ocean. Meteorol. Atmos. Phys. 1991, 47, 37–48.
27. Jury, M.R. A preliminary study of climatological associations and characteristics of tropical cyclones in the SW Indian Ocean. Meteor. Atmos. Phys. 1993, 51, 101–115.
28. Matyas, C.J. Tropical cyclone formation and motion in the Mozambique Channel. Int. J. Climatol. 2015, 35, 375–390.
29. Barimalala, R.; Blamey, R.C.; Desbiolles, F.; Reason, C.J.C. Variability in the Mozambique Channel Trough and Impacts on Southeast African Rainfall. J. Clim. 2020, 33, 749–765.
30. Cook, H.H. The South Indian Convergence Zone and Interannual Rainfall Variability over Southern Africa. J. Clim. 2000, 13, 3789–3804.
31. Barimalala, R.; Desbiolles, F.; Blamey, R.C.; Reason, C. Madagascar Influence on the South Indian Ocean Convergence Zone, the Mozambique Channel Trough and Southern African Rainfall. Geophys. Res. Lett. 2018, 45, 11380–11389.