The Unexpected Relationship Between Extreme Shear Events and AMO

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Research Article

Keywords: Vertical shear, AMO, ITCZ, Climate change

Posted Date: August 11th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-795944/v1>

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Abstract

The vertical shear—the change in wind speed with height-of horizontal winds is a serious threat to the safety of aircraft. Yet their global distribution is not fully understood. We creatively used a precise method to calculate different types of vertical shear at four isobaric surfaces during the period of 1979~2018. The occurrence of severe shear events has increased by 19%, and they mostly occur over the equatorial ocean and within the mid-high latitude zone of the Northern hemisphere, while light shear event occurrence has been reduced by 21%. Variations of severe shear are modulated by the Atlantic Multidecadal Oscillation (AMO), which affects the frequency of shear events by influencing the intertropical convergence zone (ITCZ). Our study implies that severe shear events are regulated by internal climate variability.

Introduction

At present, we have a substantial amount of advanced equipment available to observe weather conditions and help us make forecasts so that we can avoid the influence of disastrous weather ^{1,2}. In addition, the technique of numerical modelling, a result of the advances made in both theory and practice, appears to be quite revolutionary ³. However, some weather phenomena cannot be observed promptly, or by the time we do observe them, they have already caused very serious harm. Vertical shear, which is the change in wind speed with height, falls into this category; the frequency and intensity of vertical shear events cause serious consequences, such as the generation of typhoons and the production of clear air turbulence (which can easily cause aircraft accidents) ⁴⁻⁶.

Wind shear is a weather phenomenon that has received much attention ^{7,8}; due to its associated dangers and the difficulty of detecting its characteristics, there are always some obstacles to researching this phenomenon. However, research on wind shear mainly focuses on the synoptic scale, and there is a lack of climate research that only focuses on the formation of typhoons ^{9,10}. Therefore, there are still many deficiencies in the climatological research of wind shear.

Results

Temporal and spatial distribution of shear events

As shown in Figure. 1, serious shear events have occurred almost exclusively over the ocean. The lower levels (1000 hPa and 850 hPa) and upper levels (500 hPa and 200 hPa) of atmospheric pressure show different spatial patterns of shear forces (Figure. 1). Severe shearing in the lower levels (Figure. 1(a), (b)) occurs more often at low latitudes than at high latitudes, especially east of the tropical Pacific and tropical Atlantic. The areas between North and South America and mid-Africa are the main occurrence areas of severe shearing. The distribution of severe shear events is symmetric on both sides of the equator in the mid-troposphere (Figure. 1(c)), mainly in the 90°E ~ 180° range, at approximately 30°N/30°S on both hemispheres. As shown in Figure. 1(d), severe shear in the upper pressure levels only

occurs in the Northern Hemisphere's mid-high latitude zone, especially over the North Pacific, North America, Europe, and North Atlantic. The locations of wind shear activities at higher pressure levels are consistent with the location of the jet stream, and in the context of global warming, the jet stream shows an increasing trend ¹¹. Moreover, wind shear tends to occur within specific weather systems. One of the most common causes of severe wind shear is thunderstorms; during a thunderstorm, strong vertical wind shear is caused by strong downdrafts from rainfall. According to the Optical Transient Detector (OTD) and Lightning Imaging Sensor (LIS) ¹²⁻¹⁴, which are low Earth orbit instruments that detect lightning flashes, the annual distribution of lightning is similar to that of low-latitude severe shear events at the 1000 hPa and 850 hPa levels.

To identify the temporal distribution of vertical shear at different pressure levels, we calculate the annual variations in severe and light wind shear. Remarkably, the trend of heavy shear events is opposite to that of light shear events. The annual distribution of light shear events shows a clear downward trend (Figure. S1). The distributions of light shear events show significant decreases at 1000 hPa (-1610 per decade, Figure. S1(a)) and 200 hPa (-1040 per decade, Figure. 2d). The distributions of light shear events show less notable increases at the 850 hPa (540 per decade, Figure. S1(b)) and 500 hPa (420 per decade, Figure. S1(c)) pressure levels. In addition, the distributions of serious shear events show considerable enhancement at most levels: 790 per decade at 1000 hPa (Figure. S1(e)), 2710 per decade at 500 hPa (Figure. S1(g)), and 3900 per decade at 200 hPa (Figure. S1(h)). However, the distribution of severe wind shear events at 850 hPa shows a considerable decrease (-1570 per decade). The increased number of shear events and increased shear strength have been attributed to the upper-level meridional temperature gradient ¹⁵. In addition, severe shear events occur more frequently in winter and spring, and light shear events occur more frequently in summer (figure not shown).

The impact of the AMO on shear events

To assess the relationship between global vertical shear events and the AMO, the variations in both are shown in Figure. 3. The time series of the AMO has a positive correlation with that of annual serious shear events occurring at the 1000 hPa (Figure. 2(a), 0.52, $P < 0.01$), 500 hPa (Figure. 2 (c), 0.64, $P < 0.01$) and 200 hPa (Figure. 2 (d), 0.68, $P < 0.01$) pressure levels. However, the time series of the AMO has a significant negative correlation with annual light shear events at the same altitudes (-0.74 at 1000 hPa, $P < 0.01$; -0.64 at 200 hPa, $P < 0.01$). In addition, the correlation between the AMO and annual light shear events at 850 hPa is -0.57 (Figure. 2 (b)), which is significant at the 0.01 level. During boreal winter (1000 hPa, 0.53, $P < 0.01$; 850 hPa, -0.16, $P < 0.3$; 500 hPa, 0.57, $P < 0.01$; 200 hPa, 0.75, $P < 0.01$) and summer (1000 hPa, 0.53, $P < 0.01$; 850 hPa, -0.66, $P < 0.01$; 500 hPa, 0.44, $P < 0.01$; 200 hPa, 0.65, $P < 0.01$), the correlations between serious shear events and the AMO are similar on an annual scale. For light shear events, most levels reported negative correlation coefficients in boreal winter (1000 hPa, -0.65, $P < 0.01$; 850 hPa, -0.37, $P < 0.05$; 500 hPa, 0.06, $P < 0.7$; 200 hPa, -0.45, $P < 0.01$) and boreal summer (1000 hPa, -0.18, $P < 0.25$; 850 hPa, -0.04, $P < 0.81$; 500 hPa, -0.31, $P < 0.05$; 200 hPa, -0.36, $P < 0.05$). Therefore, the relationship between the AMO and severe shear more significant than light shear events. And from 1979 to 1998, the correlation coefficients between AMO and shear events (light and severe) were very strong,

but after the late 1990s, such relationship changed suddenly and was no longer significant (figure not shown). It is worth noting that the shear events changed at the end of the 1990s, which is consistent with the interdecadal changes of many climate events. For example, the increase of tropical cyclones in the South China Sea in 1993 led to an increase in precipitation in South China ¹⁶. Ning and Qian ¹⁷ found that summer extreme precipitation events in South China increased suddenly in the 1990s. This may be related to the sudden change of the East Asian summer monsoon that occurred in the mid-1990s ¹⁸. European climate also had a substantial shift during the 1990s ¹⁹. Moreover, in addition to the AMO, the PDO also exhibited a phase change in the late 1990s ²⁰. The monsoon system before 1994 was mainly linked to the warming of SST in the Niño-3 region ($5^{\circ}\text{S} - 5^{\circ}\text{N}$, $150^{\circ}\text{W} - 90^{\circ}\text{W}$), which was associated with a combination of developing and decaying ENSO phases. However, this was associated with SST warming in the Niño-4 region ($5^{\circ}\text{S} - 5^{\circ}\text{N}$, $160^{\circ}\text{E} - 150^{\circ}\text{W}$) during the developing ENSO phase after 1994 ²¹. Therefore, the interaction of internal climate variability at different time scales is worthy of in-depth study.

High-level shear events occur more frequently within jet stream areas due to global warming. How do low-level shear event variations respond to the AMO? We use composite and regression analysis to evaluate this relationship in this study. Taking the annual pattern as an example, in Figure. 3, the global atmospheric circulation regressed by the AMO index shows significant shear events over our focused areas (black box). In Figure. 3(a), significant wind patterns occur mostly at low to middle latitudes. In the eastern Pacific, the southeasterlies cross the equator, turn into southwesterlies and converge with the northwesterlies. A similar wind pattern can be seen over equatorial Atlantic. The southeasterlies convert to southwesterlies when they cross the equator. Shear events are more obvious at 850 hPa (Figure. 3(b)). The southeasterly amplitude is strong and covers the northwesterlies in the eastern Pacific. However, the southeasterlies are weak, and the northwesterlies are weak as well ²¹.

Interestingly, the shear event high incidence area was the Intertropical Convergence Zone (ITCZ), which is one of the most recognizable aspects of global circulation that can be seen from space. The ITCZ forms a zonally elongated band of clouds at low latitudes where the northeasterly and southeasterly trade winds converge ²². The AMO has been shown to play a major role in the multidecadal variability of the Northern Hemisphere, impacting ITCZ-driven precipitation across Africa and South America ²³. The distribution of precipitation regressed onto the AMO index (Figure. S2) shows a longitudinal tripole pattern over the eastern Pacific. The precipitation is higher within $8^{\circ} \sim 20^{\circ}\text{N}$ and $110^{\circ} \sim 90^{\circ}\text{W}$, lower within $4^{\circ} \sim 8^{\circ}\text{N}$ and $130^{\circ} \sim 90^{\circ}\text{W}$ and higher within $10^{\circ}\text{S} \sim 4^{\circ}\text{N}$ and $130^{\circ} \sim 90^{\circ}\text{W}$. In the equatorial Atlantic, precipitation shows a latitudinal dipole pattern. Such patterns correspond with large-scale atmospheric circulation. In the western Pacific, the stronger northeasterly and southeasterly convergence and negative geopotential height anomalies lead to more precipitation. In the eastern Pacific and Equatorial Atlantic, the positive geopotential height anomalies with subsidence motion lead to low precipitation over portions of these areas. However, the wind speed convergence zone experiences more precipitation.

Figure. S3(a) shows the distribution of annual precipitation anomalies during AMO-positive years. The amount of precipitation was higher in the Central Pacific and lower in the Western Pacific warm pool. This indicates that when the AMO turns to its positive phase, the CP El Niño may develop, which is an opposite conclusion of previous studies²⁴. Turning to our focus areas, the precipitation pattern is similar to that discussed in Figure. S2, which shows a latitudinal tripole pattern. In the equatorial Atlantic, the precipitation band was trending northwards, and the area with less precipitation was located south of 5°N. However, during the AMO negative phase (Figure. S3(b)), the precipitation pattern is opposite to that during the positive phase. The precipitation occurring in the eastern Pacific was lower, while in the equatorial Atlantic, the centre of precipitation was located south of the equator. The difference in precipitation between the AMO-positive and AMO-negative phases is displayed in Figure. S3(c). The amount of precipitation was higher over the eastern Pacific and north equatorial Atlantic during the AMO-positive phase. In the southern equatorial Atlantic, the precipitation is still low.

The longitudinal and latitudinal distributions of vertical velocity over the eastern Pacific are shown in Figure. S4. The distribution of vertical velocity shows a similar pattern to that of rainfall, which exhibits a tripole pattern in the longitudinal direction during AMO-positive phases (Figure. S4(a)). The centre of ascending motion is concentrated near the equator and 10°N, and the sinking motion is located north of 4–7°N and 10°N. The distribution in the latitudinal direction is relatively simple, and all are ascending (Figure. S4(c)). During AMO-negative phases (Figure. S4(b)), there is a slight upward movement to the south of 6°S and north of 10°N, while in the middle, there is a sinking movement of the whole layer (Figure. S4(d)). The west direction basically exhibits a sinking movement.

Over the equatorial Atlantic, the descending motion occurs south of the equator, while the ascending motion occurs north of the equator during the AMO-positive phase (Figure. S5(a), (c)). During the AMO-negative phase, the meridional direction presents a pattern opposite to that of AMO-positive years (Figure. S5(b), (d)). The ascending movement is dominant south of the equator, and sinking is dominant to the north. The centre of the latitude sinking movement appears at approximately 60°W, and the centre of ascending movement appears at approximately 40°W and 20°W. Overall, the longitudinal circulation is stronger than the latitudinal circulation.

The correlation coefficients between shear events and the AMO index are significant in boreal winter and summer (Figure. S6, S7). In boreal winter, during the positive phase of the AMO, more precipitation occurs in the eastern Pacific and less precipitation occurs near the equatorial Atlantic (figure not shown). The minimum rainfall intensity is located near 140°W during boreal summer, while the maximum precipitation intensity is located near 140°W during the Northern Hemisphere cooling season²⁵. This is very similar to the precipitation field returned by the AMO index. It is worth noting that when the Western Pacific warm pool is in a positive AMO phase, there is less precipitation, which deviates greatly from the regression field. The vertical movement of the atmosphere corresponds to the location of the precipitation area. In boreal summer, the precipitation area is opposite to that in winter. When the AMO is in a positive phase, there is less precipitation occurring in the equatorial eastern Pacific and more precipitation in the equatorial Atlantic.

Discussion

In summary, we used a novel method to accurately calculate the vertical wind shear, obtained the temporal and spatial distribution characteristics of wind shear at different degrees, and found that these patterns are affected by the natural variability of the climate system. This kind of influence is mainly realized through the influence of the AMO on the large-scale circulation field. At low altitudes, it mainly influences the occurrence of shear by influencing the position of the ITCZ. In the context of climate change at high altitudes, more shear occurs in the rapids.

Although our outlined process of how internal climate variability affects vertical shear is absent from the models, the importance of such potential links should not be ignored. In these analyses, we did not exclude the natural variability of the processes resulting from anthropogenic effects, and recent changes in SST are strongly influenced by anthropogenic forcing^{26–28}. The transit patterns of SST under a warmer climate state would lead to the more frequent occurrence of severe shear events.

The AMO induced the variation of vertical shear events. Atlantic warming leads to an increase in trade wind and Walker circulation variations. The increased frequency of trade wind leads to a stronger cold tongue in the tropical Pacific, strengthening the cross-equatorial flow and leading to a more northward displacement of the ITCZ over the Pacific^{29,30}. However, in our study, during the AMO-positive phase, the SST is warmer than that during the AMO-negative phase, and along with the convergence of trade winds and cross-equatorial airflow, the number and strength of shear events increase, and the increase in cross-equatorial airflow has a weakening effect on the background wind pattern, which will increase the SST and convective activity, leading to a stronger precipitation intensity (Figure. 4). In particular, it should be emphasized that the increased vertical shear at 200 hPa is consistent with the intensification of clear-air turbulence because of the climate change influence on the jet stream over the North Atlantic^{8,15,31,32}.

Environmental shear flows can heavily influence the variability of the intensification rate of tropical cyclones³³. It is important to understand the mechanisms of and relationships between tropical cyclone intensification and shear flows. However, whether climate change has influenced tropical cyclone activities remains ambiguous due to the limited period of consistent observations³⁴. Furthermore, no clearly detectable anthropogenic influence has yet to be identified for several tropical cyclone activities that are strongly related to the magnitude of vertical shear³⁵.

In addition, we cannot ignore the effect of vertical shear on aircraft accidents (Figure. S8). Since 1979, the occurrence of air crashes related to shear events has basically mirrors the areas where severe shear is concentrated (Figure. S8, Figure. 1). Both the International Civil Aviation Organization (ICAO) and the Federal Aviation Administration (FAA) have identified wind shear as a potential risk to aircraft landings and takeoffs³⁶. The aviation industry has grown considerably over the first decade of the 21st century, and the effect of the climate on aviation should be of research focus³⁷.

Materials And Methods

Datasets

The atmospheric dataset is derived from the National Centres for the Environmental Prediction-Department of Energy Reanalysis II (NCEP-DOE Reanalysis-II, <https://www.esrl.noaa.gov/psd/>)³⁸ six-hour reanalysis dataset with a 2.5° horizontal resolution, which includes horizontal winds, geopotential heights and vertical velocities. The fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-5, <https://www.ecmwf.int/en/forecasts/datasets/browse-reanalysis-datasets>)³⁹ dataset is also used to identify the distribution of shear forces. Precipitation data were obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC, <https://psl.noaa.gov/data/gridded/data.cpc.globalprecip.html>)^{40–42}. The analysis is based on annual mean boreal summer (June to August) and boreal winter (December to February of the next year) conditions for the period of 1979–2018. The Atlantic Multidecadal Oscillation (AMO) indices were downloaded from the NOAA website (<https://psl.noaa.gov/data/climateindices/list/>).

Calculation of vertical shear

Previous studies calculated vertical shear by taking a centred vertical finite difference using the zonal wind speeds of two adjacent pressure levels. The interval between the two levels ranged up to several hundred metres, which did not meet the infinitesimal limit definition.

To make the calculation more accurate, we first adopted the Lagrange interpolation method to interpolate the wind speed in the u and v directions at 17 levels and then obtained 16th-order polynomials. Then, we differentiated and synthesized each polynomial at the specified height, and the resultant derivative value was the wind shear at that height.

The pressure levels of 1000 hPa, 850 hPa, 500 hPa, and 200 hPa were denoted as the specified heights, which we then interpolated by using the actual height of the isobaric surface (unit: m). We chose four pressure levels (1000 hPa, 850 hPa, 500 hPa, and 200 hPa) to analyse the distribution of vertical shear.

First, we used Lagrange interpolation to interpolate each specific time, location and height polynomial.

$$f(z) = \sum_{i=1}^n u_i \prod_{j \neq i} \frac{z - z_j}{z_i - z_j}$$

Then, the derivative of this value is the vertical wind shear at that height.

$$\frac{df(z)}{dz} = \sum_{i=1}^n u_i \sum_{j \neq i} \left| \frac{1}{z_i - z_j} \prod_{k \neq i, k \neq j} \frac{z_0 - z_k}{z_i - z_k} \right|, z = z_0$$

which is considered an accurate method for calculating the vertical shear at any height (units: s⁻¹).

This article defines a shear event that exceeds the 99th percentile of 40 years of global shear data as a severe shear event and a shear event that is below the 1st percentile of 40 years of global shear data as a light shear event.

As shown in Table.1, the 99th and 1st percentile thresholds exhibit no significant differences within a day for any given level, so we averaged the four thresholds to obtain certain thresholds for specific levels. The 99th percentile thresholds (unit: 10^{-3} s^{-1}) were 74.84 (1000 hPa), 12.81 (850 hPa), 8.28 (500 hPa), and 10.16 (200 hPa). The 1st percentile thresholds (unit: 10^{-3} s^{-1}) were 0.18 (1000 hPa), 0.04 (850 hPa), 0.03 (500 hPa), and 0.03 (200 hPa).

Regression analysis and composite analysis

We used ordinary least square regression to calculate the linear trends of severe and light shear events that occurred between 1979 and 2018, and their 95% and 99% confidence intervals were chosen.

Composite and regression analyses are used to illustrate the reason for shear event variation. A year exceeding 1.5 times the standard deviation will be chosen to demonstrate an AMO-positive year or AMO-negative year. Based on these criteria, 1998, 2010, and 2016 are positive years, and 1985 and 1986 are negative years.

Declarations

Acknowledgments

We thank Prof. Lixin Wang for his constructive comments that helped greatly to improve the original manuscript. The work was supported by the National Key Research and Development Program of China (Grant 2019YFA0606904 & 2018YFC1509003).

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Competing Interest Statement: The authors declare that they have no competing interests.

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Tables

Table 1. Thresholds of shear (units: 10⁻³s⁻¹)

	1000hPa		850hPa		500hPa		200hPa	
	1 st	99 th	1 st	99 th	1 st	99 th	1 st	99 th
0h	0.18	74.80	0.04	12.90	0.03	8.31	0.03	10.24
6h	0.17	74.69	0.04	12.83	0.03	8.25	0.03	10.08
12h	0.17	75.15	0.04	12.75	0.03	8.31	0.03	10.22
18h	0.18	74.72	0.04	12.74	0.03	8.26	0.04	10.10

Figures

Figure 1

The distributions of the quantities of severe shear events. (a)-(d) represent the 1000 hPa, 850 hPa, 500 hPa and 200 hPa pressure levels, respectively. Red rectangles highlight the locations with the maximum numbers of severe vertical shear events. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

The relationships between the AMO index (grey bar) and the number of annual light shear events (blue line) and annual severe shear events (red line). (a)-(d) represent the 1000 hPa, 850 hPa, 500 hPa and 200 hPa pressure levels.

Figure 3

Global large-scale atmospheric circulation regressed on the AMO index. (a)-(d) represent the 1000 hPa, 850 hPa, 500 hPa and 200 hPa pressure levels (units: hPa). Wind patterns (units: m/s) are statistically significant at the 10% level. Black boxes highlight the locations of the maximum number of severe vertical shear events. Significant trends are indicated by stippling (two-tailed t-test; $P < 0.05$; $n = 40$). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

Schematic diagram summarizing how the AMO can impact shear events and precipitation in the Pacific and Atlantic. The base plot shows the SST anomaly occurring between the AMO-positive and AMO-negative phases.

Supplementary Files

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