An improvement of wind gust estimate (WGE) method for squall lines

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ABSTRACT
Severe wind gusts produced by squall lines are difficult to monitor and forecast. This paper assessed and improved the physics-based Brasseur WGE (wind gust estimate) method for diagnosing wind gust of squall lines by coupling the WGE methods with the WRF (Weather Research and Forecasting) model. The simulation results show that the Brasseur WGE method accurately captured the strong gust feature with 32 m s\(^{-1}\) maximum wind speed during the disastering Shipwreck event occurred over Yangtze River on 1 June 2015, but overestimated the extended area of severe gust speeds. Analysis of the kinematic structure and boundary-layer conditions of the squall line confirmed the theoretical applicability of the Brasseur WGE method for squall lines. A novel gust-front-area limiting method was introduced to modify the Brasseur WGE method, which effectively reduces its gust wind overestimation area. Furthermore, five squall line events occurred in the middle China during 2021 were simulated to test the modified WGE method and the results exhibit significant improvements to the wind gust forecasts, with an average false alarm rate decreased from 0.89 to 0.54, and the critical success index (CSI) increased from 0.1 to 0.4.

Significance statement
Wind gusts produced by thunderstorms are difficult to forecast due to their small scales and suddenness of occurrences. While the broadly-used Brasseur WGE (wind gust estimate) method has a clear physical mechanism and good forecasting ability in...
non-convective weather, it tends to overestimate the gust area in severe convective weather. In this paper, we analyze the formation mechanism of the gusts that caused the shipwreck of the "Oriental Star" and improve the Brasseur WGE method to reduce the overestimation of the gust area. The modified WGE method reduced the overestimation area by 90% and decreased the RMSE of wind gust from 8.00 m·s\(^{-1}\) to 2.31 m·s\(^{-1}\). The new WGE method is applicable to squall line systems.

1. Introduction

Gust is a sudden, brief increase in speed of winds. It can be classified into convective or non-convective gust (Sheridan 2011). In general, non-convective gusts are generated in stable boundary layer, which have some certain statistical features and a relatively low damage on human life safety and social activities (Peltola et al. 2013; Lombardo et al. 2014). Conversely, convective gusts generated in severe convective environment are stronger and more destructive. For example, gusts may be produced by downward transportation of strong horizontal winds from the upper layers to the surface (Bech et al. 2011; Xiang-E and Xue-Liang 2012) in a squall line system often cause severe damage to aviation, ground transportation, electricity, communications, buildings, or even loss of human lives (Metz and Bosart 2010; Gatzen 2013). Thus gusts produced by squall line systems have been one of the important research foci (Crook et al. 1990; Bryan and Parker 2010; Clark 2011). A severe wind gust developed in squall lines occurred over the Yangtze River in Jianli, Hubei Province, China and caused shipwreck of “Oriental Star” and 442 fatalities (Meng et al. 2016), at about 13:31 UTC on 1 June 2015.

With their small scales, short lifetime, suddenness and low probability of occurrences (Sheridan 2018), severe wind gusts are difficult to monitor and forecast (Fujita 1981; Hofherr and Kunz 2010; Efthimiou et al. 2017). In particular, in regions with sparse meteorological stations and radar facilities, the ground observation networks are generally insufficient to capture the small-scale wind gusts produced in convective systems. For instance, when the "Oriental Star" capsized, the maximum instantaneous wind speed reported by the nearest station (Jianli station, \(\sim 13\) km from the location of shipwreck) was only 9.2 m·s\(^{-1}\), which was too weak to cause the ship to be capsized. Based on the observations by the weather radar located at Yueyang, about 49 km from the shipwreck location, along with some on-site damage survey and diagnostic analysis, a downburst with wind gusts of 32–38 m·s\(^{-1}\) was inferred at the time of shipwreck (Meng et al. 2016).

Modern high-resolution weather models, such as the WRF (Weather Research and Forecasting Model), ARPS (Advanced Regional Prediction System), etc., make it possible to simulate and forecast severe convection accurately when an accident occurs (Fierro et al. 2012; Sun and Wang 2013; Ferdousi et al. 2015). Duan et al. (2017) used ARPS with assimilation of radar observation data and horizontal intervals of 200 m to simulate the convective system that caused the Oriental Star to capsize. They identified a downburst within the squall line as the main reason causing the ship to capsize. The ARPS model simulated a maximum wind speed of 16 m·s\(^{-1}\),
which was still too weak to cause the ship capsize. Therefore, it is highly desired to find an effective method to estimate wind gusts accurately.

The existing methods for estimating wind gusts can be divided into two categories. The first category relies on the convective index to forecast the gust potential, such as the Showalter index, Lifted index and DCAPE (Showalter 1953; Galway 1956; George 1960; Emanuel 1994). By combining with the typical features of the observed radar echo, such as bow echo and Mid-Altitude Radial Convergence (MARC) (Wakimoto et al. 2006; Wurman et al. 2013), one can infer and nowcast the wind gusts within 0–2 h (Wilson and Roberts 2003). Although these wind gust estimation approaches have been applied for general use for wind gust forecasting, there are some issues when they are used to predict wind gusts associated with severe convection. For example, the critical success index (CSI) of thunderstorm gust forecast was only 0.04–0.07 during 2010–2015 in China (Tang et al. 2017), which means that only 4–7 prediction were accurate for every 100 gust forecasts.

The second category was established based on some physical hypotheses about the gust formation, such as Nakamura et al. (1996) method, GUSTEX (Geerts 2001) and WGE method (Brasseur 2001). Nakamura et al. (1996) developed a gust estimate method based on the transport equation of the downdrafts within deep convection. The GUSTEX method (Geerts 2001) is established by the vertical momentum equation, which considers downdraft potential and horizontal momentum transport from a 500 hPa level. The WGE (wind gust estimation) method established by Brasseur (2001) considers the wind gust that occurs at the surface whenever the mean turbulence kinetic energy (TKE) in a boundary layer is sufficient to overcome the net buoyant energy contained within that layer. Due to its clear physical basis and good forecasting ability in several case studies in non-convective weather, the WGE method has been widely used by many scholars (Goyette et al. 2003; Belusić and Bencetić Klaić 2004; Pinto et al. 2009; Chan et al. 2011).

Although Brasseur (2001) believed that the WGE method could be applied to estimate gust speeds in both non-convective weather and severe convective weather, it overestimates the wind gust speed in the convective cases (Chan et al. 2011). To correct the error, Kurbatova et al. (2018) used the Richardson number (Ri) to determine the unstable area (if the Ri < 0) and limited the use of the WGE method inside of this area. However, much of the overestimation by the WGE method was still remained. In general, WGE and similar methods have rarely been applied to forecast gust speeds associated with severe convection.

In this paper, the Brasseur (2001) WGE method and WRF model were used to estimate the wind gust that was responsible for the drastic loss of the Oriental Star. The model results were compared with the observation data. By analysing the kinematic structure and boundary-layer conditions within the squall line system, the mechanism of the severe wind gusts within the squall line system was illustrated. Furthermore, the Brasseur (2001) WGE method is modified by identifying the extent of the gust front area and suppressing the use of gust magnitude within this area. The modified Brasseur WGE method significantly improves the accuracy of severe convective gust forecasting for the squall line that caused “Oriental Star” shipwreck and also five other squall line events that were selected to test the methods.
2. Data and methods

2.1. Description of the convective storm

A severe convective weather event occurred over the Yangtze River in Jianli, Hubei Province, China, caused the shipwreck of "Oriental Star", at about 13:31 UTC (Local standard time — 08:00, the same below) on 1 June 2015. The shipwreck location is 112.92°N and 29.72°E. Unfortunately, due to the sparse distribution of surface weather stations, no direct wind observation was available near the shipwreck location for accurate analysis of the weather process causing the accident.

The weather observations at the closest weather station, the Jianli station (Station number: 57573), ~13 km from the shipwreck location (Figure 1a), observed some typical features of strong convection (Appendix: Figure A1). Within one hour around the accident (13:00–14:00 UTC), the surface pressure increased from 996 hPa to 998 hPa, the 2 m temperature decreased from 28°C to 25°C, the wind direction changed from southeast to northeast, and the rainfall exceeded 65 mm·h⁻¹. However, the maximum instantaneous wind speed observed at Jianli was only 9.2 m·s⁻¹, which was far less than the safety range (24–28 m·s⁻¹) that the Oriental Star was built for.

To investigate the cause of the shipwreck and the temporal variation of the wind gust at the wreck location, the investigation team from China’s State Council conducted several on-site surveys. The experts analysed the observational data of satellite, radar, and weather stations and examined the damage to trees, buildings, utility poles, and other damage indicators in the disaster area and recovered the time series of wind gust speed at the shipwreck location. The survey report was published (Xinhua News Agency 2015) and it pointed out that the severe wind gusts were likely produced by a convective downburst associated with a squall line system and inferred a maximum gust speed of approximately 32–38 m·s⁻¹.

2.2. Data resources

The ERA-Interim reanalysis data (with 60 vertical levels, a horizontal resolution of 0.75° and time intervals of 6 h) were collected from the European Centre for Medium-Range Weather Forecasts (ECMWF). The observed wind speeds (2 min-average wind speed at 10 m height) were obtained from ground stations in the research area. The time series of wind gusts speed at the shipwreck location could be found in the survey report mentioned in the above section.

2.3. Wrf model configuration

The WRF model was run for the shipwreck case for the period between 12:00 UTC 31 May and 12:00 UTC 02 June 2015. The ERA-Interim reanalysis data were used as the initial and lateral boundary conditions for the WRF model. The simulation was run for 48 h and the output was saved every 6 min. The first 12 h model output was excluded because it contains spin-up noise.
WRF was set with three two-way nesting model domains (Figure 1b), with grid spacings of 9, 3, and 1 km, respectively. The model was run with 45 vertical layers, of which 20 layers were located in the lowest 3 km of the atmosphere. The model top was set at 50 hPa. The finest nested-grid simulation was conducted for an area of 112° to 114° E, 29° to 31° N. The following physics options were employed for the WRF simulation: the Rapid Radiative Transfer Model (RRTM) longwave scheme (Mlawer et al. 1997), the Dudhia shortwave radiation scheme (Dudhia 1989), and the Eta Similarity Scheme were used to calculate surface heat and moisture fluxes (Monin and Obukhov 1954). The boundary layers were parameterised using the MYJ scheme (Janjić 1994), which has a local closure with the prediction of turbulent kinetic energy (TKE). Meanwhile, the boundary layer height was defined as the model level where the TKE decreases to a prescribed value of 0.2 m²·s⁻². The microphysics was calculated using the Ferrier scheme and the Kain Fritsch cumulus convection scheme (Kain 2004) was used on the outer domain (9 km). The USGS (United States Geological Survey) terrain elevation data, and FAO (Food and Agriculture Organization) soil data with 30 arc-second resolution were used to define the static surface fields in the model. The land-use categories were prescribed from the 30 arc-second resolution 20-category MODIS land use and land cover dataset published in 2018 (https://ladsweb.modaps.eosdis.nasa.gov/).

2.4. Description of brasseur WGE method

According to Brasseur (2001), surface wind gusts resulted from downwards deflection of air parcels in the planetary boundary layer (PBL) by turbulent eddies. If the mean TKE of large turbulent eddies is greater than the buoyant energy between the surface and the height of the parcel, the air parcel at a given height (z_p) will be able to reach the height of z’. The gust speed is thus determined as the wind speed prevalent in the layer if the following condition is fulfilled:
\[
\frac{1}{z_p - z'} \int_{z'}^{z_p} E(z)\,dz \geq \int_{z'}^{z_p} g \frac{\Delta \theta_v(z)}{\theta_v(z)} \,dz,
\]
where \( z_p \) is the parcel height, \( g \) is the acceleration of gravity, \( E(z) \) is the local turbulent kinetic energy at the given layer, \( \theta_v(z) \) is the virtual potential temperature of a parcel at height \( z \), \( \Delta \theta_v(z) \) is the difference of the virtual potential temperature between \( z \) and \( z_p \) (Goyette et al. 2003). The gust speed at height \( z' \) is the maximum wind speed for all parcels at \( z_p \) which satisfy (1).

### 2.5. Test of the WGE and modified WGE method for other squall lines

Besides the simulation study of the squall line case that causes “Oriental Start” shipwreck, the outputs of an operational WRF forecast system operated by the Henan Weather Bureau were also used to evaluate the WGE and modified WGE methods for predicting the wind gust. Five squall line events occurred in Henan, China, from 1 May to 15 July 2021 were assessed. The spatial resolution of the forecast field was \( 2.5 \times 2.5 \) km and the temporal resolution is 1 h. The finest nested-grid simulation was conducted for an area of \( 112^\circ \) to \( 116^\circ \) E, \( 32^\circ \) to \( 37^\circ \) N, and the physical scheme of the model was all chosen the same as in Section 2.3.

In this study, the critical success index (CSI), probability of detection (POD), and false alarm rate (FAR) were computed to evaluate the accuracy of the gust prediction with the WGE and modified WGE method for other squall lines (Schaefer 1990).

\[
\text{CSI} = \frac{\text{NA}}{\text{NA} + \text{NB} + \text{NC}}
\]

\[
\text{POD} = \frac{\text{NA}}{\text{NA} + \text{NB}}
\]

\[
\text{FAR} = \frac{\text{NB}}{\text{NA} + \text{NB}}
\]

where NA is the number of correct predictions, NB is the number of false alarms, and NC is the number of false predictions.

### 3. Model results

#### 3.1. Wrf output verification

The WRF model captured the squall line reasonably well. At 13:30 UTC, the simulated radar reflectivity (Figure 2b) shows that the apex of the squall line system moved over the shipwreck location, and the maximum reflectivity at the convection core near the shipwreck location was over 50 dBZ, which is consistent with the observations (Figure 2a).
Because there was no weather station near the shipwreck location, the model verification was carried out between the simulated and observed wind speeds at the weather station in a larger area centred at the shipwreck location. Firstly, the observed 2-minute average wind speed (Figure 3a) and direction (Figure 3b) from the nearest Jianli station (WMO number: 57573) were compared with the simulation. The results show that the observed and simulated wind speed remained 2 m\(\text{s}^{-1}\) with the northerly wind direction before 13:00 UTC. When the squall line system moved over the Jianli station (13:00–14:00 UTC), the simulated wind speed increased rapidly to 8.61 m\(\text{s}^{-1}\) and the wind direction changed from northerly to southerly, which was close to the observations.

Next, the simulated wind speeds at 12 other weather stations around the shipwreck location were compared with the observation (Table 1). The results show that the correlation coefficients between simulated and observed wind speed range from 0.4 to 0.6 and RMSE is 1–3 m\(\text{s}^{-1}\). The simulated wind speed was slightly stronger than the observations. In general, the WRF model successfully captured the wind field of the squall line system, but the simulated maximum wind speed of 8.61 m\(\text{s}^{-1}\) was much weaker than that causing the ship to capsize.

### 3.2. Wind gust estimated by the WGE

Although the wind speed simulated by WRF near the shipwreck location exceeded 8 m\(\text{s}^{-1}\), it is too weak to cause the ship to capsize. In fact, the WRF model was designed to simulate the average wind speed instead of gusts. Herein the WRF model outputs were used to drive the WGE method to estimate the wind gust speed at the shipwreck location.

The temporal variation of the wind gust speed estimated by the WGE method is shown in Figure 4. It is obvious that the gust speeds from the survey report at the shipwreck location were well captured by the WGE method. Before 13:06 UTC, the estimated gust speed was only 5–6 m\(\text{s}^{-1}\). It rapidly increased to the maximum of
The temporal variations of gust speed at the shipwreck location show good agreement with the event records in the Oriental Star survey report. The report states that “At 13:03 UTC, the ship was sailing smoothly and there was light rain but no strong wind. At 13:18 UTC, the gust speed suddenly increased and exceeded 24.6 m·s\(^{-1}\) at 13:21 UTC, which forced the ship to decelerate. During 13:26–13:32 UTC, the estimated extreme wind speed further increased to 32–38 m·s\(^{-1}\), and the ship gradually lost control and capsized.” The magnitude of this simulated maximum gust wind speed is very consistent with those from the survey report, which was deduced by the on-site survey and ship voyage records. Furthermore, the WRF-WGE method exhibits a good ability to capture the rapid temporal evolution of wind gusts at the shipwreck location during the one-hour period around the wreck time.

The spatial distribution of wind gusts at 13:30 UTC estimated by the WRF-WGE method (Figure 5) revealed that the shipwreck location was located right in an intense gust centre. It can also be seen that the model simulated large areas of intense wind gusts to the southwest and southeast of the shipwreck location, with gust speeds exceeding 25 m·s\(^{-1}\). However, the observations of the instantaneous maximum wind speed from weather stations in these areas did not exceed 10 m·s\(^{-1}\), much less than the estimation from the WGE method. These results imply that the WGE method may overestimate the gust speeds in these areas and can result in serious false alarms when the method is applied for the real-time forecast of damaging gusty winds.

3.3. Analysis of the WGE method use for convective storms

The WGE method was originally developed for estimating the gust speed within the boundary layer in a non-convective environment (Brasseur 2001; Sheridan 2011). However, as discussed in the last section, when it was applied for the squall line case,
the WGE method simulated the strong gust speeds at the shipwreck location that are consistent with those from the post-wreck report in terms of both peak value and general temporal variation. Here, we analyze the simulated meteorological fields within the boundary layer to see how the WGE method works.

Figure 6 shows the vertical evolution of the wind speed and planetary boundary layer height over the shipwreck location. When the accident occurred, the boundary layer height suddenly rose from 500 m to 1000 m, and a rear inflow jet with a speed of 32 m s\(^{-1}\) formed in the boundary layer above 200 m, which corresponded to the severe gust speed inferred by the post-shipwreck survey at the shipwreck location.

The vertical profiles of the mean turbulent kinetic energy (TKE), the potential energy of buoyancy, and temperature in the boundary layer are shown in Figure 7. Before (13:00 UTC) and after (14:00 UTC) the accident, the planetary boundary layer height was maintained at approximately 300 to 500 m, and a weak inversion layer existed from 100 to 300 m above the shipwreck location. Since the mean TKE varied little, but the potential energy of buoyancy increased rapidly with height within the boundary layer, only the air parcel below 150 m could be transferred to the surface. This explains the fact that the gust winds were relatively weak at 13:00 UTC (before

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Table 1. Verification of the simulated wind speed at 12 weather stations around the shipwrecking location on 1 June 2015. The first column shows the WMO station number noted in Figure 1a. The observed and simulated maximum wind speeds (m s\(^{-1}\)), and the correlation coefficients (COR) and root mean square error (RMSE) of the simulation were given in Columns two to five. The sample size was 24 for each station.

| WMO number | Obs 2min | max | WRF sim max | COR | RMSE |
|------------|----------|-----|-------------|-----|------|
| 57475      | 3.00     | 3.64| 0.56        | 2.21|
| 57476      | 4.00     | 4.82| 0.45        | 3.24|
| 57477      | 2.70     | 4.09| 0.57        | 2.52|
| 57485      | 3.80     | 5.26| 0.55        | 3.14|
| 57571      | 4.20     | 5.57| 0.46        | 2.96|
| 57573      | 7.60     | 8.61| 0.53        | 2.99|
| 57574      | 4.20     | 6.45| 0.50        | 3.21|
| 57575      | 4.50     | 6.17| 0.49        | 2.32|
| 57577      | 3.90     | 5.77| 0.60        | 2.24|
| 57581      | 3.90     | 5.15| 0.45        | 2.16|
| 57584      | 3.60     | 4.86| 0.52        | 2.69|
| 57585      | 3.10     | 4.39| 0.59        | 1.92|

Figure 4. The simulated (blue line) and observed (red triangles) gust speeds (m s\(^{-1}\)) at the shipwrecking location. The observed records (triangles) were estimated based on the on-site survey.
wreck) and 14:00 UTC (after wreck). At the time of the shipwreck (13:30 UTC), the downdraft within the squall line broke the inversion layer, and the planetary boundary layer height rose from 500 m to 960 m. As the mean TKE increased, and the potential energy of buoyancy decreased within the boundary layer, the mean TKE at 400 m could counteract the buoyancy force (Figure 7b) and transfer the air parcel with the momentum of horizontal wind speed of 32 m·s\(^{-1}\) (Figure 6) to the surface. Thus the strong wind gust that led to the loss of the Oriental Star were from the horizontal wind momentum transferred from upper boundary layer.

The above analysis makes it clear that, although the WGE method was developed for non-convective weather, the theory of the WGE method fits the squall line

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**Figure 5.** A comparison of the observed (number) and simulated (contour shading) gust speeds in a region around the shipwrecking location at 13:30 UTC. The black cross represents the shipwrecking location.

**Figure 6.** The simulated time-height cross-section of horizontal wind speed (m·s\(^{-1}\)) and planetary boundary layer height (PBLH, solid dashed black line) over the shipwrecking location from 12:30 UTC to 14:30 UTC on 1 June 2015. A, B and C represent the time points before, during and after the accident occurred, corresponding to Figure 7a–c, respectively.
situation adequately. In the simulated squall line, the WGE method allows turbulent eddies to counteract the buoyancy force and transfer the upper layer air parcel momentum to the surface.

3.4. Improvement of the WGE method for squall line induced gust

The updraft ahead of the squall line system would lead the atmosphere in the region to be conditionally unstable (Kingsmill 1995) and increase the turbulent transport within the boundary layer. The spatial distribution of the difference between the mean TKE and the potential energy of buoyancy within the boundary layer (Figure 8) confirms this phenomenon. However, a severe wind gust does not usually occur in front of the squall line system, but in the rear of the gust front (Schmidt and Cotton 1989). Therefore, the use of the WGE method in unstable areas in front of the squall line system would lead to the overestimation of wind gusts there.

To refine the WGE method to more accurately estimate wind gusts in a convective environment, the vertical wind fields at the time when the accident occurred were analysed. Figure 9 shows the vertical cross-section of the wind field simulated by the WRF model at 13:30 UTC. It displayed a typical kinematic structure and an outline of the thunderhead in the mature stage of a squall line system (Houze 1989). The shipwreck location (at 112.92°E, 29.72°N) was at the bottom of the gust front, and an updraft from the apex of the gust front extended up through the convective region to slope more gently into the trailing stratiform cloud at about 11 km height. The updraft and cold air at mid-levels were assembled, and a downdraft was formed behind the gust front.

Evidently, there was a downdraft (20–24 m·s⁻¹) in the rear of the squall line system at about 8–10 km height (at 112.7°E), which formed a wall on the left of the squall line system at the height of 6–10 km, and the inflow of the squall line system was forced by this wall and formed an anticlockwise vertical vortex at 6–10 km height.
Additionally, an inclined inflow (about 20–24 m·s⁻¹) from 10 km height at 112.4°E and the downdraft inside the squall line system at 112.7°E were assembled and formed an intense wind centre at the lowest 2-km height of the squall line system, which likely produced the severe wind gust at the shipwreck location.
Meanwhile, associated with the sloping updraft, there is a thin layer of backflow in front of the gust front, forming a low-level jet (approximately 24–28 m\(\text{s}^{-1}\)) at a height of 0.2–1 km. The TKE in the layer is greater than the buoyancy energy and causes the WGE method to overestimate the gust in this region. However, based on the kinematic structure of the thunderstorm, gusts will only occur in the region affected by the gust front. Therefore, the WGE method is not proper for such regions and should be contained. To do so, we need to identify the extent of the gust front area.

The algorithm to determine the extent of the gust front follows the work of Lompar et al. (2018). The first step of this method was to determine the precipitation grid point \((i, j)\) below the cumulonimbus (Cb) cloud, which is shown in Figure 10a.

Then, the storm propagation is estimated by the mean wind speed \((\text{spd})\) and direction\((\text{D})\) between 9 – 13.5 km height calculated using the WRF model output:

\[
D = \frac{180}{\pi} \left( 2\arctan \left( \frac{\text{spd}(i,j) - V_{i,j}}{U_{i,j}} \right) + \pi \right)
\]  

(5)

Where \(U_{i,j}\) and \(V_{i,j}\) represent the mean meridional and zonal wind components between 9 and 13.5 km height of the model layers, respectively:

\[
U_{i,j} = \frac{1}{k_{13.5} - k_9 + 1} \sum_{k=k_9}^{k_{13.5}} U_k(i,j)
\]  

(6)

\[
V_{i,j} = \frac{1}{k_{13.5} - k_9 + 1} \sum_{k=k_9}^{k_{13.5}} V_k(i,j)
\]  

(7)

Figure 10. (a) Spatial distribution of rainfall (colour shading) and the direction of the squall line movement (arrow) simulated by WRF. The dashed black line representing the gust front of the squall line. The area between the black dashed line and the rainfall area represents the extent of the gust front. (b) The simulated gust wind speed with the modified WGE method.
\[
\text{spd}(i, j) = \sqrt{U_{i,j}^2 + V_{i,j}^2}
\]  

(8)

Where \(k_9\) and \(k_{13.5}\) represent the number of model layer at 9 km and 13.5 km, respectively.

Finally, the extent of the gust front is found in the heading boundary of the precipitation area (about 18 km) in the direction of the storm propagation (Figure 10a). Based on the above results, we limited the use of WGE for gust wind estimate outside of the extent of the gust front area(GFA). It can be expressed as:

\[
\text{Gust} = \max[U(Z_p)] \text{ if } (i,j) \in \text{GFA and } Z_p \text{ satisfy Eq}(1)
\]  

(9)

If a grid point \((i,j)\) was outside the extent of the GFA, the TKE method of Kurbatova et al. (2018) was used to estimate the gust wind speed:

\[
\text{Gust} = \text{spd}(i,j) + 3\sqrt{\text{TKE}(i,j)} \text{ if } (i,j) \notin \text{GFA}
\]  

(10)

After applied the modification, the gust areas that were overestimated by the original WGE methods were generally decreased (Figure 10b), and meanwhile, the estimated gust speed at the wreck location is unchanged from that estimated by the original WGE method and the locations of the intense wind centre were consistent with the observations from the on-site survey. Table 2 compares the wind gust speed estimated by WGE and the modified WGE method at the site. The results show that the modified WGE method significantly reduces the overestimation of the wind gust speed. The original WGE method generally overestimates the gust speed with bias ranging from 1.79 m s\(^{-1}\) to 17.88 m s\(^{-1}\) and a mean bias of 6.86 m s\(^{-1}\). The modified WGE method reduced the mean bias to 0.81 m s\(^{-1}\) and the simulated mean wind gust speed is 8.0 m s\(^{-1}\) which is closer to the observations (7.2 m s\(^{-1}\)). These results indicate that the modified WGE method properly overcomes the overestimation of the wind gust region.

Table 2. Verification of the wind gust speed (m s\(^{-1}\)) estimated with WGE and modified WGE. The first column shows the WMO station number noted in Figure 1a. The observed maximum gust speed, the simulated maximum gust speed with WGE and modified WGE and their bias are given in Columns two to six.

| WMO number | Obs (m\(\text{s}^{-1}\)) | WGE (m\(\text{s}^{-1}\)) | Modified WGE (m\(\text{s}^{-1}\)) | Bias (WGE) (m\(\text{s}^{-1}\)) | Bias (modified WGE) (m\(\text{s}^{-1}\)) |
|------------|----------------|----------------|-----------------------------|----------------|----------------|
| 57475      | 6.10           | 7.89           | 4.63                       | 1.79            | -1.47           |
| 57476      | 6.10           | 9.69           | 5.16                       | 3.59            | -0.94           |
| 57477      | 6.20           | 8.38           | 3.31                       | 2.18            | -2.89           |
| 57485      | 7.30           | 12.66          | 8.61                       | 5.36            | 1.31            |
| 57571      | 7.90           | 9.77           | 6.73                       | 1.87            | -1.17           |
| 57573      | 9.20           | 19.81          | 9.82                       | 10.61           | 0.62            |
| 57574      | 6.60           | 24.48          | 12.69                      | 17.88           | 6.09            |
| 57575      | 6.90           | 12.54          | 8.56                       | 5.64            | 1.66            |
| 57577      | 5.30           | 11.13          | 7.56                       | 5.83            | 2.26            |
| 57581      | 7.50           | 10.26          | 8.64                       | 2.76            | 1.14            |
| 57584      | 8.40           | 22.92          | 9.68                       | 14.52           | 1.28            |
| 57585      | 8.90           | 23.21          | 10.66                      | 14.31           | 1.76            |
| Average    | 7.20           | 14.06          | 8.00                       | 6.86            | 0.80            |
3.5. Evaluation of applicability of the modified WGE method

To evaluate the applicability of the modified WGE method for forecasting wind gust of squall line systems, the output of an operational WRF forecasting system were used to drive the WGE and modified WGE method to predict the wind gust. Five squall line events occurred in Henan, China, from 1 May to 15 July 2021 were collected and analysed. Table 3 shows the occurring time, observed and forecast daily maximum gust speed of the five squall line events. The modified WGE method has small impact on the forecasting result of maximum gust speed, but the RMSE of the gust speed within the forecast area is decreased dramatically from 8.00 to 2.31 m·s⁻¹.

**Table 3.** The wind observations and forecasts of five squall line events in Henan Province, China. The first column shows the occurrence date of squall line events. The observed maximum gust speed, and the predicted maximum gust speed with WGE and modified WGE and their RMSE are given in Columns two to six.

| Cases (Date)      | obs max (m·s⁻¹) | WGE (m·s⁻¹) | Modified WGE (m·s⁻¹) | RMSE (WGE) (m·s⁻¹) | RMSE (Modified WGE) (m·s⁻¹) |
|-------------------|-----------------|-------------|----------------------|--------------------|----------------------------|
| Case1 (6 May 2021)| 23.60           | 32.71       | 32.71                | 12.32              | 2.16                       |
| Case2 (15 May 2021)| 19.60           | 33.64       | 33.64                | 9.26               | 1.39                       |
| Case3 (2 June 2021)| 24.10           | 25.82       | 22.14                | 5.89               | 2.26                       |
| Case4 (9 July 2021)| 28.30           | 26.91       | 24.56                | 5.21               | 3.51                       |
| Case5 (11 July 2021)| 31.20           | 30.13       | 30.13                | 7.35               | 2.23                       |
| Average           | 25.36           | 29.82       | 28.62                | 8.00               | 2.31                       |

**Figure 11.** Evaluation of the WGE and Modified WGE methods for predicting wind gusts over 15 m·s⁻¹ for five squall line cases occurred between 1 May to 20 July 2021 in Henan province, China. (a)CSI, (b)FAR, (c)POD, and (d)RMSE.

3.5. Evaluation of applicability of the modified WGE method

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Figure 11 shows the forecast skill scores of the WGE and modified WGE method for gust exceeded 15 m s\(^{-1}\) within the five squall line events (more detail about the spatial distribution of the predicted gust were shown in Appendix Figure A2). The modified WGE method obtained higher critical success index (CSI) and lower false alarm rate. For case 1, 2, and 5, CSI of the WGE method was less than 0.2 and the false alarm rate (FAR) was 0.8 to 0.9, while the modified WGE raised CSI to 0.5 and reduced FAR to 0.45. The RMSE of the modified WGE method is reduced by 2–10 m s\(^{-1}\) compared to the WGE method. Overall, the modified WGE method is able to significantly reduce the overestimation of the wind gust region.

It is worth noting that the forecasting capability of the modified WGE method also relies on the accuracy of the WRF forecasts. For example, the meteorological field in case 4 was not accurate and the modified WGE method does not bring an insignificant improvement. Furthermore, the accuracy of the gust estimate also relies on the resolution of the meteorological field. Higher resolutions weather fields result in better gust estimates.

4. Conclusion

The Brasseur WGE method and the WRF model were used to simulate the squall line gust winds that caused the Oriental Star shipwreck. Analysis of the wind, TKE and unstable potential energy of the simulated squall line confirms a good applicability of the Brasseur WGE method for diagnosing the wind gusts produced by the convection core. It successfully forecasted over 32 m s\(^{-1}\) wind gust, which is agreeable to the estimated winds from the shipwreck survey report. In addition, the analysis revealed that, for squall lines, the Brasseur WGE method tends to overestimate the wind gust in the outer regions of the convective core and an algorithm was developed to suppress the errors. The main results are summarised as follows:

The WRF simulation was able to reasonably reproduce the general severe weather features of the intense squall line that occurred during the Oriental Star shipwreck. The radar reflectivity and average wind speed were successfully captured and the timing was good, but the simulated wind speed was too low in comparison to those causing the ship to be capsized.

By Coupling the Brasseur WGE method to the WRF model output, the model successfully estimates the magnitude and the temporal evolution of the severe wind gusts at the shipwreck location. Analysis confirms that the physical theory of the WGE method adequately aligns with the squall line thermodynamical and dynamical structures. In the “Oriental Star” shipwreck case, at the time of shipwreck, the Brasseur WGE method captured the downwards transfer of the air parcel with a horizontal wind speed of 32 m s\(^{-1}\) to the surface, generating the severe wind gust that forced the ship capsized.

The Brasseur WGE method tends to overestimate the area of severe wind gust of the squall line. The kinematic structure and boundary-layer conditions within the thunderstorm suggest that surface gusts are likely to be associated with descending flow within the gust front. Therefore, we incorporated Lompar’s method to determine
the extent of the gust front and suppressed the wind gust estimate of the WGE method in this region.

The WGE and modified WGE method were coupled with the output of a WRF model running operationally at the Henan Weather Bureau to forecast the wind gust. Five squall line events occurred in Henan, China, from 1 May to 15 July 2021 were collected to assess the gust diagnostic schemes. Comparing with the WGE method, the modified WGE method significantly reduced the overestimation area of wind gust with an average false alarm rate decreased from 0.89 to 0.54, and the Critical Success Index (CSI) increased from 0.1 to 0.4.

The above results indicated that the modified Brasseur WGE method can be coupled with high-resolution numerical weather prediction model for real-time forecast of damaging wind gusts associated squall line systems. The modified scheme successfully extend the applicability of the Brasseur WGE method from non-convective to severe convective environments. In future work, we will conduct more sensitivity experiments and long-term evaluations of the modified WGE method for more diversified convective systems. Finally, the current study neglects the small-scale drag, evaporation, and cooling effects of rainfall within the thunderstorm. These factors may significantly affect the strength of gusts. In addition, the impact of topography-convection interaction on gust speed was not considered and it should be included in future work.

**Disclosure statement**

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted. No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

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**Data availability statement**

The data used to support the findings of this study are available from the corresponding author upon request.

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Figure A1. Time series of the observed surface 2 m temperature (a), surface pressure (b), relative humidity and hourly precipitation rate (black bars) (c), and instantaneous wind speed and direction (d) at Jianli Station.
Figure A2. Comparisons of the observed gust speeds (a-e) with those forecast of the WGE method (f-j) and the modified WGE method (k-o). Columns one to five represent Case 1 to Case 5, respectively.