Development and Application of a Physical Approach to Estimating Wind Gusts

O. BRASSEUR*

Institut d’Astronomie et de Géophysique G. Lemaître, Université Catholique de Louvain, Louvain, Belgium

(Manuscript received 11 May 1999, in final form 11 May 2000)

ABSTRACT

A new wind gust estimate method (denoted WGE method) is proposed. Contrary to most techniques used in operational weather forecasting, the determination of gusts in this approach is fully based on physical considerations. The main motivation for developing such an approach is to improve the knowledge of the physical processes that control the determination of gusts. The proposed approach assumes that surface gusts result from the deflection of air parcels flowing higher in the boundary layer, which are brought down by turbulent eddies. The WGE method takes into account the mean wind and the turbulent structure of the atmosphere. Moreover, this method includes the computation of a bounding interval around the gust estimate, which provides a range of likely gust magnitudes.

The WGE method has been tested on two explosive cyclogenesis events that were satisfyingly simulated with the Modèle Atmosphérique Régional mesoscale model nested in the ECMWF analysis. Daily maximum gusts are predicted with good accuracy, while the hourly temporal evolution of estimated gusts depends strongly on the accuracy of the meteorological fields generated by the model. Typical error range for the gust estimates range is about 5 m s⁻¹. The bounding interval is useful for determining the uncertainty around estimated gusts. Statistical evaluation of the WGE method shows that the main features of the climatology of gusts during the period from January to March 1990 are reproduced, even though estimated gusts have a negative bias (from 3% to 10%) compared to observations. An interesting aspect of the WGE method is the reliability of the bounding interval, with 73% of the predicted daily gusts lying in this interval. Compared to other approaches, the WGE method is as good as other methods used in weather forecasting although extensive testing remains to be done.

1. Introduction

The determination of wind gusts is of importance in weather forecasting, especially during winter storm events. Gusts have many implications on a lot of sectors. For instance, they influence the design and structure of buildings and bridges. When gusts exceed a given threshold, damage to buildings can be expected due to wind-induced loads on the structure. An accurate estimate of gusts appears important to prevent or limit the damage due to severe winds or, in the case of typhoons or tropical cyclones, to organize the safety of people.

The determination of gusts can be also useful for specific climate applications. The climatology of wind gusts is not redundant with the climatology of mean wind since there is no simple relation between the mean wind and gusts. Even though a constant ratio between the mean wind and gusts can constitute a satisfying approximation for weak to moderate wind gusts, this relation becomes less accurate and less recommendable for severe gusts (e.g., see section 6a). Consequently the determination of gusts can give complementary information to the climatology of mean wind, particularly for determining the occurrence of severe gusts. In particular, an important concern in the framework of climate change impact studies consists of determining the impact of a possible climate change on the intensity and the frequency of extreme meteorological events. Considering the specific category of storms, a way to assess possible changes on such events is to compare climatology of gusts from multiyear simulations done for present and future climates. In this context, the proposed physical approach to estimate gusts can be useful.

However the estimation of gusts is not an easy task due to the great variability of wind. McCallum and Norris (1990) found that there exists no simple relation between the severity of surface wind gusts and amount of deepening of a storm depression. The determination...
of maximum wind speed cannot be resolved by only referring to dynamics or turbulence fluctuations. In operational weather prediction, a standard but simple method for the determination of wind gusts considers a constant ratio of maximum gust to hourly average surface wind speed. This ratio ranges from 1.3 in open sea to about 2.3 over large cities (e.g., Durst 1960; Krayer and Marshall 1992; U.K. Met. Office 1993; Ahmed 1994), and depends mainly on surface roughness. A variant of this approach consists of considering the wind immediately above the boundary layer (Bradbury et al. 1994) instead of the 10-m wind. When deep convection occurs, a correction is added to take into account the impact of intense vertical motions (Nakamura et al. 1996). Another more sophisticated method (Quinet and Néméghaire 1991) takes into account the properties of the surface layer, assuming that gusts at the surface are produced by the deflection of air parcels flowing at the top of the surface layer. This method includes corrections for representing the impact of stable or unstable stratification.

In this paper, a new wind gust estimate method (denoted WGE method) is proposed. The motivation in deriving a new method is twofold. First, the determination of gusts up to now has mostly been based on statistical or empirical approaches that poorly explain the physical mechanisms responsible for gusts. This does not mean that these techniques fail miserably and have to be rejected since they generally give satisfying gust estimates. Considering only the requirements of the operational weather forecasting, statistical approaches sometimes could be preferable to physical approaches. This is generally the case when the physical approach includes a large number of parameters that are not precisely known, while the statistical approach relies on a limited number of parameters that are less sensitive to small errors than sophisticated physical models. For example in the prediction of ozone concentrations, considering the accuracy of their predictions for operational use, statistical models are generally preferred to pollution models that include sophisticated chemical packages. But the main advantage of models based on physical concepts is that they allow a continuous improvement in the understanding of processes and, through this continuous progress, they may eventually give better results than statistical approaches. In the present paper, a technique that is fully based on physical considerations will be shown to predict estimates with an accuracy at least equal to that of other techniques. Second, the gust estimate given by all previously available methods does not give any idea about the confidence on this predicted value. Consequently, it appears that the specification of a range of possible gust speeds (called bounding interval in this paper) is at least as important as the estimate itself. The approach developed in this study includes the determination of this bounding interval around the estimate that should include observed gusts with a high probability. None of the other current approaches include the prediction of such an interval.

The physical considerations that justify the presented approach and the detailed description of the WGE method are presented in section 2. Because of the dependence of the WGE method on simulated meteorological fields, section 3 includes a brief assessment of the simulation results produced by the Modèle Atmosphérique Régional (MAR) mesoscale model. This paper presents two applications of the WGE method: first, wind gusts have been predicted for two short-range situations of explosive cyclogenesis (section 4), and second, a medium-range period (section 5) is studied that includes a great variety of storms. The short-range applications test the limits of the proposed approach and allow an examination of its behavior in detail. The statistics of estimated gusts and predicted bounding interval are presented with the analysis of the medium-range period. Section 6 is devoted to a comparison of the WGE method with two other approaches used in operational weather forecasting, in particular the surface-roughness (U.K. Met. Office 1993) and surface-layer deflection (Quinet and Néméghaire 1991) approaches.

2. Estimation of wind gusts

In contrast to current methods used in operational weather forecasting that are based on empirical or statistical approaches, we develop a new method fully based on physical considerations. The basic ideas and the fundamental assumptions of this new method are presented in section 2a, while the method is described in detail in section 2b.

a. General considerations

Local characteristics (such as the roughness length, the influence of surface disturbances, the impact of buildings, . . .) of a given area have an impact on the mean wind, but not especially on the maximum observed wind speed. For example, Sneyers et al. (1988) have shown that a new building close to the observation site at station Uccle (Belgium) has modified the mean wind statistics (reduced by 0.24 m s⁻¹) but has not influenced the statistics of wind gusts, which seem mostly dependent on the large-scale wind characteristics. Another important point is that the turbulent fluctuations given by turbulent parameterizations near the surface are not able to explain such wind speeds.

Wind gusts observed at the surface seem to originate from air parcels flowing at higher levels in the boundary layer that are deflected downward to the surface (Fig. 1). We assume that the trigger mechanism for the deflection of air parcels can be attributed to vertical mixing by turbulent eddies. Consider the energy balance between the turbulent kinetic energy and the buoyancy forces: if the vertical component of the turbulent kinetic energy associated with a given air parcel is intense
enough to counteract the buoyancy forces, the parcel will be able to reach the surface. From this consideration, it is clear that the stability of layers is a very important factor. For instance, a stable layer prevents the deflection of an air parcel flowing at the top of the boundary layer. In contrast, an unstable layer favors the vertical transport and is able to deflect air parcels. This assertion is confirmed by radar measures analyzed by Bond et al. (1981) and Blackall et al. (1990). They found that the convection brought unmodified air parcels to the surface by downdrafts, and that the echo speed was characteristic of the wind speed 1–2 km above the surface. These observations confirm and extend the analysis done by Sneyers et al. (1988) at the local scale.

Consequently, the wind gust speed should be a function of the large-scale wind, the turbulence, and the stability of the boundary layer. These general ideas for the development of a gust estimate method are in agreement with Bradbury et al. (1994) and Nakamura et al. (1996) who have shown that two processes are important for the determination of wind gusts: the production of horizontal momentum by pressure gradient forces, and the downward transport of horizontal momentum by convective downdrafts in the presence of vertical shear. In our approach, these two processes will, respectively, correspond to the large-scale wind and the turbulent eddies that deflect air parcels to the surface.

b. WGE method

The determination of gusts is closely related to the representation of the three-dimensional meteorological fields, and therefore the accuracy of estimated gusts is highly dependent on these fields. Moreover, the local variability and the specific environment near the site of the instruments are important factors that cannot be neglected when comparing model gust estimates to wind gust observations. To illustrate this fact, Fig. 2 shows the daily wind gust speed during the months of January and February 1990 for the two coastal synoptic stations of Koksijde and Middelkerke (see Fig. 3 for the location of these stations) that are 20 km apart.

In Fig. 2, we note that the differences found in the wind gust speed measurements for two close stations are about 1.6 ± 1.5 m s\(^{-1}\). These differences increase with the gust strength and can reach about 7 m s\(^{-1}\). This highlights the difficulty in obtaining an accurate estimate of wind gust speeds. Consequently, four categories of errors have to be taken into account when the gust estimates are compared to the observations: local variability, accuracy of measurements, computed meteorological fields, and limits of the WGE method itself. For these reasons and in the framework of operational weather forecasting, it seems at least as important to determine the confidence that can be attributed to the estimated gust as to compute an accurate estimate. Consequently, our approach includes not only the computation of gust estimate, but also the specification of a bounding interval (which requires the determination of its lower and upper bounds) around this estimate that should contain observed gusts with a high probability.

1) Determination of Gust Estimate

The fundamental assumptions of the WGE method are that (i) gusts are the result of the deflection of air
parcels flowing in the (whole) boundary layer, and (ii) the deflection process is explained by the presence of large eddies that are sufficiently energetic to transport air parcels to the surface. Estimating wind gusts is done by assuming a parcel flowing at a given height will be able to reach the surface if the mean turbulent kinetic energy of large turbulent eddies is greater than the buoyant energy between the surface and the height of the parcel (see Fig. 4). This assertion can be summarized with the following relation:

\[
\frac{1}{z_p} \int_0^{z_p} \theta(z) \, dz \geq \int_0^{z_p} \frac{\Delta \theta(z)}{\Theta(z)} \, dz,
\]

where \(z_p\) is the height of the considered parcel, \(g\) is gravity, \(\Theta(z)\) is the virtual potential temperature, and \(\Delta \theta(z)\) is the variation of virtual potential temperature over a given layer. The right part of (1) corresponds to the potential energy of buoyancy. Here, \(E(z)\) is the Local turbulent kinetic energy that is computed according to the standard prognostic equation:

\[
\frac{\partial E}{\partial t} = -u'w' \frac{\partial U}{\partial z} - v'w' \frac{\partial V}{\partial z} + g \frac{\partial \theta}{\partial z} - w'E' + \frac{w'p}{\rho_0} - \varepsilon.
\]

Equation (2) includes, respectively, the following terms: shear production (for \(x\) and \(y\) wind components), buoyancy, vertical transport of turbulence (modeled with the gradient assumption), and dissipation. Equation (2) is used in all turbulent parameterizations with closure order equal or larger than 1.5. In particular, this is the case with the Therry and Lacarrère (1982) closure used in MAR (see section 3a). The determination of turbulent kinetic energy is therefore a fundamental aspect of this approach, which must be obtained from a numerical model.

Considering (1), it is clear that many parcels at different heights \(z_p\) will satisfy this condition. The value of the gust estimate is then chosen as the maximum wind speed for all parcels in the boundary layer satisfying (1):

\[
W_{g_{\text{estimate}}} = \max \left[ \sqrt{U^2(z_p) + V^2(z_p)} \right]
\]

for \(z_p\) satisfying (1) (3) with \(U\) and \(V\), respectively, the \(x\) and \(y\) components of the mean wind. Let us remark that the roughness length has a very weak (but not zero) influence on the estimate of the gust, since it only modifies the turbulent kinetic energy and the mean wind near the surface.

2) LOWER BOUND OF THE BOUNDING INTERVAL

The determination of the lower bound is based on the same approach as the computation of the estimate. But this time, it is assumed that the local vertical turbulent kinetic energy given by the variance of vertical velocity (instead of the mean turbulent kinetic energy for the estimate) is the only mechanism that triggers the deflection process of air parcels (see Fig. 5). The main difference between the determination of the lower bound
and the estimate is just the size of eddies that trigger the deflection mechanism. Similar to (1), only air parcels satisfying the following relation will be considered as able to reach the surface:

\[ \frac{w'w'(z_p)}{2} \geq \int_0^\infty g \frac{\Delta \theta(z)}{\Theta(z)} dz, \]

where \( w'w'(z_p) \) is the vertical variance of the velocity as a function of the height \( z_p \). Since the vertical variance is not directly computed using a one-and-a-half-order closure, this quantity is determined with a diagnostic relation:

\[ \frac{w'w'(z)}{2} = \frac{2.5}{11} E(z). \]

The ratio of 2.5/11 (Stull 1988) is chosen as an intermediate value between the generally accepted value of 1.7/12.5 in the surface layer (e.g., Merry and Panofsky 1976) and the value of \( \frac{1}{3} \) when the turbulence is closely isotropic in mixed layers (Caughey and Palmer 1979).

The lower bound is then given by the maximum speed of parcels that satisfies (4):

\[ W_{g_{\text{lower}}} = \max[\sqrt{U_\text{top}^2(z_p)} + V_\text{top}^2(z_p)] \]

for \( z_p \) satisfying (4). (6)

In the present formulation, it is intuitively obvious that the estimate given by the relations (1) and (2) is always greater than the lower bound obtained from (4) and (6), since the consideration of local turbulence is a less constraining trigger mechanism than the deflection process for the large eddies. From a physical and mathematical point of view, this assertion is equivalent to proving that the mean turbulent kinetic energy below a given level in the boundary layer is higher than the local turbulent kinetic energy at this level. First, in the case of a nearly neutral or stable boundary layer, the shear is the main production term of turbulence, and the turbulent kinetic energy decreases nearly linearly with height (e.g., Grant 1992; Brasseur et al. 1998). This configuration ensures that the local turbulent energy is always less than mean energy below the considered level. Second, when the boundary layer is unstable, a maximum of turbulent kinetic energy is generally reached in the lowest part of the boundary layer (e.g., Lenschow et al. 1980; Brasseur et al. 1998). This means that it is unlikely that the lower bound can be larger than the estimate in the lowest boundary layer (below the maximum of turbulent kinetic energy). Moreover if one remembers the principles of the WGE method, air parcels responsible for the stronger gusts in an unstable atmosphere are deflected from nearly the top of the boundary layer. In other words, only the upper boundary layer is concerned, and consequently, the estimate will be necessarily greater than the lower bound.

3) UPPER BOUND OF THE BOUNDING INTERVAL

The determination of the upper bound is easier than the lower bound. If one assumes that the vertical motions triggered by the turbulence explain the deflections of air parcels, the boundary layer is the only region of the atmosphere that must be considered, since the free atmosphere located above the boundary layer is characterized by very weak turbulent motions and reduced vertical exchanges (with the exception of deep convection that will require a specific treatment). The upper bound is consequently given by the maximum wind speed in the boundary layer:

\[ W_{g_{\text{upper}}} = \max[\sqrt{U_\text{top}^2(z_p)} + V_\text{top}^2(z_p)] \] for \( z_p \approx z_{\text{top}} \)

with \( z_{\text{top}} \) the boundary layer height. According to a currently used definition of the boundary layer depth, \( z_{\text{top}} \) is defined as the height where the turbulent kinetic energy is a fraction of its surface value:

\[ E_{\text{top}} = 0.01 \cdot E_{\text{surface}}, \]

where \( E_{\text{surface}} \) and \( E_{\text{top}} \) are the turbulent kinetic energy, respectively, at the surface and at the top of the boundary layer. To ensure the robustness of the method, it is desirable that the upper bound is not too sensitive to the determination of the boundary layer height. This requirement should be met since the wind speed does not vary significantly at this height. A sensitivity study to the definition of the inversion height fixed by (8) is further presented in section 4c.

4) IMPACT OF DEEP CONVECTION

The influence of deep convection on the determination of gusts can easily be taken into account in the WGE method. In this case, the procedure for gust estimates is modified as follows. When the convective adjustment scheme is triggered in the model, the deflection of air parcels has to be considered over the column affected by the downdrafts (and not only over the boundary layer depth). Instead of considering only the mean wind norm given by the model, the velocity of air parcels includes also the (nonnegligible) downward vertical wind component estimated by the convective parameterization in addition to the horizontal mean wind computed by the MAR. This modified wind norm will explain the local severe gusts observed during thunderstorms. Nevertheless, this method should be carefully applied when considering large grid spacing (such as 50 km for instance), because it could lead to overestimates of gusts since only a small fraction of the cell is really affected by the downdraft. This technique has not been tested in the present work, but, in further studies, it would be interesting to include an estimate of gusts associated to thunderstorm events as complementary information to the standard gust estimate.
3. Three-dimensional simulations of storms

The aim of this section is not to present new investigations about the simulation of cyclogenesis, but rather to give an idea of the accuracy of the simulated meteorological fields that will be used as input by the WGE method. The model used for the simulations of explosive cyclogenesis is the MAR: it is briefly described in section 3a. Section 3b is devoted to the simulation of specific situations characterized by explosive cyclogenesis, while a 3-month simulation including a variety of storms is presented in section 3c.

a. Overview of the model and description of the experiments

The formulation of the present version of MAR is described in Gallée and Schayes (1994) and Gallée (1995, 1996). MAR is a hydrostatic primitive equation model in which the vertical coordinate is the normalized pressure \( \sigma = (p - p_r)/(p_s - p_r) \), where \( p \), \( p_s \), and \( p_r \) are the actual pressure, the surface pressure, and the model-top pressure, respectively. The solar radiation scheme is that of Fouquart and Bonnel (1980). The long-wave radiation scheme follows a wide-band formulation of the radiative transfer equation (Morcrette 1984). The heat and moisture exchanges over land are represented with the surface model of Deardorff (1978). The hydrological cycle is fully described in Gallée (1995). The MAR also includes a convective adjustment scheme derived from Fritsch and Chappell (1980) for the representation of deep convection. The boundaries are treated according a dynamic relaxation that includes a Newtonian term (Davies 1976) and a diffusion term (Davies 1983; Anthes et al. 1989).

The parameterization scheme for the surface layer is based on Businger (1973) and Duynkerke (1991) formulations. As already explained in section 2, the representation of the turbulence in the boundary layer is an important input for the WGE method. Brasseur et al. (1998) have shown that one-and-a-half-order closures allow generally a good compromise between accuracy and computing cost, and the differences with second-order closures have no significant impact on the mean variables. Since the examined situations are rather marked by well-mixed boundary layers, a closure including a diagnostic relation for the mixing length is used (Brasseur et al. 1998). Therefore, the vertical subgrid-scale fluxes are treated using the one-and-a-half-order turbulent closure of Thierry and Lacarrère (1982).

For all experiments presented in section 3a, a unique three-dimensional simulation domain is used. The vertical discretization includes 30 levels. The vertical grid size is determined with arithmetic and geometric progressions, producing a finer resolution close to the surface layer and in the boundary layer. As shown later (Fig. 7), the horizontal mesh covers western Europe with a horizontal extent of 3500 by 3500 km², and is centered on 55.5°N, −2°E. Two horizontal resolutions are considered in these experiments: 25 and 50 km. The 25-km horizontal resolution implies a horizontal grid of 140 by 140 points and is rather expensive in computing resources. Therefore such a fine resolution is only used for short-range simulations (about 2 days). Since it would be more suitable and reasonable for runs over longer periods, a 50-km resolution (grid of 70 by 70 points) is chosen for the 3-month simulation. The vertical discretization contains 30 levels, with an increased resolution close to the surface. The first model level is at 10-m height. The atmospheric and surface variables are initialized and forced at the boundaries with European Centre for Medium-Range Weather Forecasts (ECMWF) analysis.

b. Short-range simulations of explosive cyclogenesis

The period from 24 January to 28 February 1990 was notable for the succession of storms that battered northwest Europe. The period opened with a storm on 25 January. It ended with a deep low and following wave depression on 26–28 February. The two situations responsible for the greatest damage over Belgium during the 1990 winter are specifically examined in this paper: 25 January 1990 and 26 February 1990. Both these cases are characterized by explosive cyclogenesis at the synoptic scale, producing wind gusts reaching at least 45 m s⁻¹ over Belgium. Due to the importance of the damage, the situation of 25 January 1990 has been called the “Burns’ Day storm” (McCallum and Norris 1990).

Sections 3b(1) and 3b(2) present the simulation results obtained with MAR. As previously mentioned, the high horizontal resolution of 25 km is used for these short-range experiments. Both simulations were started 1 day before the period of maximum storm intensity, that is, respectively, at 0000 UTC 24 January and 0000 UTC 25 February, and were integrated for 48 h using boundary conditions from the ECMWF analysis.

1) Storm of 25 January 1990

On 24 January 1990, an extreme case of explosive cyclogenesis started over the Atlantic Ocean and propagated over northern Europe. The deepening rate of the storm, which caused damage over Belgium, was 38 hPa per day on 25 January 1990. Between 0000 and 1200 UTC on 24 January, the storm deepened about 28 hPa. The most severe gusts were observed during the afternoon of 25 January. Many weather forecasters (e.g., Heming 1990; Blackall et al. 1990) have investigated the conditions that are responsible for the development of this strong storm.

The simulated mean sea level pressure field is compared with the ECMWF analysis fields at 1200 UTC 25 January (i.e., when the storm had produced the most severe damage over land) in Fig. 6. The agreement between simulation and analysis is rather close for this
deepening cyclone considering the above-mentioned deepening rates, with only a difference of 9 hPa at the center of the depression. The simulated 700-hPa temperature field in Fig. 6 also satisfactorily agrees with the ECMWF analysis: the temperature gradient is well represented close to the warm front, while it seems less strong in the region of the cold front. As shown in Fig. 7, the trajectory path of the storm is well simulated. A time difference of about 2 h is noted, but it remains acceptable if one remembers that the temporal resolution of the ECMWF fields is 6 h. It is also interesting to analyze the evolution of the minimum pressure. At the end of the simulation, the difference with analysis amounts to only 6 hPa, while at 0600 UTC 25 January this difference reaches 13 hPa. This means that there exists a delay in the simulated deepening, but the model tends to converge toward the analysis after a few hours.

In the next sections, the WGE method will be applied to this simulation produced by MAR. The estimated gusts will be compared to the observations from the Belgian synoptic network. Before discussing gust estimates, the representation of the simulated 10-m wind field is assessed in order to determine its accuracy and how this may impact the predicted gusts. In Fig. 8, the simulated 10-m wind is compared with the observations for the synoptic stations of Middelkerke, Zaventem, and Saint-Hubert. The wind is very well simulated at the station of Saint-Hubert, but it tends to underestimate the observations at the stations of Middelkerke and Zaventem. This is particularly the case on the afternoons of 24 and 25 January, in particular when the storm reaches its maximum intensity over Belgium (around 1600 UTC 25 Jan).

In addition, the sensitivity to the horizontal resolution has been briefly examined: a simulation similar to the previous one has been performed with a horizontal resolution of 50 km. This sensitivity test is important since the medium-range simulation presented in section 3c is run with this coarser resolution. When the 50-km run is compared with the 25-km run, one notes no significant change in the storm trajectory. But degradation appears in the cyclone deepening: the difference between the
FIG. 7. Simulated (solid line) and observed (dashed line) trajectory path of the storm of 25 Jan 1990. The values correspond to the pressure (units, hPa) in the center of the explosive cyclone. They are shown since 1800 UTC 24 Jan 1990, and the time interval between two consecutive values is 6 h. The simulated mean sea level pressure field at the end of the simulation is overplotted. The dashed lines parallel to the lateral boundaries delimit the computing domain and the relaxation zone required by the nesting procedure.

simulated minimum pressure with the 50-km grid and the ECMWF fields amounts to 11 hPa at the end of the simulation, while it was only 5 hPa with the 25-km resolution. These results are in agreement with Hedley and Yau (1991), who have also noted high sensitivity of the structure of the warm front observed ahead of the cyclone to changes in horizontal resolution, and the importance of a high horizontal resolution in simulating the mesoscale features of rapidly deepening cyclones.

2) STORM OF 26 FEBRUARY 1990

The situation of 26 February shows characteristics similar to the case of 25 January. During the period of interest for the present simulation, the deepening was about 25 hPa per day, with an intense deepening of 8 hPa between 0000 and 0600 UTC 26 February. Since the most severe gusts over Belgium took place on 26 February between 0600 and 1200 UTC, Fig. 9 presents the simulated sea level pressure and 700-hPa temperature fields at 0600 UTC compared to the ECMWF analysis fields. It is noted that the pattern of the sea level pressure field satisfactorily agrees with that of the ECMWF. In addition, the simulated explosive cyclone situated over Scotland has not deepened, with a deficit of about 10 hPa. The pattern of the 700-hPa temperature field (see Fig. 9) is in good agreement with the ECMWF analysis, even if the thermal gradient in the region of the cold front seems slightly too strong in the simulation. The trajectory path of the storm is presented in Fig. 10.

The simulated timing and trajectory are well represented (better than for the situation of 25 January). The differences in the central pressure of the cyclone do not exceed 10 hPa, and are only 5 hPa at the end of the run.

Similar to the methodology presented in section 3.b(1), Fig. 11 shows a comparison between the simulated hourly mean wind and the observations. The 10-m wind is generally very well predicted but, as for the situation of 25 January, the simulation tends to underestimate the mean wind when the storm reaches its maximum intensity over Belgium. This is particularly the case for the Zaventem and Saint-Hubert stations around 1000 UTC 26 February. The underestimate of mean wind at these times is a consequence of the cyclone central pressure being too high and the model not completely capturing its development.

c. Medium-range simulation of cyclogenesis

The chosen period for the medium-range simulation covers the months from January to March 1990 that were characterized by an unusual frequency of storms. The MAR model is initialized at 0000 UTC 1 January 1990 and is run continuously over the 3-month period, being forced at its boundaries by the ECMWF analysis. The domain is the same as in the previous section, but the horizontal grid resolution is fixed at 50 km. This simulation will not be analyzed in detail for each storm event, except for the two situations of explosive cyclogenesis [treated in sections 3.b(1) and 3.b(2)] that are among the most difficult events to accurately simulate.

The simulation results corresponding to the two situations examined in section 3.b(1) and 3.c(2) are presented, respectively, in Figs. 12 and 13. If decreasing the horizontal resolution has induced a negative impact on the simulation of deepening rate [see section 3.b(1)], starting the simulation earlier has a positive impact on the deepening of the cyclone. For the situation of 25 January, the difference of minimum pressure at the end of the simulation is the same as with the 25-km simulation, but the temporal evolution of this central pressure is better represented with the medium-range simulation. The same conclusions can be drawn for the storm of 26 February: the minimum pressure at the end of the simulation is only 1 hPa, which is a better result than with the short-range 25-km run. Nevertheless the trajectory is less well simulated during the 26 February simulation, with a drift increasing with time.

The results of the medium-range run can also be examined through the analysis and the comparison of the 10-m wind with the observations. As previously done in the analysis of short-range simulations, this comparison is important to assess the representation of the mean wind before applying a gust estimate method that will be based on the characteristics of the mean wind. In Fig. 14, the daily mean wind is compared with observations at stations Middelkerke, Zaventem, and Saint-Hubert. These three stations are selected because of their
spatial location: there are, respectively, located in the north (coastal area), center, and south of Belgium. Looking for the temporal evolution of daily mean wind, we generally note a good agreement between the simulation and the observations, except some systematic errors for the storms of 28 January, and 3 and 8 February. Zaventem seems to give the best results. Middelkerke and Saint-Hubert are also satisfactorily simulated except for overestimation during severe storms, especially during 25 January at Middelkerke, and 12 and 26 February at Saint-Hubert.

The statistics of mean wind are presented in Table 1. In addition to the three above-mentioned stations, the synoptic stations of Gosselies and Deurne have also been included in the analysis since complete series of measurements are available for both these other stations. Table 1 shows the wind speed at the 10-m height averaged over the 3 months. Zaventem gives the smallest error (only 3%) among the five stations examined here, which confirms the results presented in Fig. 14. For the four other stations, differences with observations range from 9% (Gosselies) to 23% (Saint-Hubert). The root-mean-square (rms) error is also shown in Table 1. It ranges between 2.0 and 3.3 m s\(^{-1}\). Note that the rms error does not vary inland (around 2.1 m s\(^{-1}\)), while the larger rms error occurs in the coastal area (Middelkerke). This is confirmed by linear correlation coefficient (Table 1): the time series of mean wind are better represented inland (correlation about 0.84) than in the coastal area (0.77 for Middelkerke).

Some inappropriate roughness lengths may explain the differences between the simulated and observed 10-m wind. For all simulations presented in this paper, the roughness length has been fixed to the mean values of \(10^{-1}\) m over land and \(10^{-3}\) m over ocean. These values do not necessarily correspond to the reality. In addition, even if a correct averaged roughness length in a grid box is specified, this average could be different from a particular point in the grid box and, thus, different from the roughness of a synoptic station site. This is especially true for the coastal area that cannot be properly represented with a horizontal resolution of 50 km. The only way to limit the above-mentioned deficiencies is simultaneously to refine the horizontal resolution in order to represent more local surface characteristics, and to use a high-resolution database of the roughness length over Europe. Another possible and significant source of error is the imperfect representation of the simulated meteorological fields: for instance, insufficient deepening of storms will lead to underestimated winds.

4. Application to short-range, high-resolution simulations

Section 3 was devoted to the assessment of the meteorological fields simulated by MAR considering storm events. This preliminary step was absolutely necessary for the evaluation of the WGE method. If the WGE approach produces a bad estimate, it is indeed important to investigate the reasons: is the failure due to the input fields and/or due to the conceptual approach itself? The problem is similar if a good estimate is obtained for a wrong reason, for instance due to error compensation.

The WGE method described in section 2 is tested on the two situations of explosive cyclogenesis presented in section 3b. Studying events over short periods (a few days) allows establishing a detailed diagnostic of the advantages and shortcomings of the developed method (sections 4a and 4b). This diagnostic includes the ability of the WGE method to reproduce the temporal evolution and the daily maximum gusts. A sensitivity experiment to assess the importance of the boundary layer height for the determination of the upper bound on wind gusts is examined in sections 4c.
**a. Daily wind gusts**

Figure 15 represents the maximum daily wind gust speed for nine synoptic stations over Belgium for the situations of 25 January (Fig. 15a) and 26 February 1990 (Fig. 15b). For the storm of 25 January, it can be noted that all observed values are in the bounding interval delimited by the lower and upper bounds of the WGE method, except for the station of Beauchevain (25 Jan) where an exceptional value of wind gust (47 m s\(^{-1}\)) has been recorded. Observed gusts during the storm of 26 February are generally in the bounding interval, except Gosselies, Deurnes, and Florennes where the lower bound has slightly overestimated the observations. The lower and upper bounds seem therefore able to provide a reliable interval of maximum wind speed, even though the subgrid variability of gusts in a grid cell of 25 by 25 km\(^2\) cannot be taken into account. The estimates also fall within an error range of 5 m s\(^{-1}\) (8 m s\(^{-1}\) for a few stations), particularly for the storm of 25 January.

In order to analyze the spatial distribution of gusts predicted by the WGE method, Figs. 16 and 17 present...
a comparison between the 700-hPa geostrophic wind and the predicted gust field, respectively, for the situations at 1200 UTC 25 January and 0600 UTC 26 February 1990 (i.e., the same situations as in Figs. 6 and 9). Examining the geostrophic wind at the 700-hPa pressure level underlines the role of the large-scale wind field in the prediction of gusts. Since surface gusts occurring in well-mixed layers are explained by the deflection of air parcels flowing nearly to the top of the boundary layer, the 700-hPa height has been chosen as an upper bound of the boundary layer top. For both these situations of explosive cyclogenesis, the geostrophic wind reaches a maximum intensity over the Atlantic Ocean and is characterized by a strong gradient along the north coast of France. The gust fields show similar variations but despite some obvious similarities, the pattern of geostrophic wind is not sufficient to fully explain the pattern of gusts. The turbulence in the boundary layer is another key aspect of the WGE method that significantly influences the determination of gusts.

b. Hourly evolution of wind gusts

Figure 15 shows the results obtained with the WGE method for a period of 1 day. This is probably the most important information for operational use in weather forecasting. Nevertheless, other useful information is the time during the day at which the maximum gust takes place. The temporal behavior of the method is examined on the situation of 25 January and 26 February, which allows investigating the behavior of the WGE method on less extreme gusts. Figures 18 and 19...
show the hourly evolution of wind gusts for three synoptic stations.

The analysis of Fig. 18 (situation of 24–25 Jan 1990) reveals interesting features of the WGE method. During 24 January 1990, the estimate computed with the WGE method has reproduced well the hourly wind gust evolution, even if it is unable to generate the sudden observed decrease of wind speed at the coastal Middelkerke station in the evening. For the next day, a time difference is found between simulation and observation, especially during the growth of wind speed, that is, the first 12 h of 25 January. This can be partly explained by the time difference in the representation of pressure fields [already mentioned in section 3.b(1)]. Another explanation is that the simulated growth of the boundary layer is too fast compared to the reality. Since the WGE method depends on the characteristics of the boundary layer, too intense mixing in the boundary layer would imply (i) an overestimated lower bound and wind gust estimate due to values too large for the turbulent kinetic energy and (ii) an overestimated upper bound due to a too deep boundary layer. The second explanation is suggested by the fact that the overestimation is particularly marked after sunrise. Other sites behave in a similar manner, even though the time difference seems less marked for stations located in the south of Belgium (Saint-Hubert), which are slightly less affected by the time difference in the pressure field than the stations located in the north of Belgium.

Table 1. Comparison of the simulated and observed 10-m winds (units, m s$^{-1}$) for the period from Jan to Mar 1990 for the synoptic stations of Middelkerke, Zaventem, Deurne, Gosselies, and Saint-Hubert (see Fig. 3 for the location of these stations). The last two columns include the root-mean-square errors (units, m s$^{-1}$) on the time evolution of the simulated mean wind, and the linear correlation coefficient for the observed and simulated time series (6-hourly wind).

<table>
<thead>
<tr>
<th>Synoptic station</th>
<th>Simulation</th>
<th>Observation</th>
<th>Rms error</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middelkerke</td>
<td>9.5</td>
<td>8.7</td>
<td>3.3</td>
<td>0.77</td>
</tr>
<tr>
<td>Zaventem</td>
<td>7.2</td>
<td>7.0</td>
<td>2.0</td>
<td>0.84</td>
</tr>
<tr>
<td>Deurne</td>
<td>7.2</td>
<td>6.1</td>
<td>2.2</td>
<td>0.85</td>
</tr>
<tr>
<td>Gosselies</td>
<td>7.0</td>
<td>6.5</td>
<td>2.1</td>
<td>0.80</td>
</tr>
<tr>
<td>Saint-Hubert</td>
<td>6.6</td>
<td>5.4</td>
<td>2.2</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Fig. 14. Simulated and observed daily 10-m wind (units, m s$^{-1}$) for the period from Jan to Mar 1990 at Middelkerke, Zaventem, and Saint-Hubert. The simulated mean wind at 10 m is represented with solid lines, and the observations are indicated with dots (●).

Fig. 15. Simulated (circle) and observed (diamond) maximum daily gusts (units, m s$^{-1}$) during the storms of (a) 25 Jan and (b) 26 Feb 1990 for nine Belgian synoptic stations. The bounding interval is delimited with bars (solid lines) around the estimates.
Fig. 16. Situation at 1200 UTC 25 Jan 1990: (a) simulated 700-hPa geostrophic wind field, where solid lines represent the norm of the geostrophic wind (units, m s\(^{-1}\)), and (b) gust estimates (units, m s\(^{-1}\)) predicted by the WGE method.

Fig. 17. As in Fig. 16 except that the fields are presented for 0600 UTC 26 Feb 1990.

The same remarks can be addressed to the situation of 25 and 26 February in Fig. 19. During the second day, the lower bound is closer to the observation than the estimate. This fact confirms the results shown in Fig. 15b where the estimated value produced by the WGE method generally overestimates the observation. Nevertheless, the overestimation could be specific to these extreme situations, and cannot be extended systematically to other cases. In contrast to the situation of 25 January, no significant time difference in the simulation of the pressure field can explain the overestimation of wind gusts. The slightly deficient representation of the boundary layer is the only possible explanation in this case. At the end of 26 February, particularly between 1200 and 1800 UTC, the observed wind gust speed is out of the computed interval and is lower than the predicted values of the lower bound. During this period, the simulated deepening rate is about 16 hPa per day, which is four times bigger than the observed deepening rate. This fact explains the high values of wind gust estimates between 1200 and 1800 UTC. The rms error on the time evolution of hourly estimated gusts is shown in Table 2 for the two storm event. It is noted that the rms errors generally range between 4.4 and 7.7 m s\(^{-1}\), and the above-mentioned time differences and deficiencies in the representation of the boundary layers directly affect them.

The analysis of WGE output in Figs. 15 and 18 and 19 leads to the following conclusions: (i) the interval delimited by the lower and upper bounds is very reliable over a period of 1 day (daily wind gust), and (ii) the estimate gives a satisfying temporal representation within a typical rms error of 5.6 m s\(^{-1}\) (from Table 2). Obviously, all these results are extremely dependent on the correct representation of the boundary layer (inten-
Fig. 18. Simulated and observed hourly gusts (units, m s\(^{-1}\)) during the storm of 25 Jan 1990. Hourly estimate (asterisks), and lower (solid line with triangles) and upper bounds (solid line with squares) are compared with the observations (dots) for the synoptic stations of (a) Middelkerke, (b) Zaventem, and (c) Saint-Hubert.

Fig. 19. As in Fig. 18 except for the storm of 26 Feb 1990.

Table 2. Root-mean-square errors (units, m s\(^{-1}\)) on the time evolution of hourly gusts computed with the WGE method for the storms of 25 Jan 1990 and 26 Feb 1990. Four synoptic stations are considered (see Fig. 3 for the location of these stations). The computation of gusts is done from the MAR simulations at 25 [short range; see section 3b(1)] horizontal resolutions.

<table>
<thead>
<tr>
<th>Synoptic station</th>
<th>Storm of 25 Jan 1990</th>
<th>Storm of 26 Feb 1990</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middelkerke</td>
<td>5.5</td>
<td>4.4</td>
</tr>
<tr>
<td>Gosselies</td>
<td>5.1</td>
<td>7.7</td>
</tr>
<tr>
<td>Zaventem</td>
<td>4.5</td>
<td>6.1</td>
</tr>
<tr>
<td>Saint-Hubert</td>
<td>5.1</td>
<td>6.7</td>
</tr>
</tbody>
</table>

As mentioned in section 2b, the upper bound of the WGE method is computed as the maximum wind speed in the boundary layer. Consequently this speed depends on the definition of the boundary layer height given by (8). For the WGE method, the boundary layer height is defined as the level at which the turbulent kinetic energy reaches 1% of its surface value. Nevertheless, the currently admitted range of threshold values is between 1% and 10%. In order to determine the sensitivity of the chosen threshold in (8), Fig. 20 presents the differences between the upper bounds computed with thresholds of 1%, 5%, and 10% at Zaventem during the storms of 25 January (Fig. 20a) and 26 February (Fig. 20b).

The impact of increasing the threshold value is a decrease in the boundary layer depth, and consequently the upper bound should diminish. If the threshold of 10% is chosen instead of 1%, the computed upper bound
on wind gusts does not generally vary significantly: about 3.9% on the mean, up to 15% for well-mixed boundary layers. For instance, it is lowered by 4 m s\(^{-1}\) when the explosive cyclone of 25 January reached its maximum intensity over Belgium. With the threshold of 5%, the averaged difference on upper bounds is less by about 2.5% compared to the 1% threshold. Note also that the 5% threshold seems to give a more realistic upper bound at 1200 UTC 24 January than with the 1% threshold that gives an exaggerated upper bound. Except for this particular case, the threshold of 1% is preferred since the first objective of the upper bound is to be greater than all possible gusts.

**5. Application to medium-range simulation**

In section 4, the WGE method has been applied on two extreme cases of storms. Nevertheless it is also important to (i) assess the WGE technique on a wider variety of situations on the basis of the medium-range simulation from January to March described in section 3c, and (ii) determine its ability to reproduce climatological gust statistics.

---

**Fig. 20. Sensitivity of the upper bound of the bounding interval (units, m s\(^{-1}\)) to the boundary layer height definition for the situations of (a) 24–25 Jan 1990 and (b) 25–26 Feb at Zaventem. The upper bounds computed with the thresholds (i.e., the ratio between the turbulent kinetic energy at a given height and its surface value) of 1%, 5%, and 10% are represented, respectively, with solid, dotted, and dashed curves.**

**Fig. 21. Estimated (plus signs) and observed (dots) daily gusts (units, m s\(^{-1}\)) for the period from Jan to Feb 1990 for the synoptic stations of (a) Middelkerke, (b) Zaventem, and (c) Saint-Hubert. Solid lines represent lower and upper bounds on gust estimate, and stars indicate observed gusts.**

**Fig. 21. Estimated (plus signs) and observed (dots) daily gusts (units, m s\(^{-1}\)) for the period from Jan to Feb 1990 for the synoptic stations of (a) Middelkerke, (b) Zaventem, and (c) Saint-Hubert. Solid lines represent lower and upper bounds on gust estimate, and stars indicate observed gusts.**

**Fig. 21. Estimated (plus signs) and observed (dots) daily gusts (units, m s\(^{-1}\)) for the period from Jan to Feb 1990 for the synoptic stations of (a) Middelkerke, (b) Zaventem, and (c) Saint-Hubert. Solid lines represent lower and upper bounds on gust estimate, and stars indicate observed gusts.**

---

**a. Estimates of daily gusts**

In order to assess the statistical behavior of the WGE method, the climatology of gusts is examined through the analysis of the time series of observed and simulated daily maximum gusts. Figure 21 presents a comparison with daily observed maximum gusts from three synoptic stations: Middelkerke, Zaventem, and Saint-Hubert. The estimate is plotted, as well as the lower and upper bounds for the estimated gust.

In Fig. 21, wind gusts are generally well predicted by the WGE method. Nevertheless all observed gusts are not included in the bounding interval. Considering the stations of Middelkerke, Zaventem, and Saint-Hubert, it is noted that there are, respectively, 6, 14, and 21 days where observed gusts are less than the lower bound of the bounding interval. For these particular cases, the averaged difference between observed gusts and the
lower bound is about 2.4 m s\(^{-1}\). For the same synoptic stations, there are, respectively, 15, 8, and 11 days where observed gusts are greater than the upper bound of the bounding interval, with an averaged difference between observations and the upper bound for these particular cases of, respectively, 3.5, 2.7, and 5.5 m s\(^{-1}\). Consequently, there is a slight tendency of the WGE method to underestimate gusts in the coastal area (Middelkerke) and to overestimate gusts in the south of Belgium (Saint-Hubert). However these incorrect predictions of the bounding interval occur for weak intensities of gusts (see section 5b) and are mostly related to imperfect representation of the mean wind in the surface layer.

Table 3 presents a comparison between the time average (from January to March) of the observed gusts, lower bound, estimate, and upper bound given by the WGE method. This table also includes the rms and the linear correlation coefficient for the observed and simulated time series of 6-hourly gusts. The averaged lower and upper bounds are, respectively, below and over the average of observed gusts for all examined synoptic stations. However for climatic applications (e.g., statistics of gusts in multiyears runs), the statistics of the bounding interval appear less useful than the statistic of the estimated gusts. One remarks that the statistics of the estimate systematically underestimate the observations: this underestimation ranges from 3% to 10%, which remains acceptable. The WGE method is capable of capturing the differences that occur between different station locations, which suggest that the spatial variability in the model generated gusts may be realistic (e.g., the intensity of gusts that decreases from the north to the south of Belgium) although this has not been examined over a broad region.

The rms error (Table 3) computed for five synoptic stations is generally about 4 m s\(^{-1}\). The smallest errors (around 3.5 m s\(^{-1}\)) are found in the center of Belgium, while the largest errors (4.5 m s\(^{-1}\)) are found in the coastal area and in the south of Belgium. In the coastal area, the larger rms error at Middelkerke is explained by an incorrect representation of the mean wind close to the surface, which is probably due to an underestimated roughness length and an insufficient representation of the coastal area with a horizontal resolution of 50 km. The error at Saint-Hubert is related to an imperfect representation of the wind in the surface layer as mentioned in section 3c. The correlation coefficient in Table 3 confirms that Saint-Hubert gives the less satisfying results for the rms error as well as the for the representation of the time evolution of gusts. On the contrary, the estimated gusts Zaventem reproduce well the observed temporal evolution. Note also that the correlation coefficients for time series of gusts is as good as those of the mean wind shown in Table 1 and discussed in section 3c.

In order to complete the statistical analysis, it is interesting to examine the results for specific situations. Considering the particular storm of 25 January, maximum daily gusts computed from the medium-range simulation are better than those computed from the short-range simulation at 50-km resolution (Table 4). This is logical since the medium-range simulation has better represented the cyclone deepening than with the short-range simulation (section 3b). On the contrary, the estimates computed from the short-range run at 25-km resolution remain the best (Table 4), which suggests the need to refine the horizontal resolution to improve the gust prediction.

Among the situations characterized by imperfect or incorrect gust estimates of the WGE method during the period from January to March 1990, the incorrect prediction of gusts is generally due to inaccurate representation of meteorological fields by the model. For instance the storm events of 28 January and 3 February have been poorly predicted. Estimated daily maximum gusts at Zaventem are 15.6 and 16.1 m s\(^{-1}\), respectively, for 28 January and 3 February, while the observations are 29.7 and 29.2 m s\(^{-1}\). For both these situations, the difference between simulated and observed gusts is explained by underestimated cyclone deepening rates. Compared to the analysis, the simulated pressures at the center of the cyclone are underestimated by 20 and 10 hPa, respectively, for the situations of 28 January and 3 February. These large differences explain why

<table>
<thead>
<tr>
<th>Synoptic station</th>
<th>Observation</th>
<th>Lower bound</th>
<th>Estimate</th>
<th>Upper bound</th>
<th>Rms error</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middelkerke</td>
<td>13.5</td>
<td>10.3</td>
<td>12.1</td>
<td>17.4</td>
<td>4.5</td>
<td>0.82</td>
</tr>
<tr>
<td>Zaventem</td>
<td>12.1</td>
<td>10.1</td>
<td>11.5</td>
<td>17.4</td>
<td>3.4</td>
<td>0.86</td>
</tr>
<tr>
<td>Deurne</td>
<td>10.9</td>
<td>10.2</td>
<td>11.6</td>
<td>17.6</td>
<td>2.2</td>
<td>0.83</td>
</tr>
<tr>
<td>Gosselies</td>
<td>11.5</td>
<td>9.6</td>
<td>11.1</td>
<td>17.0</td>
<td>2.1</td>
<td>0.84</td>
</tr>
<tr>
<td>Saint-Hubert</td>
<td>11.2</td>
<td>9.0</td>
<td>10.4</td>
<td>16.5</td>
<td>2.2</td>
<td>0.79</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Synoptic station</th>
<th>Observation</th>
<th>WGE—50 km short range</th>
<th>WGE—50 km medium range</th>
<th>WGE—25 km short range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middelkerke</td>
<td>40.0</td>
<td>34.7</td>
<td>34.4</td>
<td>37.5</td>
</tr>
<tr>
<td>Gosselies</td>
<td>38.1</td>
<td>30.8</td>
<td>33.6</td>
<td>35.8</td>
</tr>
<tr>
<td>Deurne</td>
<td>33.3</td>
<td>31.4</td>
<td>35.3</td>
<td>36.9</td>
</tr>
<tr>
<td>Zaventem</td>
<td>33.9</td>
<td>31.1</td>
<td>34.3</td>
<td>35.6</td>
</tr>
<tr>
<td>Saint-Hubert</td>
<td>42.2</td>
<td>31.4</td>
<td>33.6</td>
<td>37.2</td>
</tr>
</tbody>
</table>
WGE method has widely underestimated wind gusts. The reasons explaining the deficiencies in the simulation of these meteorological fields are not investigated in this paper. Note that a finer horizontal resolution would probably improve the representation of the simulated fields and therefore the prediction of gusts.

b. Reliability of the bounding interval

The bounds of the bounding interval are indeed fundamental. The lower bound represents the lowest gust speed that can be expected given a good model simulation. The usefulness of the lower bound depends on its intensity. For instance, if it exceeds given thresholds (e.g., 30 m s\(^{-1}\)), there is a very high probability that the observed gusts will be larger than this value. With such gust intensities, varying amounts of damage to buildings can be expected. Consequently the lower bound gives information about the minimum damage that can result from severe winds. The upper bound gives the strongest gust speed that can occur. It has therefore an informative or preventive role. From these considerations, it appears that a correct prediction of the bounding interval is as important as the determination of the estimate itself.

In Fig. 21, it is seen that the bounding interval contains nearly all daily observed gusts (i.e., the maximum wind speed recorded over a day), even during the severe storms of 25 January and 26 February. Considering only observed gusts that are out of the bounding interval, it is noted that they are in most cases less that the computed upper bound of the bounding interval, which enforces the reliability of the upper bound and its usefulness to predict the most severe gusts.

The important aspect of the results presented in Fig. 21 is that, when the mesoscale model represents with sufficient accuracy the meteorological fields, the WGE method and its physical approach seem able to explain gusts observed at the surface. To confirm these results, the reliability rate of the bounding interval is computed for nine Belgian synoptic stations from January to March 1990. Complete series of observations are available for the stations of Middelkerke, Zaventem, Deurne, Gosselies, and Saint-Hubert, while only observed gusts exceeding 5 m s\(^{-1}\) are available for Chievres, Florennes, Beaucechain, and Bierset. The bounding interval is said to be reliable if the observed gusts are included in this interval. If a given observation is only 1 m s\(^{-1}\) less than the lower bound or greater than the upper bound, the bounding interval is not considered reliable. When this criterion is applied to the results of the WGE method, an averaged (for the nine synoptic stations and for the complete period from Jan to Mar 1990) reliability rate of 73% is obtained (see Table 5). The rate ranges between 56% (Deurne) and 81% (Bierset).

Since the reliability rate does not have the same relevance for severe gusts as for weak gusts, three classes of gusts have been considered: 1) up to 10 m s\(^{-1}\), the wind can be considered calm; 2) between 10 and 20 m s\(^{-1}\), the weather is said to be windy, but it does not produce any damage; 3) above 20 m s\(^{-1}\), some buildings are damaged, and the road circulation is disturbed by lateral gusts. Considering gusts less than 10 m s\(^{-1}\), the reliability rate is about 52%, which is much less than the global rate of 73%. This can be explained by a systematic overestimation of the simulated mean wind in the surface layer when the wind is weak. But this class of wind gusts is surely the less interesting in weather forecasting. The best rate is obtained for gusts between 10 and 20 m s\(^{-1}\) with a reliability of 81%. For gusts exceeding 20 m s\(^{-1}\), the reliability rate is 73%, which is less than the intermediate class of wind gusts. This result is logical since the difficulty for representing the winds associated with a depression increases with the deepening rate, particularly for situations marked by explosive cyclogenesis.

6. Comparison with other methods

The WGE method seems sufficiently accurate for use in weather forecasting or climate applications, but it is useful to compare WGE with other methods currently used in operational weather prediction. The two selected methods are the surface-roughness-based approach (U.K. Met. Office 1993) and the surface-layer deflection method proposed by Quinet and Neméghaire (1991).

a. Surface-roughness-based approach

The fully empirical surface-roughness-based (SR) method is currently used in weather forecasting to determine wind gusts. It consists of determining a ratio of maximum gust to hourly averaged speed. For regions where information about wind gusts is not available, tables of the gust factor for standard sites are used. Table

<table>
<thead>
<tr>
<th>Location</th>
<th>Range of ratios</th>
<th>Estimated avg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open sea</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Isolated hilltops</td>
<td>1.4–1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Flat open country</td>
<td>1.4–1.8</td>
<td>1.6</td>
</tr>
<tr>
<td>Rolling country (few windbreaks)</td>
<td>1.5–2.0</td>
<td>1.7</td>
</tr>
<tr>
<td>Rolling country (numerous windbreaks)</td>
<td>1.7–2.1</td>
<td>1.9</td>
</tr>
<tr>
<td>Centers of large cities</td>
<td>1.9–2.3</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Table 7. Averaged error on 6-hourly gust estimates (units, m s$^{-2}$) computed with WGE (diamond and gray solid thick line) and SR (square and black solid thick line) methods, and observed daily gusts (circle and black dashed line) for the period from Jan to Feb 1990 at Zaventem.

<table>
<thead>
<tr>
<th>Date</th>
<th>Observation</th>
<th>SR method</th>
<th>WGE method</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 Jan</td>
<td>33.9</td>
<td>28.8</td>
<td>34.2</td>
</tr>
<tr>
<td>28 Jan</td>
<td>27.2</td>
<td>14.6</td>
<td>15.6</td>
</tr>
<tr>
<td>3 Feb</td>
<td>29.2</td>
<td>16.1</td>
<td>16.1</td>
</tr>
<tr>
<td>7 Feb</td>
<td>26.7</td>
<td>22.7</td>
<td>27.5</td>
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<td>8 Feb</td>
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<td>22.7</td>
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<td>11 Feb</td>
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<td>12 Feb</td>
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<tr>
<td>29 Feb</td>
<td>29.2</td>
<td>22.7</td>
<td>26.4</td>
</tr>
</tbody>
</table>

In order to analyze the differences of the predicted gusts for both SR and WGE methods, daily gusts for Zaventem are presented in Fig. 22. From this figure, the SR method seems able to predict gusts with an acceptable accuracy and is in many cases close to the WGE method. These results demonstrate that the linear dependence of wind gusts on mean wind is generally a good approximation. Nevertheless, the superiority of the WGE method appears in the determination of strong gusts. Table 8 shows a comparison of daily gusts predicted by the SR and WGE methods for the situations where gusts exceeding 25 m s$^{-1}$ have been observed. These cases are obviously the most important in the framework of weather forecasting, since damage can be expected with such gust speeds. For nearly all these situations, and particularly for the situations of 25 January, and 7, 8, 13, 26, and 28 February, the WGE method has significantly improved the prediction compared to the SR method. If one excepts the situations of 28 January and 3 February (already discussed in section 5), the averaged error on daily gusts in Table 8 is 6.2 m s$^{-1}$ with the SR method, while it is only 3.1 m s$^{-1}$ with the WGE method (i.e., a reduction by a factor 2).

<table>
<thead>
<tr>
<th>Stability classes</th>
<th>Wind gust determination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral atmosphere</td>
<td>Wind velocity at the top of the SL</td>
</tr>
<tr>
<td>Stable atmosphere</td>
<td>Wind velocity at the top of the SL corrected (subtraction) by the effect of the stable stratification</td>
</tr>
<tr>
<td>Unstable atmosphere</td>
<td>Wind velocity in the layer where ( \frac{d\theta}{dz} &lt; 0 )</td>
</tr>
</tbody>
</table>

b. Surface layer deflection approach

Quinet and Nemégahaire (1991) have developed this approach in the framework of operational weather forecasting at the Royal Meteorological Institute of Belgium. The fundamental assumption of this method is that gusts observed at the surface result from the deflection of air parcels flowing at the top of the surface layer. The surface layer deflection (SL) method takes into account the influence of the stratification. Depending on the stability of the atmosphere, the determination of gusts can be summarized as presented in Table 9.

The SL method has some similarities to the WGE method. Both methods assume that gusts are explained by the deflection of air parcels to the surface. However, the approach of the WGE method seems more general essentially for two reasons: (i) the whole boundary layer is considered instead of only the surface layer in the SL method, and (ii) the turbulent eddies are assumed to be the main physical process that deflects air parcels to the surface, whatever the stability of the atmosphere may be. For the first point, there is no physical and objective reason to consider only the surface layer, particularly if there is a neutral layer above the (neutral) surface layer. Quinet and Nemégahaire (1991) justify this choice by the fact that the wind is generally constant between the surface layer and the free atmosphere. For the second above-mentioned point, the WGE method does not treat the unstable case differently, since the trigger mechanism for air parcel deflection is attributed to turbulence.

A practical difference between the two gust estimate methods is that the SL method is—up to now—designed for a graphical use from an observed sounding. An implementation on computers will imply the specification of thresholds required for the determination of the top of the surface layer that is defined as the height where the real wind deviates from the logarithmic profile. The specification of this threshold can be very important (and sensitive) for vertical profiles given by models, since these profiles are smoothed compared to the profiles from sounding measurements.

Table 10 shows a comparison of wind gusts produced by the SL and WGE methods. In order to avoid any misinterpretation in the determination of the surface layer with the SL method, we have directly considered the results presented in the paper of Quinet and Nemégahaire (1991). We have therefore compared gusts predicted by the SL method that are based on sounding measurements with those given by the WGE method that are based on model output (from the medium-range simulation) at the same time. For all chosen dates in Table 10, the maximum gust is reached most of the time either around 0000 or 1200 UTC, that is, at the sounding time.

Before discussing the results, let us remark that this comparison does not favor the WGE method, since it uses output of the medium-range simulation that does not perfectly reproduce the observations. Nevertheless, the WGE method produces very acceptable results compared to the SL method. If one excepts the situation of 28 January (already mentioned in section 5) not correctly simulated by MAR, the averaged error is 1.7 m s\(^{-1}\) with the SL method and 1.9 m s\(^{-1}\) with the WGE method. From this comparison, we cannot strictly conclude that the WGE method gives better or worse estimates than the SL method in the operational conditions determined by the limitations of the SL method. Once again, the usefulness of the bounding interval can be underlined: all observed gusts (except 28 Jan) are included in the bounding interval. The distinction between the stability classes of the atmosphere has revealed an interesting feature of this interval: its width is reduced for the unstable atmosphere, while neutral atmospheres generally give a large width. The bounding interval is therefore more accurate in unstable than in neutral boundary layers.

The advantages of the WGE method compared to the SL method are (i) the more general formulation independently on stability classes (see Table 9 for the SL method), and (ii) the determination of a bounding interval on gust estimate. Moreover the WGE method is ready to compute gusts directly from the meteorological fields given by operational models. On the other hand, it is not able to determine gusts only from a sounding since it requires the specification of the turbulent kinetic energy.

TABLE 10. Comparison between gust estimates (units, m s\(^{-1}\)) computed with the SL and WGE methods and the observations at Uccle. Only situations of the year 1990 treated in Quinet and Nemégahaire (1991) have been considered.

<table>
<thead>
<tr>
<th>Atmospheric situation</th>
<th>Observed gusts</th>
<th>SL method estimate</th>
<th>WGE method estimate</th>
<th>WGE method bounding interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral atmosphere</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0000 UTC 2 Feb</td>
<td>24.7</td>
<td>25.0</td>
<td>23.9</td>
<td>19.2–31.3</td>
</tr>
<tr>
<td>1200 UTC 7 Feb</td>
<td>27.2</td>
<td>26.1</td>
<td>27.0</td>
<td>20.6–33.6</td>
</tr>
<tr>
<td>0000 UTC 8 Feb</td>
<td>28.8</td>
<td>30.0</td>
<td>27.5</td>
<td>20.8–34.4</td>
</tr>
<tr>
<td>Stable atmosphere</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1200 UTC 26 Feb</td>
<td>38.6</td>
<td>32.8</td>
<td>33.9</td>
<td>31.9–38.9</td>
</tr>
<tr>
<td>Unstable atmosphere</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1200 UTC 28 Jan</td>
<td>29.7</td>
<td>22.2</td>
<td>10.8</td>
<td>9.2–14.7</td>
</tr>
<tr>
<td>1200 UTC 2 Feb</td>
<td>19.4</td>
<td>18.1</td>
<td>20.0</td>
<td>17.2–23.8</td>
</tr>
<tr>
<td>1200 UTC 12 Feb</td>
<td>22.5</td>
<td>21.1</td>
<td>20.6</td>
<td>18.1–24.1</td>
</tr>
<tr>
<td>1200 UTC 15 Feb</td>
<td>26.7</td>
<td>26.1</td>
<td>22.8</td>
<td>21.1–26.7</td>
</tr>
</tbody>
</table>
7. Conclusions

A new method (denoted WGE) to estimate wind gusts has been examined. Contrary to most of techniques used in operational weather forecasting, the determination of gusts in this approach is fully based on physical considerations. The main motivation for developing such an approach is to improve the knowledge of the physical processes that control the determination of gusts. The assumptions of the WGE method have been tested through the analysis of estimated gusts on real cases. This analysis includes the application of the WGE method on severe storms, a statistical evaluation on a wide range of situations, and a comparison with other approaches currently used.

The approach assumes that gusts observed at the surface result from the deflection of air parcels flowing higher in the boundary layer. The trigger mechanism for the deflection is attributed to turbulent eddies. The WGE method takes into account the mean wind and the turbulent structure of the atmosphere, and therefore both large-scale and regional features influence estimated gusts. In addition, the confidence in the predicted gust is assessed through the computation of a bounding interval around the estimate. The usefulness of this interval is twofold: the lower bound of the interval is the lowest gust that can be expected and it can help in anticipating the consequences of severe wind gusts; the upper bound of the interval corresponds to the strongest gust that can occur and it has an informative or preventive role. The main operational features of the WGE method can be summarized as follows: (i) prediction of the spatial distribution of gusts and sensitivity to regional characteristics, (ii) prediction of the instant at which the daily maximum gust takes place, (iii) determination of a bounding interval around the gust estimate, and (iv) estimate of gusts using a complete physical approach. Note that the WGE method requires the knowledge of the vertical profile of turbulent kinetic energy (simulated by the atmospheric model).

As first stringent tests, the WGE method is applied on two cases of explosive cyclogenesis: 25 January 1990 and 26 February 1990. These two severe storms, which were responsible for some of the strongest damage over Belgium during the winter 1990, have been simulated using the MAR mesoscale model. The MAR, nested in ECMWF analysis, has been able to reproduce with a satisfying accuracy the generation and the deepening of depressions, and the general characteristics of low pressure systems. The results of the WGE method are specifically compared with the observations from the Belgian network. Daily gusts are predicted with good accuracy, while hourly temporal evolution of estimated gusts depends strongly on the fields generated by the atmospheric model. Compared to observations, it produces satisfying estimates of daily wind gusts within a typical error of about 5 m s\(^{-1}\). The bounding interval seems reliable and proves its usefulness for determining the uncertainty around estimated gusts.

In order to assess the WGE method on a greater variety of wind gusts, a statistical evaluation is done for the period from January to March 1990. This period was characterized by a high frequency of storms. The WGE method has been able to reproduce the main features of the climatology of gusts over Belgium during this period. From this analysis, the statistics of estimated gusts tend to underestimate the observations (bias from 3\% to 10\%) but they appear able to reproduce the tendencies at different stations. An interesting aspect of the WGE method is that the bounding interval has shown a reliability rate of 73\% for the prediction of daily gusts. Considering classes of wind gusts, this rate is about 81\% for gusts between 10 and 20 m s\(^{-1}\) and 73\% for gusts exceeding 20 m s\(^{-1}\). With such reliability rates, the bounding interval appears as a useful tool for the determination of daily gusts. Note also that most of the incorrect predictions of gusts can be explained by deficiencies in the simulated meteorological fields. All these results tend to confirm the validity of the assumptions and the physical approach of the WGE method.

Compared to other methods used in weather forecasting, the WGE method is at least as accurate as other approaches even if it does not significantly improve gust estimates in the same operational conditions determined by the limitations of these approaches. For instance, the SR approach generally predicts gusts with the same accuracy as the WGE method, except for severe gusts where the WGE method has proven its superiority with an error on the estimate reduced by a factor 2 for gusts exceeding 25 m s\(^{-1}\). The SL approach has produced predicted gusts with an accuracy similar to that of the WGE method, but the SL method has used observed vertical profiles while the WGE method has considered only model output that does not perfectly reproduce the observations. Compared to all existing methods, the bounding interval computed by the WGE method is an advantage.

Since the WGE method depends essentially on the representation of mean wind and turbulence in the boundary layer, possible improvements of the estimates obtained with this approach are (i) increasing the horizontal resolution in order to allow a better modeling of rapidly deepening systems and mesoscale dynamics that influence the properties of the boundary layer, (ii) refining the vertical resolution to improve the representation of vertical exchanges, and (iii) using a more accurate turbulence parameterization. The last point is not necessarily related to the closure order.

Acknowledgments. I would like to thank Dr. H. Gallée (Institut de Recherches pour le Développement, Grenoble, France), Dr. C. Tricot (Institut Royal Météorologique, Brussels, Belgium), and Professor G. Schayes (Université Catholique de Louvain, Louvain-la-Neuve,
Belgium) for helpful discussions. I thank the department Services Opérationnels et aux Usagers of the Institut Royal Météorologie of Belgium for providing observation data. I am also grateful to the reviewers for their comments and suggestions that have helped to improve this paper. This research is supported by the Fonds National de la Recherche Scientifique in Belgium.

REFERENCES