Estimation of the maximum velocity of convective wind gusts

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Contents

Chapter 1

Introduction

In this report, an investigation into the possibilities for the prediction and detection of convective wind gusts using upper-air sounding data, numerical weather prediction models, and data from weather radars is presented. In the project "Development of a product for detection of severe weather phenomena using non-Doppler radar data" (KNMI project 2301), a tool for the detection and display of severe weather phenomena related to convective systems, like wind gusts and summer hail, is being developed. On the radar-based hail detection product has been reported in detail elsewhere (Holleman, 2001). This study on wind gusts has been limited to algorithms that attempt to estimate the maximum velocity of a convective wind gust. As a result, methods which can only indicate the possibility of a (strong) wind gust based on signatures of the possibility or presence of strong updrafts in upper-air sounding data or weather radar data, respectively, have not been considered.

There may be some overlap between the "Indices voor onweer en convectie" (IOC) and "Gust theorie onderzoek" (GUSTO) projects at KNMI and this project.

1.1 Origin of convective wind gusts

Convective wind gusts are induced by rapidly descending air masses in a thunderstorm or squall line, so-called downdrafts. On impact with the ground the air contained by the downdraft is deflected by the surface and causes the wind gusts. The resulting (strong) wind gusts can cause considerable damage for an aircraft at low-altitude (Fujita and Wakimoto, 1983; Wolfson, 1990). Fujita and Wakimoto (1983) defined a downburst as a strong downdraft which induces an outburst of damaging winds on or near the ground. Two types of downbursts with distinct temporal and spatial scales have been recognized, i.e., microbursts and macrobursts (Fujita and Wakimoto, 1983). A microburst is a small downburst,

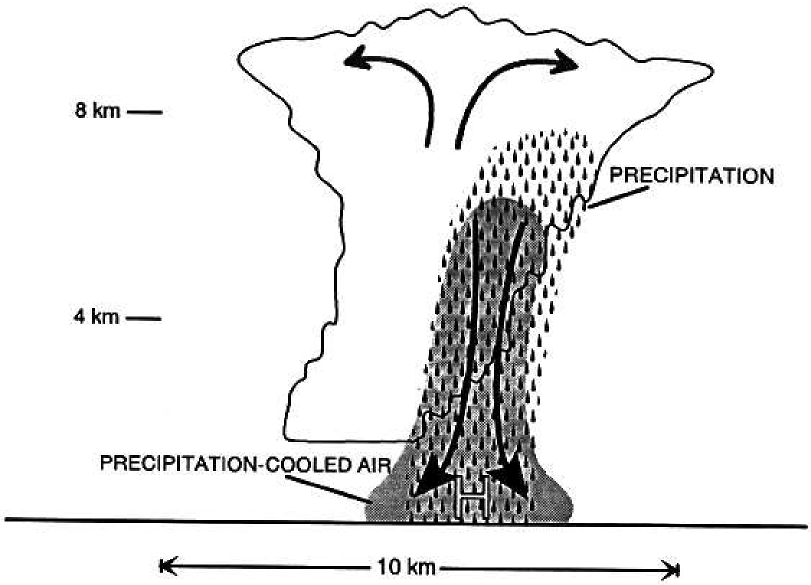

Figure 1.1: Schematic view of the mature stage of a convective cell. The precipitation is indicated by the drops, and the surrounding air which is cooled by evaporation and melting of the precipitation is indicated by the shaded area (figure taken from Doswell (1994)).

less than 4 km in outflow size and with peak winds lasting only 2 to 5 minutes, while a macroburst is larger, with an outflow size of 4 km or larger and with peak winds lasting 5 to 20 minutes. A microburst can generate dangerous tailwinds for aircrafts and limited damage, whilst a macroburst can produce tornado-like damage. The microburst type has been subdivided again into dry and wet microbursts depending on the rainfall intensity indicating that different mechanisms are driving the microburst.

In Figure 1.1 a schematic overview of a mature thunderstorm is given. The falling precipitation and the downdraft region have been indicated. The convective updraft in a cumulus cloud is driven by thermal energy and latent heat release. For the downward return motion within the convection cell, these driving forces are absent when no precipitation is produced. The descending motion has therefore much lower velocity and a larger spatial scale than the convective updraft. The downdrafts in the neighborhood of thunderstorms generally originate from precipitation falling from inclined or horizontally-spreading clouds into dry air of the middle troposhere. The surrounding air cools due to evaporation and melting of this precipitation, and it is accelerated downward by the acquired negative buoyancy (Kamburova and Ludlam, 1966; Emanuel, 1981). The spatial scale of the downdraft, a few kilometers, is determined by that of the falling precipitation, which is coupled to the scale of the updraft region.

The rainfall evaporation in thunderstorm downdrafts has been studied by Kamburova and Ludlam (1966). Their calculations showed that favorable conditions for the production of a strong downdraft are: a temperature lapse rate close to the dry adiabatic from the ground into the middle troposphere, a small droplet size, and a high rainfall intensity. Srivastava (1985) has constructed a simple one-dimensional model for an evaporatively driven downdraft and has applied it to microburst downdrafts. Srivastava has investigated the influences of several parameters, like temperature and raindrop size distribution, on the velocity of the downdraft. He concluded from a comparison with observed microbursts that a majority of those microbursts was evaporatively driven and originated near the cloud base.

Using observations by multiple Doppler radars, upper-air soundings and a three-dimensional numerical cloud model, Knupp (1987) examined the kinematic structure of downdrafts associated with mature precipitating convection. Five types of downdrafts within or near convective clouds are summarized by Knupp. He has investigated in detail the structure of the low-level precipitation-associated downdraft, the only one which systematically reaches the surface. Knupp (1987) concludes that the origin of the downdraft air reaching the surface appears to be the transition level, where the temperature lapse rate changes from roughly dry adiabatic or conditionally unstable to about saturated adiabatic. This is consistent with the observations by others that strong downdrafts can only develop when the environmental lapse rate is close to dry adiabatic (Kamburova and Ludlam, 1966; Srivastava, 1985). Because the cloud base and the transition level will generally be close, the downdraft origin observed by Knupp is in agreement with that observed by Srivastava (1985).

Atkins and Wakimoto (1991) have studied the wet microburst activity over the Southeastern United States. From an analysis of upper-air sounding data, it appears to be possible to distinguish between days with and without wet microbursts using profiles of the equivalent potential temperature. The minimum value of the equivalent potential temperature aloft is more than 20 K lower than that at the surface for days with microbursts, while this temperature difference is less than 13 K for days where no microbursts have been observed. The rationale behind this rule of thumb is that mixing of potentially cold, dry air aloft may enhance the production of negative buoyancy through sublimation, melting, and evaporation.

The idea that (wet) microbursts are strong downdrafts caused by evaporation and melting of precipitation in strong thunderstorms has been disputed by Emanuel (1981). Emanuel argues that the comparatively small scale of downbursts suggests that these are caused by a different dynamical mechanism. Squires (1958) was the first to propose a mechanism for penetrative downdrafts in cumulus clouds. When a parcel of dry air enters the top of a growing cloud, it will be cooled by evaporation of cloud water and descend into the cloud due to negative buoyancy. Using a simple model, Squires showed that air can penetrate several kilometers into a growing cloud in this way. Emanuel (1981) has formulated a similarity theory for unsaturated downdrafts within clouds. He proposes that these penetrative downdrafts are responsible for downbursts and account for their high intensity and small scale. Knupp (1987) states, however, that this type of downdrafts is only common to nonprecipitating convective clouds and upper regions of precipitating convective clouds.

1.2 Outline

In the next chapter the vertical momentum equation including a parameterization for the precipitation loading is presented. Through integration of this one-dimensional equation, a general expression for the maximum velocity in a downdraft is obtained. The maximum velocity of the convective wind gust is assumed to be equal to the maximum downdraft velocity. Furthermore, the three distinct processes driving the downdraft and the importance of the height of the downdraft origin are highlighted.

In chapter 3 an overview of four existing methods for detection or prediction of the maximum wind gusts due to convective downdrafts is given. These methods use data from upper-air soundings, numerical weather prediction models, and/or data from weather radars. The layout of the methods will be compared to that of the integrated vertical momentum equation, and the input data employed by each method will be discussed. Finally, the findings for the methods will be summarized and compared.

The conclusions of the analysis and intercomparison of the wind gust methods are given in the final chapter. The characteristics of a possibly improved method for the estimation of the maximum velocity of convective windgusts are presented. The use of two versions of the same method based on the vertical momentum equation, one for forecasting and one for nowcasting of convective wind gusts, is proposed.

Chapter 2

Vertical momentum equation

Using conservation of momentum and a parametrization for the precipitation loading, the equation describing the vertical motion of an air parcel in a given environment is deduced. Subsequently, this vertical momentum equation is integrated to obtain an equation for the velocity of a downdraft. Finally, the three contributions to the velocity of a downdraft are discussed, and ways to determine them using observation and/or model data are presented.

2.1 Vertical momentum equation

The basic equation for the conservation of momentum of an air parcel is considered for the vertical motion only (Holton, 1992):

$$\frac{dw}{dt} = -\theta \frac{\partial \Pi}{\partial z} - g \tag{2.1}$$

$$\tag{2.2}$$

where the potential temperature (θ) and the Exner function (Π) are defined as follows:

$$\theta \equiv T \cdot \left(\frac{p_0}{p}\right)^{\kappa} \tag{2.3}$$

$$\Pi \equiv c_p \cdot \left(\frac{p}{p_0}\right)^{\kappa} \tag{2.4}$$

$$\kappa = \frac{c_p - c_v}{c_p} \tag{2.5}$$

The constant κ, which is defined in terms of the specific heats at constant pressure (c_p) and at constant volume (c_v), is equal to 2/7 for a diatomic gas. The reference pressure, p_0, is usually 1000 hPa.

The Boussinesq approximation (Holton, 1992), in which each variable is split into a reference state and a (small) time-dependent deviation from this state, is applied:

$$\theta(z,t) \equiv \bar{\theta}(z) + \theta'(z,t) \tag{2.6}$$

$$\Pi(z,t) \equiv \bar{\Pi}(z) + \Pi'(z,t) \tag{2.7}$$

$$\frac{\partial \bar{\Pi}}{\partial z} = -\frac{g}{\bar{\theta}} \tag{2.8}$$

Hydrostatic balance for the reference states (last equation) implies that $w_0 = 0$, and therefore $w = w'(z,t)$. Using the expressions for θ and Π and the assumption that $\theta' \ll \bar{\theta}$ and $\Pi' \ll \bar{\Pi}$, the basic equation for w can be rewritten into:

$$\frac{dw}{dt} = -\bar{\theta}\frac{\partial \Pi'}{\partial z} + g\frac{\theta'}{\bar{\theta}} \tag{2.9}$$

The second term on the right hand side of this equation reflects the buoyancy of the air parcel while the first term is the vertical pressure gradient force on the parcel. The main pressure gradient force is created by the downdraft itself, and it generally opposes the downward motion. This gradient force is often neglected when considering downdrafts and updrafts, because it only has significant effect on the updraft in supercell storms (Doswell, 1994).

The effects of water vapor and precipitation on the basic equation have not been considered yet. The reduction of the density of air due to the presence of water vapor is accounted for by the assignment of a slightly higher temperature to the air parcel. The so-called virtual temperature is defined as:

$$\theta_v \equiv \frac{1 + r_v/\varepsilon}{1 + r_v}\theta \tag{2.10}$$

where r_v is the mixing ratio of water vapor in kg/kg and ε the ratio between the mass of a water molecule and the mean molecular weight of dry air. The effect of precipitation loading on the vertical motion of the air parcel, i.e., downward acceleration due to viscous forces, is parameterized by the term $-gL$, where L is the precipitation mass mixing ratio (kg/kg) (Emanuel, 1981; Wolfson, 1990; Doswell, 1994). The final vertical momentum equation for an air parcel thus becomes:

$$\frac{dw}{dt} = -\bar{\theta}_v\frac{\partial \Pi'}{\partial z} + g\frac{\theta_v'}{\bar{\theta}_v} - gL \tag{2.11}$$

2.2 Integration of momentum equation

The left hand side of the vertical momentum equation, i.e., total vertical acceleration, can be rewritten as:

$$\frac{dw}{dt} \equiv \frac{\partial w}{\partial t} + w\frac{\partial w}{\partial z} \approx w\frac{\partial w}{\partial z} \; = \; \frac{1}{2}\frac{\partial w^2}{\partial z} \tag{2.12}$$

The neglect of the explicit time-derivative of w corresponds to the assumption that the environment of the air parcel is static on the time scale of the downdraft and only depends on the vertical coordinate z. Insertion of this equation in the vertical momentum equation and subsequent integration over the vertical coordinate results in:

$$w^2(z) = w_0^2 + 2g\int_0^z \frac{\theta_v'}{\overline{\theta}_v}dz - 2g\int_0^z L dz \tag{2.13}$$

where the pressure gradient force has been neglected as suggested previously.

In the case of updrafts, the most important term of the integrated vertical momentum equation is the buoyancy term. The positive buoyancy is often estimated from upper-air sounding data or model data by calculation of the Convective Available Potential Energy (CAPE):

$$\text{CAPE} \equiv g\int_{LFC}^{LNB} \frac{\theta_v'}{\overline{\theta}_v}dz \; = \; \frac{w_{max}^2}{2} \tag{2.14}$$

where LFC is the level of free convection and LNB the level of neutral buoyancy. The CAPE is a measure for the maximum realizable updraft given that an air parcel at the surface can reach the level of free convection.

In the case of downdrafts, one is interested in the vertical velocity at the surface (w_0) which is deflected by the surface in horizontal direction. Assuming that the downdraft starts at height H above the surface, the velocity at the surface can be obtained from the integrated vertical momentum equation:

$$w_0^2 = -2g\int_0^H \frac{\theta_v'}{\overline{\theta}_v}dz + 2g\int_0^H L dz + w_H^2 \tag{2.15}$$

where w_H is the velocity at the start of the downdraft. Incorporation of horizontal momentum of the air parcels at high altitudes by the downdraft can be parameterized using w_H. From the preceding consideration of the vertical momentum equation, it appears that three processes contribute to the terminal velocity of a downdraft. These processes are from left-to-right in the righ-hand side of the last equation: (negative) buoyancy due to evaporation or melting of precipitation, precipitation loading, and incorporation of horizontal momentum. The relative importance of these three processes will be discussed later on. Using data from upper-air soundings, numerical weather prediction models, and/or weather radars, the quantities in this formula for the downdraft can be estimated. Finally, the maximum velocity of the convective wind gust is assumed to be equal to the maximum downdraft velocity, which probably holds true for the innermost air parcels of the downdraft/wind gust.

2.3 Estimation of individual parts

Several simplifications can be employed when estimating the magnitudes of the buoyancy and precipitation loading parts in the equation for the maximum velocity of a downdraft. The buoyancy part of the downdraft equation is given by:

$$\text{NAPE} \equiv 2g \int_0^{LFS} \frac{-\theta_v'}{\bar{\theta}_v} dz \tag{2.16}$$

$$\simeq \frac{2g}{\bar{\theta}_v} \int_0^{LFS} -\theta_v' dz \tag{2.17}$$

where NAPE, the Negative Available Potential Energy, is downdraft equivalent of CAPE and LFS is the level of free sink (H, in this study). Because the relative changes of θ_v' are much larger than those of $\bar{\theta}_v$, the potential temperature of the environment $\bar{\theta}_v$ is often assumed to be a constant. The estimation of the NAPE part is not straightforward, and several different methods are conceivable. Firstly, one can take a constant temperature difference between the air parcel and the environment:

$$\text{NAPE} = \frac{-2g\theta_v' H}{\bar{\theta}_v} \tag{2.18}$$

Note that, when the air parcel is colder than the environment ($\theta_v' < 0$), the NAPE part will be accelerating the downdraft.

A second possibility is to assume that the lapse rate of the temperature difference is constant and that the temperature difference at the origin of the downdraft is zero:

$$\theta_v'(z) \equiv (z - H) \cdot \left[\frac{d\theta_v'}{dz}\right] \tag{2.19}$$

$$\text{NAPE} = \frac{gH^2}{\bar{\theta}_v} \left[\frac{d\theta_v'}{dz}\right] \tag{2.20}$$

$$= \frac{-gH\Delta\theta_s}{\bar{\theta}_v} \tag{2.21}$$

where $\Delta\theta_s$ is the temperature difference between the air parcel and the environment at the surface. The NAPE part will be accelerating the downdraft when, at the surface, the air parcel is colder than the environment ($\Delta\theta_s < 0$).

When the potential temperature of the air parcel is constant during the descent and the lapse rate of the potential temperature of the environment is Γ, the lapse rate of the potential temperature difference becomes: $d\theta'_v/dz = -\Gamma$. In this case, the NAPE part becomes:

$$\text{NAPE} = \frac{-g\Gamma H^2}{\bar{\theta}_v} = -N^2H^2 \tag{2.22}$$

where N is the Brünt-Väisälä frequency ($\equiv \sqrt{g\Gamma/\theta_v}$). Note that, when the stratification of the atmosphere is stable ($\Gamma > 0$), the NAPE part will be negative and actually will decelerate the downdraft.

The precipitation loading (LOAD) part can be estimated directly from radar observations of the Vertically Integrated Liquid water (VIL):

$$\begin{aligned} \text{LOAD} &= 2g\int_0^H L dz = \frac{2g}{\rho_0}\int_0^H \rho_0 L dz &(2.23)\\ &\approx \frac{2g}{\rho_0}\int_0^H M dz = \frac{2g}{\rho_0}\text{VIL} = 20.3\text{VIL} &(2.24)\end{aligned}$$

where M is the precipitation loading per unit of volume and ρ_0 the vertically-averaged density of air. This averaged density is approximated by that of the standard atmosphere between 0 and 5 km which is equal to 0.968 kg/m^3. The precipitation loading can also be determined using the rainfall intensity obtained from a numerical weather prediction model or again radar observations:

$$\begin{aligned} \text{LOAD} &\simeq 2gLH = \frac{2gMH}{\rho_0} &(2.25)\\ &= \frac{2gRH}{3600\rho_0 v_f} = 5.63\frac{RH}{v_f} &(2.26)\end{aligned}$$

where v_f is the terminal fall velocity of the rain drops in m/s, R the rainfall intensity in mm/h, and H the height of the downdraft origin in km.

The maximum horizontal momentum that can be incorporated by the downdraft (HMOM= w_H^2) has to be determined directly from upper-air soundings or numerical weather prediction models. Using the preceding definitions the equation for the maximum downdraft velocity simply reads:

$$w_0 = \sqrt{\text{NAPE} + \text{LOAD} + \text{HMOM}} \tag{2.27}$$

From the preceding estimations or definitions of the three parts of this equation, it is evident that they all depend (strongly) on the height of the downdraft origin.

This height, therefore, will be a key parameter for an accurate estimation of the maximum downdraft velocity. An indication of the relative importance of the three different parts can be obtained by a comparison of their typical magnitudes. Using equation 2.18 with $H = 3$ km and $\bar{\theta}_v = 300$ K, a NAPE of 200 m^2/s^2 is obtained with a relatively small temperature deficit of $\theta'_v = -1$ K (Knupp, 1987; Doswell, 1994). For a rainfall intensity of 30 mm/h, a LOAD of 100 m^2/s^2 is found using equation 2.26 with $H = 3$ km and $v_f = 5$ m/s. The wind velocity at an altitude of about 3 km is typically between 10 and 20 m/s (Knupp, 1987; Hand, 2000), and therfore the magnitude of the HMOM part will typically be between 100 and 400 m^2/s^2. It appears that the three parts are comparable in magnitude, and thus they are equally important when estimating the maximum downdraft velocity. In literature several methods have been described which try to estimate the maximum wind gust in convective situations using (parts of) this last equation.

Chapter 3

Existing methods

In this chapter four existing methods for prediction or detection of the maximum velocity related to convective downdrafts will be described. The method of Ivens (1987) is used by operational forecasters at KNMI. The other methods have been taken from literature.

3.1 Method of Ivens

The method of Ivens (1987) is used by the forecasters at KNMI to predict the maximum wind velocity associated with heavy showers or thunderstorms. The method of Ivens is based on two multiple regression equations that were derived using about 120 summertime cases (April to September) between 1980 and 1983. The upper-air data were derived from the soundings at De Bilt, and observations of thunder by synop stations were used as an indicator of the presence of convection. The regression equations for the maximum wind velocity (w_{max}) in m/s according to Ivens (1987) are:
If $T_x - \theta_{w850} < 9$°C:

$$w_{max} = 7.66 + 0.653\,(\theta_{w850} - \theta_{w500}) + 0.976 U_{850} \tag{3.1}$$

If $T_x - \theta_{w850} \geq 9$°C:

$$w_{max} = 8.17 + 0.473\,(\theta_{w850} - \theta_{w500}) + (0.174 U_{850} + 0.057 U_{250}) \cdot \sqrt{T_x - \theta_{w850}} \tag{3.2}$$

where T_x is the maximum day-time temperature at 2 m in K, θ_{wxxx} the potential wet-bulb temperature at xxx hPa in K, and U_{xxx} the wind velocity at xxx hPa in m/s. The amount of negative buoyancy, which is estimated in these equations by the difference of the potential wet-bulb temperature at 850 and at 500 hPa, and horizontal wind velocities at one or two fixed altitudes are used to estimate the maximum wind velocity. The effect of precipitation loading is not taken into account by the method of Ivens. Although the method of Ivens has been designed for sounding data and summertime situations only, forecasters at KNMI apply the method throughout the year and on profiles from numerical weather prediction models as well. Currently, the method of Ivens is being optimized for this more general use within the framework of the GUSTO project.

3.2 Method of Wolfson

Using the Boussinesq form of the vertical momentum equation, Wolfson (1990) concluded that the square of the downdraft velocity is proportional to the product of a forcing and the downdraft depth. The forcing consists of two parts: a buoyancy term (NAPE) and a precipitation loading term (LOAD). From calculations by Srivastava (1985) of the temperature excess of descending air parcels, Wolfson (1990) concludes that the buoyancy forcing is proportional to the square of the temperature lapse rate of the environment. In addition, Wolfson has incorporated the observation by Knupp (1987) that the downdraft depth is related to the transition level in an upper-air sounding. The transition level is defined as the height where the lapse rate changes from roughly dry adiabatic or conditionally unstable to approximately saturated adiabatic (Knupp, 1987). By comparison of numerical modelling studies to the expected dependencies, a quantitative equation for the maximum downdraft velocity has been developed by Wolfson (1990):

$$w_{max}^2 = (7.3\Gamma^2 - 480 + 9.75LD) \cdot \frac{H_{tr}}{3.3} \tag{3.3}$$

where Γ is the mean temperature lapse rate from surface to freezing level in K/km, L is the precipitation mixing ratio in g/kg, D is the depth of the precipitation core in km, and H_{tr} is the transition level of the sounding in km. The product LD can be estimated from radar observations of VIL (see equation 2.23). The incorporation of horizontal momentum by the downdraft (HMOM part) is not taken into account by this method. Wolfson has applied this equation in the investigation of a microburst-related airplane crash.

Based on the method of Wolfson, McCann (1994) has developed a new index for forecasting of microburst potential (WINDEX) which can easily be computed from upper-air sounding data only:

$$w_{max}^2 = 6H_m R_q(\Gamma^2 - 30 + Q_l - 2Q_m) \tag{3.4}$$

In this equation H_m is the height of the melting level in km, $R_q = Q_l/12$ but not larger than 1, and Q_l (Q_m) is the mixing ratio in the lowest 1 km (at the melting level). Using the hourly observations of moisture at the surface and assuming that they represent Q_l, McCann (1994) has studied several microburst cases using hourly "surface-based WINDEX analyses".

3.3 Method of Stewart

Based on the work of Morton et al. (1956), Emanuel (1981) has developed a set of equations to describe the dynamics of unsaturated downdrafts within clouds. Stewart (1991) has rewritten the equation for the maximum downdraft velocity to fit to parameters observed by weather radar. The maximum wind gust in m/s according to Stewart is given by (Stewart, 1991, 1996):

$$w_{max}^2 = -3.1 \times 10^{-6} \cdot \mathrm{ET}^2 + 20.6\mathrm{VIL} \tag{3.5}$$

where VIL is the Vertically Integrated Liquid water in kg/m^2 and ET is the EchoTop height determined by radar in m. The final maximum wind gust is obtained by adding one-third of the mean horizontal wind speed in the lowest 5000 feet of the atmosphere to the result of this equation (Stewart, 1991). To obtain this equation for the maximum wind gust, Stewart has rewritten the NAPE part using the equations of Emanuel (1981) as follows:

$$\mathrm{NAPE} = -\frac{N^2}{16} \cdot \mathrm{ET}^2 = -3.1 \times 10^{-6} \cdot \mathrm{ET}^2 \tag{3.6}$$

where N is the Brünt-Väisälä frequency. Note that when ET is replaced by $4H$ this equation for NAPE transforms to one obtained previously (equation 2.22). In his equation for the maximum wind gust, Stewart has used a fixed value for Brünt-Väisälä frequency of $N = 0.007$ Hz. The method of Stewart uses a NAPE that is always negative, and therefore it is actually decelerating the downdraft. Cases where the downdraft is predominantly generated by negative buoyancy will, therefore, not be represented properly by this method.

The method of Stewart has been validated by performing several case studies and by verification using about 100 predicted and/or observed events of severe wind gusts (>25 m/s) (Stewart, 1991, 1992, 1996). In addition, several reports on the use of this method by others have been published (Cummine, 1995; Amorim et al., 1999).

3.4 Nimrod algorithm

The UK Met Office operates a fully automated system for weather analysis and nowcasting called Nimrod. The Nimrod system is based around the network of

C-band rainfall radars of the UK Met Office. The Nimrod system produces (predictions of) rainfall rate, rain accumulation, precipitation type, snow probability, cloudiness, visibility, and wind gust speeds. The operational Nimrod wind gust algorithm consists of two independent parts: one for gusts originating from convective downdrafts and one for gusts originating from boundary layer shear (Hand, 2000). The algorithm for the wind gusts related to convective downdrafts has been developed by Nakamura et al. (1996). Using conservation of energy arguments, Nakamura et al. (1996) obtain the same equation for the maximum velocity of the downdraft as deduced previously (see equation 2.27). The NAPE and LOAD parts of the equation are estimated by taking a constant lapse rate of the potential temperature difference (see equation 2.21) and a constant precipitation mixing ratio (see equation 2.26), respectively. The formula for the maximum wind gust obtained by Nakamura et al. (1996) is:

$$w_{max}^2 = g\frac{\Delta T_s}{\bar{T}}H + 2gLH + w_H^2 \tag{3.7}$$

where ΔT_s is the surface cooling by the downdraft and $\bar{T}$ the environmental temperature averaged over depth H. The surface cooling by the downdraft is calculated using the wet-bulb temperature at height H and a saturated adiabat to calculate the corresponding wet-bulb temperature of the descending air parcel at the surface (Hand, 2000). In the operational version of the Nimrod algorithm, it is assumed that the downdraft originates from the height within a certain layer (0-5 km) where the wet-bulb temperature is lowest.

Hand (2000) has carried out an analysis of the components compromising the operational Nimrod convective wind gust algorithm on six days comprising over 16,000 diagnoses of wind gusts and a variety of synoptic types in all seasons. It was found that in most cases the downdrafts in Nimrod originated near 5 km height, because the wet-bulb temperature usually decreases with height. The use of the freezing level height of the wet-bulb temperature as the downdraft origin is recommended.

3.5 Summary

In this chapter a review has been given of existing algorithms for quantatively predicting or detecting wind gusts associated with convective phenomena. Using the integrated vertical momentum equation, it has been shown that all methods are rather similar. Different approximations have been used, however, to estimate the three parts that contribute to the downdraft strength and the height of the downdraft origin.

All methods except that of Stewart use temperature and moisture profiles from upper-air soundings or numerical weather prediction models to approximate the negative buoyancy (NAPE) part. Stewart (1991) uses echotops determined by radar and a fixed stratification of the atmosphere to estimate the buoyancy. The buoyancy is always decelerating the downdraft according to Stewart, which is in contrast with the other methods where the NAPE part, depending on the actual situation, can also accelerate the downdraft.

The precipitation loading (LOAD) is not taken into account by the method of Ivens (1987). All other methods use either radar reflectivity data or the predicted rainfall intensity or liquid water content to estimate the LOAD part. The contribution of the incorporation of horizontal momentum aloft by the downdraft (HMOM=w_H^2) is explicitly taken into account by the Nimrod algorithm, while this contribution is not considered by the methods of Wolfson (1990) and Stewart (1991). The method of Ivens incorporates horizontal momentum only at one or two fixed heights, i.e., 850 and 250 hPa.

In the evaluation report of the Nimrod convective wind gust algorithm, Hand (2000) presents an extensive investigation into the sensitivity of the wind gust estimation on the choice of the downdraft origin. The height of the downdraft origin is determined from the predicted or observed temperature profile by the method of Wolfson and the Nimrod algorithm. In the method of Stewart the downdraft origin is correlated with the height of the radar echotops, and Ivens (1987) has implicitly assumed 850 hPa to be the origin of the downdraft, irrespective of the actual situation.

Finally, it appears that radar reflectivity data is only of limited use for the prediction or detection of convective wind gusts. It should be stressed, however, that apart from the estimation of the precipitation loading part, radar reflectivity data can be utilized for the detection of convective phenomena in the first place. Wind gust methods which are not employing any radar data, like that of Ivens or one of the others without any radar data, can only provide a conditional statement, i.e., when and where convection occurs a certain maximum wind gust will be possible. The forecast span of methods relying on radar data is, however, limited to the life time of a convective system, which is typically on the order of an hour.

Chapter 4

Conclusions and Outlook

For forecasting of the maximum velocity of convective wind gusts one or two days ahead, a method based solely on data from a numerical weather prediction model is required. Observational data from upper-air soundings can be used to predict the strength of convective wind gusts several hours ahead. Within the framework of the GUSTO project, the statistical method of Ivens for the prediction of the maximum wind velocity in squalls, which has been developed using upper-air sounding data only, is being retuned for the use on numerical weather prediction data as well. For nowcasting of convective phenomena, a tool providing an indication of the location, time, and maximum magnitude of a convective wind gust instead of just a conditional statement could be useful. A method which uses apart from temperature, moisture, and wind profiles also radar reflectivity data could provide such an indication.

When using the integrated vertical momentum equation for obtaining the maximum velocity of convective wind gusts, an accurate estimation of both the negative buoyancy part and the height of the downdraft origin is rather difficult. The height of the downdraft origin is a key parameter, because all parts of the integrated vertical momentum equation depend on it. Depending on the method, the downdraft origin is taken to be the cloud base, the melting level, the transition level, or the radar echotop. A choice for the melting level of the wet-bulb temperature or the transition level seems physically most reasonable (Knupp, 1987; Hand, 2000). The echotops as determined by radar can be used to detect where and when the convection is strong enough to form precipitation at or above the estimated downdraft origin. Several different ways to approximate the negative buoyancy part employed by the wind gust methods have been detailed previously. When the height of the downdraft origin is given, the negative buoyancy part can be calculated by integrating the difference between the temperature of the descending air parcel and that of the environment. The temperature lapse rate of the descending air parcel is close to saturated adiabatic when the evaporation rate of the precipitation is high enough to stay close to saturation during the descent. The Vertically Integrated Liquid water (VIL) determined by radar can be used to estimate the precipitation loading, but only the part from the surface up to the downdraft origin is relevant in this case. Finally, only a certain fraction of the horizontal momentum aloft can probably be incorporated by the downdraft.

In conclusion, a method for estimation of the maximum velocity of convective wind gusts which is based on the integrated vertical momentum equation and includes accurate estimates of all three driving parts and the downdraft origin is preferred. The Nimrod algorithm (Hand, 2000), possibly completed with the modifications proposed above, can potentially be the basis of such a method. Such a method allows for use as a forecasting tool when only data from a numerical weather prediction model is used as input, and it can be used as a nowcasting tool when upper-air sounding data and radar reflectivity data are used as input. The forecasting version of the method will be comparable to the statistical method of Ivens, but will have a more profound physical algorithm. The nowcasting version of the method will provide a new tool for operational use.

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