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PARAMETERIZING CONVECTIVE VERTICAL MOTIONS for AIRCRAFT ICING FORECASTS

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1. INTRODUCTION

Cloud liquid water (CLW) needed for significant aircraft icing develops in upward vertical motions in a saturated atmosphere. A substantial percentage, if not a majority, of the upward motions in the atmosphere are convective. Unfortunately, numerical forecast models do not resolve convective motions unless their resolutions are very high, and the CLW from operational numerical models has never been successfully used in icing forecasts.

However, the environmental conditions leading to convective motions are often well resolved in coarser resolution models. These conditions are embodied in a three-ingredient method for forecasting convection outlined by Doswell et al. (1996) and long-used by human forecasters. The ingredients are a potentially unstable atmosphere, a parcel with a level of free convection (LFC), and a process that lifts the parcel to its LFC.

While this method is most often used for thunderstorm forecasting, it also applies to weaker convection and even to some non-convective vertical motions such as a stratocumulus-topped boundary layer. These conditions are often associated with significant aircraft icing (Minser 1938; Pobanz et al. 1994; and Hauf and Sxchröder 2005). This paper examines some simple cloud physics equations to show why knowledge of convective motions is fundamental to icing forecasts. Then it offers a parameterization strategy that may be applied to numerical forecast model output. VVICE is an algorithm that uses this strategy and the simple cloud physics equations to estimate the CLW potential in the atmosphere. VVICE combines the estimated CLW with the model temperature into an icing intensity metric which, when verified with pilot reports, shows comparable skill with other icing algorithms, but gives a forecast with significant differences.

2. WHY CONVECTIION?

When air rises, it cools because the pressure decreases on the air parcel. When the parcel is saturated, some of the cooling goes into condensing some of the parcel’s water vapor. The condensation rate can be derived from the governing pseudo-adiabatic equation (Rauber and Tokay 1991):

$$\frac{dq}{dt} = \left[\left(\Gamma_m - \Gamma_d \right) \frac{c_p}{L_v} - \frac{g r_v}{R_d T} \right] \rho w \qquad (1)$$

where q is the cloud liquid water, Γ_m and Γ_d are the moist and dry adiabatic lapse rates, respectively, c_p is the specific heat of dry air at constant pressure, L_v is the latent heat of vaporization, g is the acceleration of gravity, r_v is the water vapor mixing ratio, R_d is the gas constant for dry air, T is the air temperature, ρ is the air density, and w is the parcel upward vertical velocity.

If equation (1) is integrated over time, then

$$q = q_0 + \rho \left(\frac{c_p \left[\Gamma_d - \Gamma_m \right]}{L_w} + \frac{g r_w}{R_d T} \right) dz \qquad (2)$$

where q_0 is the CLW entering a control volume from below and dz is the depth of the control volume through which the parcel moves. Although in (1) the faster the vertical velocity, the faster the CLW is generated, only the temperature and the heights of and above the cloud base matter.

The generated CLW starts out as small droplets, but the droplets will eventually grow larger by collision-coalescence. Srivastava (1967) gives a simple equation describing this process, and when integrated over a similar time as in (1)

$$D = D_0 + \frac{\rho q V_D}{2 \rho_w} \frac{dz}{w} \qquad (3)$$

where D is the final droplet diameter, D_0 is the initial droplet diameter, V_D is the terminal fall speed of the droplet, and ρ_w is the density of water. From (3) the faster the upward vertical velocity, the *slower* the droplet diameter grows,

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and if the terminal fall speed is greater than the upward air speed, then the droplet falls out of the parcel as liquid precipitation. Thus, the CLW tends to grow faster in high updraft speeds because more of it can be carried aloft.

Furthermore, CLW may be 50% or greater than the mean in patches because of convection (Jameson and Kostinski 2000). The turbulence in convective updrafts tends to concentrate cloud droplets in the high strain regions of the turbulent eddies (Shaw et al. 1998). If an aircraft encounters one of these high CLW patches, it could experience a greater performance loss than otherwise would be forecast.

3. A Convective Vertical Motion Parameterization

For convection to happen, three ingredients are necessary in the atmosphere (Doswell et al. 1996). 1) The environmental lapse rate must be conditionally unstable, i.e., lower than the moist adiabatic lapse rate. 2) The parcel's initial temperature and moisture content must be high enough to have a level of free convection (LFC). 3) There also must be a mechanism that will lift the parcel to its LFC.

When lifting a parcel along the appropriate dry and moist adiabats, if it becomes warmer than its environment, the parcel will accelerate upward by buoyant forces until it becomes cooler than its environment again at the equilibrium level (EL). The amount of buoyant acceleration at any level is proportional to the temperature difference between the lifted parcel and the environment. Since one can compute the parcel acceleration, one knows the updraft velocity (w) at any level. In fact, the integrated value of the buoyant potential energy between the LFC and the EL is the Convective Available Potential Energy (CAPE) and is equal to $w^2_{max}/2$, where w_{max} is the maximum updraft velocity.

The parameterization for convective vertical velocity is similar to the VVSTORM algorithm (McCann 1999). At every model grid point determine the most unstable parcel by finding the level with the highest equivalent potential temperature. Then examine the model information for potential lifting mechanisms at that level. These include two-dimensional frontogenesis (Keyser et al. 1988), Eckman-layer lifting (Haltiner and Williams 1980), and the model's own forecast vertical motion.

The vertical velocity from these methods is usually not sufficient lift for parcels to reach their LFC. Rogers and Fritsch (1996) provide a framework for convective triggers in numerical models. Following McCann (1999), the next step is to inflate the maximum vertical velocity diagnostic from any of the three methods by a function of the model resolution and its height above ground:

$$w = w_m \frac{\delta x}{L}\left(1 - \frac{z_{agl}}{H}\right) \qquad (4)$$

where w is parameterized lifting velocity, w_m is the maximum vertical velocity diagnostic, δx is the model grid spacing, L = 1 km is the grid spacing needed to explicitly resolve the vertical motion (Ziegler et al. 1997), z_{agl} is the height above ground, and H = 3000 m. The inflation factor decreases with higher grid resolution and the higher above ground.

Next, lift the parcel upward, layer-by-layer, accounting for parcel accelerations due to parcel/environment temperature differences. One can even account for parcel accelerations due to horizontal temperature gradients (McCann 1999). Thus, potential convective velocities are computed on every level at every grid point in the model.

4. Applying the Parameterized Convective Velocity

VVICE is the algorithm that applies the parameterized convective velocity to the icing problem. It computes the condensed CLW from (2) in layers above the parcel lifting condensation level (LCL). Note that a parcel need only be above its LCL and moving upward for CLW to be generated. Often, a parcel may reach its LCL but not its LFC which is typical in stratocumulus. Similarly, a saturated parcel may have a non-buoyant upward velocity which is typically forced in a large-scale storm.

As CLW is generated, cloud droplets grow as a result of collision-coalescence. VVICE estimates the mean droplet size from (3). Then it reduces the CLW by an amount that is a function of the ratio of the mean droplet size fall speed and the parameterized upward velocity assuming a gamma droplet size distribution. In other words, some CLW, the percentage of which in droplets smaller than the mean is carried upward to become q_0 at the next level above and some is lost as falling precipitation. With small w much of the CLW becomes precipitation, while with large w much of the CLW stays suspended, i.e. large CLW occurs mainly with fast updrafts.

VVICE further diminishes the CLW by a homogeneous ice-generating process (Rasmussen et al. 2002) and by a deposition process (Koenig 1971). In the latter, the amount of ice falling into a layer from above is dependent on the ratio of the terminal fall speed of ice to the updraft velocity similar to the liquid precipitation method above.

Since terminal fall speeds of most snowflakes and raindrops < 500 µm diameter are less than 2 m s^{-1} (Byers 1965), an updraft does not have to be strong to create substantial CLW. Experience with VVICE suggests that there is often sufficient numerical model information to forecast convective updrafts as low as 1-2 m s^{-1}. VVICE even forecasts non-convective updrafts this large in stratocumulus events.

The difficulty of any CLW forecast is in its interpretation. In identical environments there are vast differences between one aircraft's response to the accumulating ice and another's. McCann (2004) showed that one can easily compute an airfoil's performance loss due to icing given the environmental CLW and temperature and certain information about the airfoil. McCann suggested that the aircraft performance loss (APL) of a Beechcraft King Air aircraft after a five minute icing exposure is a useful metric to describe an icing hazard. Figure 1 shows a sample output.

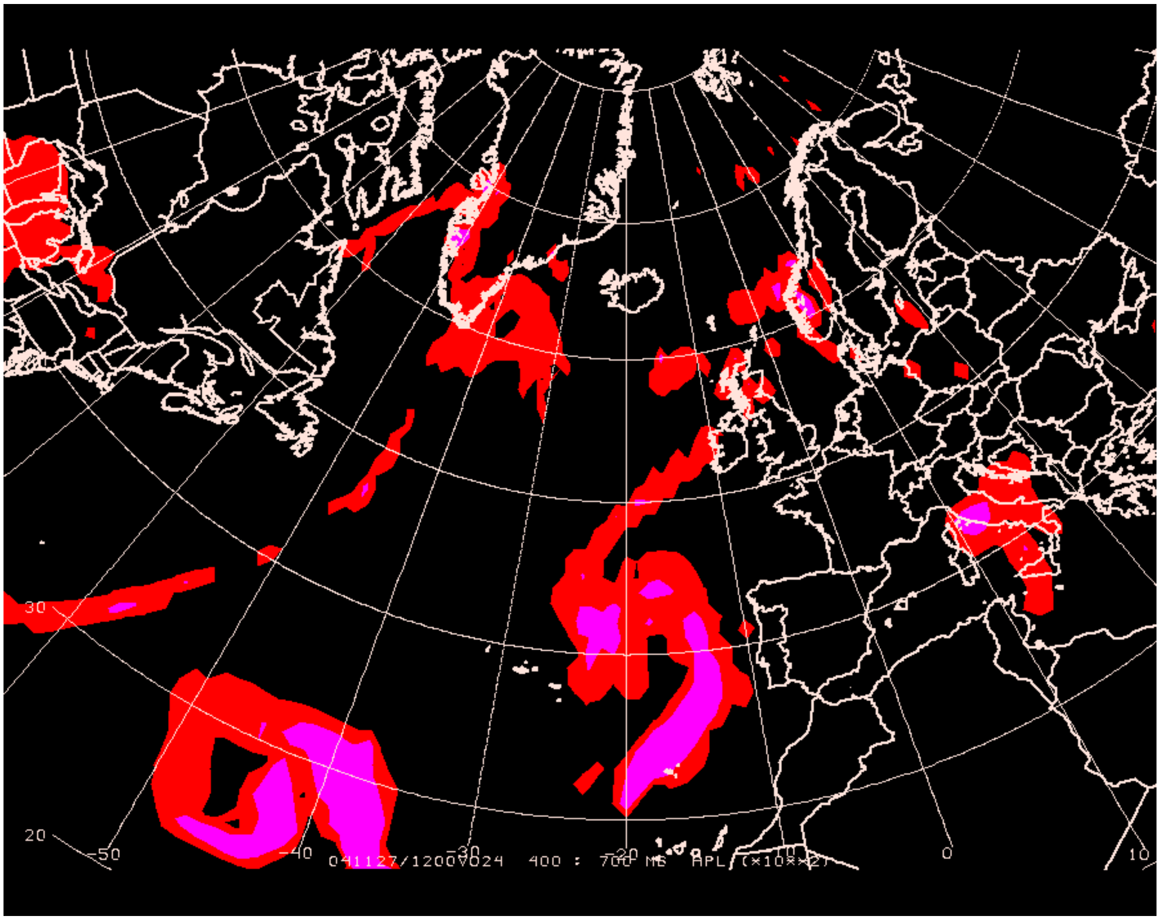

Figure 1. VVICE forecast of the maximum aircraft icing in the layer from 700 mb to 400 mb (FL100 to FL240) from the 24-hour Global Forecast System numerical model verifying at 1200 UTC, 27 November 2004, over the north Atlantic Ocean region. The red areas are greater than 10% percent power increase (PPI), a measure of the aircraft performance loss in icing (see text) and the magenta areas are greater than 60% PPI in five minutes.

Because the PPI values are a measure of how quickly the aircraft performance deteriorates, they can be related to the subjective icing intensity definitions. In Fig. 1, the red areas (10% PPI) are nominally moderate icing, and the magenta areas (60% PPI) are severe. These values are based on interviews with experienced pilots. The areas with PPI > 60% are frequently areas of forecasted thunderstorms which are known to have severe icing conditions within them. However, convective updrafts may be strong enough to create layers on severe icing, but not enough for lightning, and VVICE highlights those areas.

5. Verification Results

Table 1 shows a verification of VVICE with pilot reports with other “standard” icing forecast algorithms based primarily on forecast temperature and relative humidity. Its skill is comparable with the other icing algorithms, and it reduces the overforecast bias for moderate and greater icing that these other algorithms have.

Most small aircraft fly below 10,000 feet and so the verification statistics reflect the algorithms’ skill in lower levels. When only the pilot reports above 10,000 feet are verified, VVICE shows a significant skill difference. There VVICE’s skill does not drop off compared with its temperature/humidity cousins. Convection is a more significant cause of icing in these higher layers because the deep updrafts can create higher CLWs and scavenging ice is minimal because it cannot fall into the higher speed updrafts.

The astute reader will notice that the threshold that best verifies VVICE for moderate icing is 1 PPI rather than the 10% shown in Fig. 1. Ideally, the pilot reports should determine the PPI values that relate to the subjective intensities, however, the reports’ ambiguity have caused forecasters to overforecast the moderate or greater icing (Kelsch and Warton 1996). The algorithms that have been developed for icing guidance also overforecast because they have been tuned to maximize skill of forecasting the pilot reports (McCann 2005).

6. Conclusions

Knowing where convective updrafts may occur is useful information to icing forecasters. Because convection can occur in layers of low relative humidity, VVICE likely will find some significant icing that will be missed by the other algorithms, although this has yet to be documented.

VVICE finds atmospheric layers in which convection may occur by applying Doswell’s et al. 1996 three ingredient forecast method to numerical forecast model output. The parameterization presented outlines not only how to do it, but also quantifies the potential convective updrafts Using these updraft speeds, VVICE applies some simple cloud physics equations to compute the potential cloud liquid water. If the temperature is less than 0C, VVICE estimates the percent power increase needed for a popular small aircraft to maintain level flight and constant speed after five minutes exposure in the forecasted environment.

REFERENCES

Byers, H.R., 1965: *Elements of Cloud Physics*, University of Chicago Press, 191 pp.

Doswell, C.A. III, H.E. Brooks, and R.A. Maddox, 1996: Flash flood forecasting: An ingredients-based methodology. *Wea. Forecasting*, **11**, 560-581.

Haltiner, G.J. and R.T. Williams, 1980: *Numerical Prediction and Dynamic Meteorology*, John Wiley and Sons, 317 pp.

Hauf, T. and F. Schröder, 2005.: Aircraft icing research flights in embedded convection. *Meteorology and Atmospheric Physics.* Springer-Verlag, Published online.

Jameson, A.R. and A.B. Kostinski, 2000: The effect of stochastic cloud structure on the icing process. *J. Atmos. Sci.*, **57**, 2883-2891.

Kelsch, M. and L. Warton, 1996: Comparing PIREPs with NAWAU turbulence and icing forecasts: Issues and results. *Wea. Forecasting*, **11**, 385-390.

Keyser, D., M.J. Reeder, and R.J. Reed, 1988: A generalization of Petterssen’s frontogenesis function and its relation to the forcing of vertical motion. *Mon. Wea. Rev.*, **116**, 762-780.

Koenig, L.R., 1971: Numerical modeling of ice deposition, *J. Atmos. Sci.*, **28**, 226-237.

McCann, D.W., 1999: VVSTORM - Convection diagnosed from numerical models. *Proc. 8th Conf. on Aviation, Range, and Aerospace Meteorology*, Dallas TX, Amer. Meteor. Soc., 240-243.

________, 1999: Comments on “Evaluation and application of conditional symmetric instability, equivalent potential vorticity, and frontogenetic forcing in an operational environment.” *Wea. Forecasting*, **14**, 470-472.

________, 2004: Large versus small droplet icing. *Proc. 11th Conf. on Aviation, Range, and Aerospace Meteorology*, Hyannis MA, Amer. Meteor. Soc., paper 8.5.

________, 2005: NNICE: A neural network aircraft icing algorithm. *Env. Modeling and Software*, **20**, 1335-1342.

Minser, E.J., 1938: Studies of synoptic free-air conditions for icing of aircraft. *Bull. Amer. Meteor. Soc.*, **19**, 111-122.

Pobanz, B., J. Marwitz, and M. Politovich, 1994: Conditions associated with large-drop regions. *J. Appl. Meteor.*, **33**, 1366-1372.

Rasmussen, R.M., I. Geresdi, G. Thompson, K. Manning, and E. Karplus, 2002: Freezing drizzle formation in stably stratified layer clouds: The role of radiative cooling of cloud droplets, cloud condensation nuclei, and ice initiation. *J. Atmos. Sci.*, **59**, 837-860.

Rauber, R.M. and A. Tokay, 1991: An explanation for the existence of supercooled water at the top of cold clouds. *J. Atmos. Sci.*, **48**, 1005-1023.

Rogers, R.F. and J.M. Fritsch, 1996: A general framework for convective trigger functions. *Mon. Wea. Rev.*, **124**, 2438-2452.

Shaw, R.A., W.C. Reade, L.R. Collins, and J. Verlinde, 1998: Preferential concentration of cloud droplets by turbulence: Effects on the early evolution of cumulus cloud droplet spectra. *J. Atmos. Sci.*, **55**, 1965-1976.

Thompson G, R.T. Bruintjes, B.G. Brown, and F. Hage, 1997: Intercomparison of in-flight icing algorithms. Part I: Real-time icing prediction and evaluation program. *Wea. Forecasting*, **12**, 878-889.

Table 1. Verification of three icing algorithms at the thresholds given computed on the one-hour forecast from the 1500 UTC Rapid Update Cycle with icing pilot reports within one hour of 1600 UTC each for the period 1 November 2002 to 31 March 2003. Thompson et al. (1997) describes the RAPICE algorithm and McCann (2005) describes the NNICE algorithm. PODyes is the probability of detection of pilot reports greater than the threshold. PODno is the probability of detection of pilot reports less than the threshold. HSS is the Heidke Skill Score. Bias is the ratio of pilot reports forecast positive to pilot reports forecast negative.

	PODyes	PODno	HSS	Bias
ALL ICING				
RAPICE	.618	.909	.554	.780
NNICE = 2	.861	.818	.654	1.179
VVICE = 0.1 PPI	.487	.947	.476	.579
MODERATE OR GREATER ICING				
RAPICE	.604	.753	.188	2.992
NNICE = 4	.536	.792	.195	2.525
VVICE = 1 PPI	.450	.845	.209	1.931
ALL ICING ABOVE 10,000 FEET				
RAPICE	.708	.644	.287	.812
NNICE = 1.5	.925	.383	.289	.985
VVICE = 0.1 PPI	.554	.930	.410	.591
MODERATE OR GREATER ICING ABOVE 10,000 FEET				
RAPICE	.520	.655	.160	.777
NNICE = 4	.470	.599	.067	1.222
VVICE = 1 PPI	.476	.749	.214	1.161