# VVICE
## Scientific Description

**Background**

To many pilots aircraft icing is one of the most dangerous inflight hazards. If allowed to accumulate, ice will reduce aircraft performance by increasing drag and/or decreasing lift. Engineering studies on the icing hazard have identified many variables that influence how supercooled water accumulates as ice on aircraft surfaces. Listed below, the interaction between these variables is very complex. The most important is exposure time. Even a little ice will not disappear by itself and may act as a base for further accumulation. Therefore, a pilot must respond to any ice accumulation.

Aerodynamic and meteorological variables affecting aircraft ice accumulation:

- Body shape
- Exposure time
- Droplet size distribution
- Chord length
- Angle of attack
- Flight speed
- Liquid water content
- Air temperature

Because of the number of variables, the system for forecasting and reporting an icing hazard was developed with broad categorical terminology. Each term’s definition is a specific rate of accumulation which does not account for exposure time. Even a slow ice accumulation will eventually cause a dangerous situation (McCann 2004). Because the total ice accumulation truly determines the aircraft performance loss, it would seem that the definitions are inadequate. However, the icing intensity definitions imply that a pilot will respond to any ice buildup. Therefore, they tell the pilot how quickly he/she must react to the accumulation. Unfortunately, icing assessments are often erroneously based on an aggregated performance loss, or, worse yet, visual clues unrelated to aircraft performance. Pilots are not very sure of what the definitions really mean (Collins 1999).

Icing intensity definitions

Trace – Ice becomes perceptible. Rate of accumulation is slightly greater than rate of sublimation. Not hazardous even if no deicing/anti-icing equipment is used, unless encountered for an extended period of time – over one hour.

Light – Rate of accumulation may create a problem if flight is prolonged in this environment (over one hour). Occasional use of deicing/anti-icing equipment removes/prevents accumulation.

Moderate – Rate of accumulation is sufficient that even short encounters become potentially hazardous and use of deicing/anti-icing equipment or diversion is necessary.

Severe – Rate of accumulation is so great the deicing/anti-icing equipment fails to reduce or control the hazard. Immediate diversion is necessary

The confusion about icing reporting has also prejudiced the way icing is forecast. Forecasters rely on pilot reports for “ground truth,” yet 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).

VVICE is an icing algorithm that incorporates only the physical mechanisms outlined above, not relying on pilot report verification. There are two parts to VVICE. 1) The meteorological part computes cloud liquid water (CLW). Since CLW is primarily generated by saturated, upward-moving air, it is important to have knowledge of vertical motions, including convective motions. 2) The aircraft performance part computes an estimated performance loss which is based on the percent power increase (PPI) necessary to maintain speed and altitude after a five minute ice encounter.

## The VVICE algorithm

### *a. Cloud liquid water generation*

Cloud liquid water is generated in air parcels that are cooler than the dew point temperature. There are many processes that may cause a parcel's temperature to lower to below its dew point, however by far the most common is upward vertical motion. When a parcel moves upward, it cools because it expands as it encounters lower pressure. If the parcel moves upward far enough, its temperature cools enough to equal its dew point. Further cooling begins condensation of the water vapor.

Vertical velocity is forced by many atmospheric processes, and a prominent one is convection. For convection to happen, three ingredients are necessary in the atmosphere. 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). The magnitude of the united effects of a conditionally unstable lapse rate and a parcel with an LFC are nicely combined in a diagnostic called Convective Available Potential Energy (CAPE). One computes CAPE by lifting a parcel along the appropriate dry and moist adiabats. If, by lifting, it becomes warmer than its environment, the parcel reaches its LFC. Then the parcel will accelerate upward by buoyant forces until it becomes cooler than its environment again. That level is called 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 a potential storm. In fact, the integrated value of the buoyant potential energy between the LFC and the EL is the CAPE and is equal to $w^2_{max}/2$, where $w_{max}$ is the maximum updraft velocity. 3) There also must be a mechanism that will lift the parcel to its LFC.

Similar to the VVSTORM algorithm (McCann 1999), at every model grid point VVICE first determines the most unstable parcel by finding the level with the highest equivalent potential temperature. Then it examines the model information for potential lifting mechanisms at that level. These include two-dimensional frontogenesis, Eckman-layer lifting, and the model's own forecast vertical motion. The diagnosed upward motion is inflated by a function of the model resolution and its height above ground. VVICE follows the lifted parcel upward, layer-by-layer, to see if it reaches its lifting condensation level (LCL) and its LFC. In layers above the parcel's LCL, it computes the condensed CLW from the thermodynamic equation (Rauber and Tokay 1991).

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

where $q$ is the CLW in the layer, $q_0$ is the CLW carried upward from the layer below, $dz$ is the layer thickness, $\rho$ is the layer air density, $c_p$ is the specific heat at constant pressure, $\Gamma_d$ and $\Gamma_m$ are the dry and moist adiabatic lapse rates, $L_w$ is the latent heat of condensation, $g$ is the acceleration of gravity, $r_w$ is the mixing ratio, $R_d$ is the gas constant for dry air, and $T$ is the layer temperature. The second and third terms compute the CLW generated in the layer from upward motion. 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 droplet size (Srivastava 1969)

$$\frac{dD}{dt} = \frac{\rho q V_D}{2\rho_w}$$

where $D$ is the droplet diameter, $V_D$ is the terminal velocity of the droplets, and $\rho_w$ is the density of water. Then it reduces the CLW by an amount that is a function of the ratio of the droplet size fall velocity and the computed upward velocity. In other words, some CLW is carried upward ($q_0$), 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.

CLW may also change into ice depending on its temperature (homogeneous nucleation) (Rasmussen et. al 2002)

$$q_i = 0.005 m_i \exp[0.304(-T)]$$

where $q_i$ is the cloud ice, $m_i$ is the mass of one ice crystal, and $T$ is the temperature in degrees Celsius. A substantial amount of CLW may be converted to ice when the temperature is very low.

Ice falling into the layer from above may also reduce CLW by deposition, the process of ice growing because the vapor pressure over ice is lower than over water. Koenig (1971) provides formulae for deposition which depend on the layer temperature; the maximum deposition rate occurs at -15C. The amount of ice falling into a layer from above is dependent on the ratio of the terminal velocity of ice to the updraft velocity similar to the liquid precipitation method above.

### *b. Aircraft performance loss*

When CLW is diagnosed below 0C, VVICE computes a quantitative aircraft performance loss metric (percent power increase [PPI] needed after a five minute ice exposure to maintain speed and altitude) from the temperature and CLW based on an aerodynamic analysis of the expected ice accumulation on a standard airfoil moving at 90 m $s^{-1}$ (McCann 2004). Figure 1 shows one case from his study.

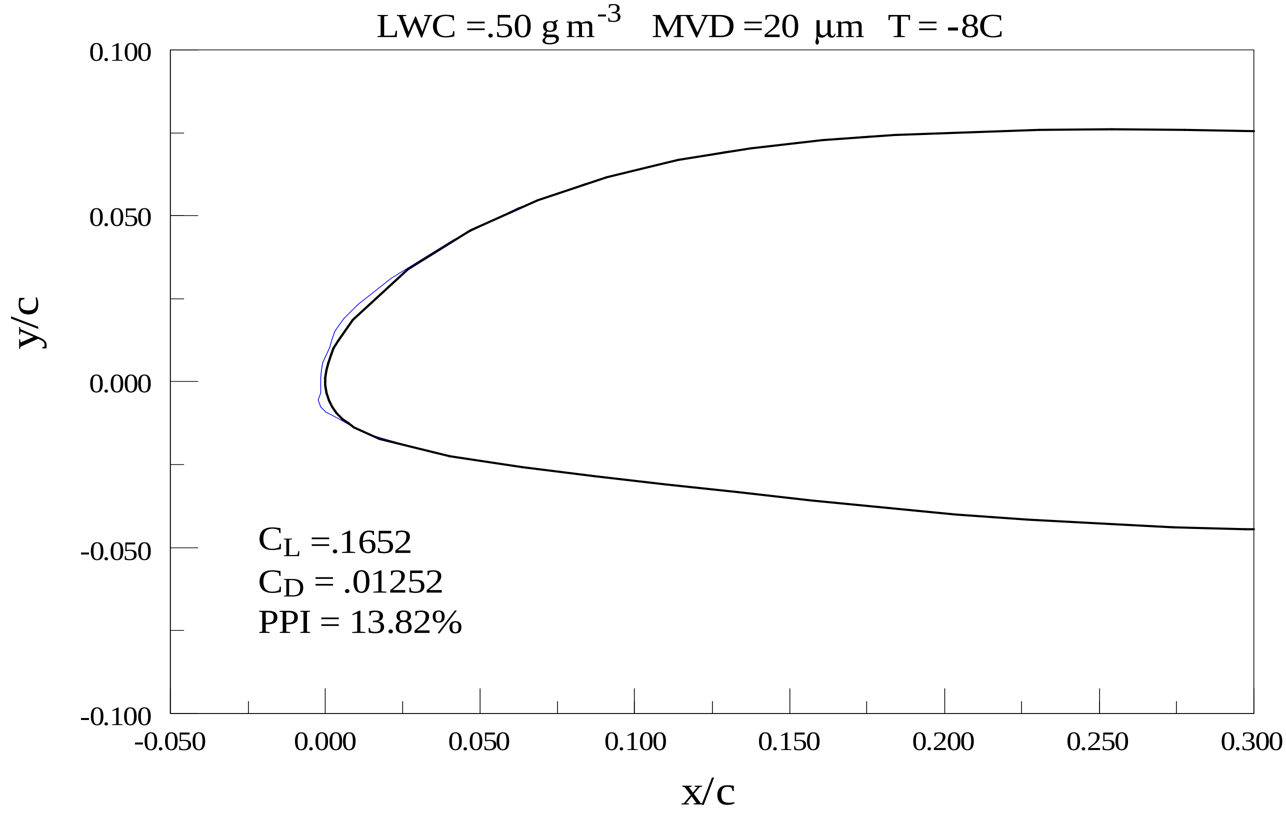

**Figure 1. The chord cross section of a five minute ice accumulation (blue) on a 1.5 m NACA 23012 airfoil moving at 90 m $s^{-1}$ with meteorological conditions noted at the top. The axes are labeled as a fraction of chord length from the leading edge. $C_L$ is the resultant coefficient of lift. $C_D$ is the resultant coefficient of drag. The accumulated ice results in a 13.82% power increase (PPI) needed to maintain speed and altitude. See McCann (2004) for details.**

## Operational Interpretation

VVICE outputs grids of PPI at all model levels. In addition, it outputs grids of cloud liquid water and cloud ice. The PPI display best shows the location, altitudes, and intensity of icing. With the temporal resolution of a numerical model, VVICE output gives guidance forecasts for icing at specific times for as far out as a numerical model can forecast. Figure 2 shows an example of a VVICE forecast.

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. 2, 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.  Ideally, the pilot reports should determine the PPI values that relate to the subjective intensities, however, as stated above, they are not reliable enough to make any statistical inferences at this time.

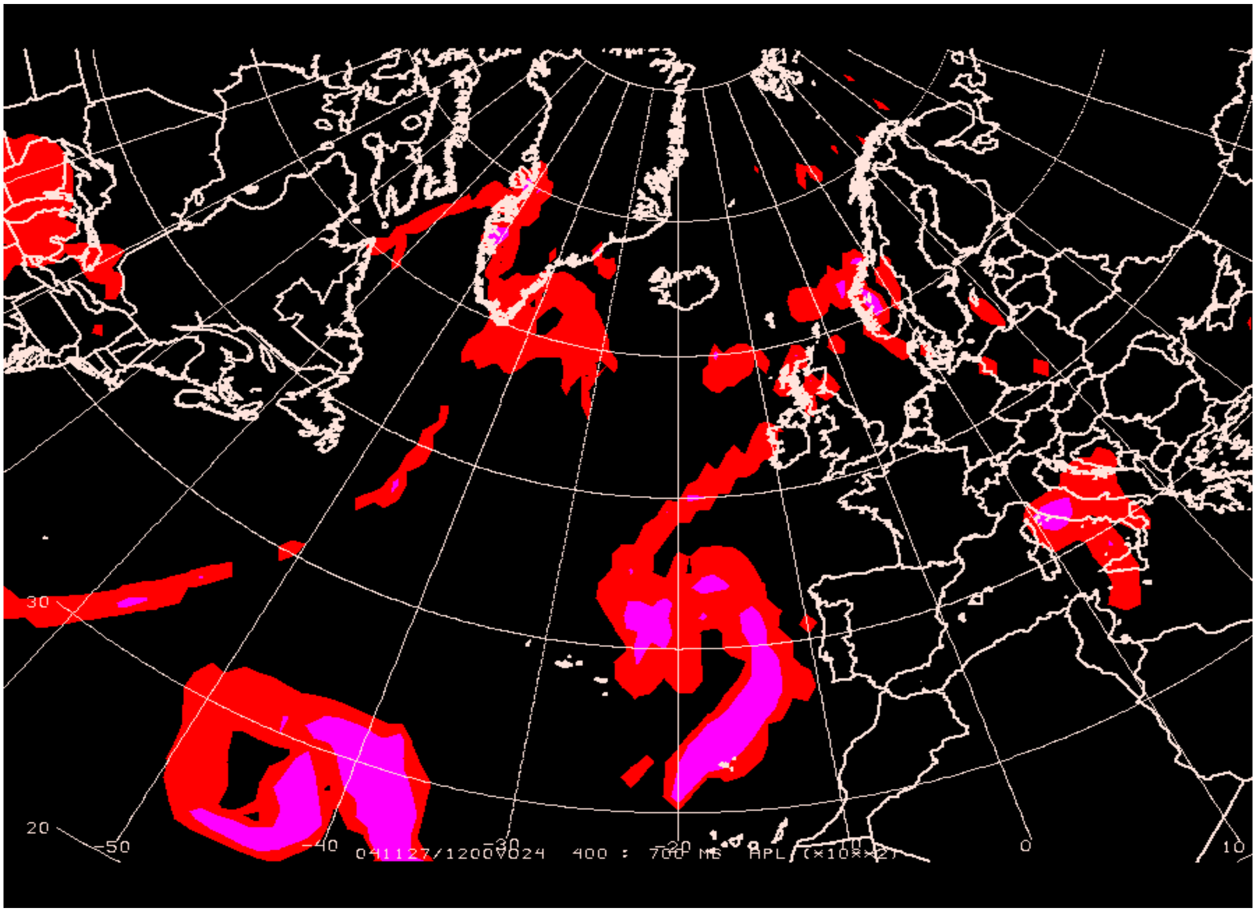

**Figure 2. VVICE forecast of the maximum aircraft icing in the layer from 700 mb to 400 mb (FL100 to FL240) from the 24-hour Global Forecast System numerical model verifying at 1200 UTC, 27 November 2004, over the north Atlantic Ocean region. The red areas are greater than 10% percent performance loss (PPI) and the magenta areas are greater than 60% PPI.**

Table 1 shows a verification of VVICE with pilot reports with other “standard” icing forecast algorithms. 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.

Table 1. Verification of three icing algorithms computed on the one-hour forecast from the 1500 UTC Rapid Update Cycle with 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.

| ALL ICING | PODyes | PODno | HSS | Bias |
|---|---|---|---|---|
| RAPICE | .618 | .909 | .554 | .780 |
| NNICE = 2 | .861 | .818 | .654 | 1.179 |
| VVICE = .001 | .487 | .947 | .476 | .579 |
| MODERATE OR GREATER ICING | | | | |
| RAPICE | .604 | .753 | .188 | 2.992 |
| NNICE = 4 | .536 | .792 | .195 | 2.525 |
| VVICE = .01 | .450 | .845 | .209 | 1.931 |

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