



AFWA Diagnostics in WRF

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1. Overview

The Air Force Weather Agency (AFWA) has made available to the Weather Research and Forecasting (WRF) model a suite of diagnostics used in its operational Mesoscale Ensemble Prediction Suite (MEPS). The suite was first included in WRF version 3.6. The release of WRF version 3.6.1 comes with new diagnostics and improvements to existing ones, as well as the ability to output them in GRIB-1 format.

This work was largely motivated by a desire to reduce the I/O burden of running a post-processor. By implementing the massively parallel architecture already present within WRF, tailored diagnostics can be generated directly from the model at a fraction of the I/O cost and computational overhead. The concept of inline diagnostics within WRF is gaining traction, and a new diagnostics driver has been created to consolidate the various diagnostics floating around WRF. This work is ongoing, but the hope is that other users will be able to add their own diagnostics in a similar manner.

Some users may find that there are variables already available within AFWA's suite of diagnostics that they wish to output from WRF. This document provides guidelines for proper use of AFWA diagnostics (Section 2) and an overview of some of the variables it outputs (Section 3).

2. How to Use

a. Diagnostics options

To turn on AFWA diagnostics, a new namelist section will need to be added to **namelist.input**. An example is below:

```
&afwa
  afwa_diag_opt           = 0, 1,
  afwa_ptype_opt         = 0, 1,
  afwa_vil_opt           = 0, 1,
  afwa_radar_opt         = 0, 1,
  afwa_severe_opt        = 0, 1,
  afwa_icing_opt         = 0, 1,
  afwa_vis_opt           = 0, 1,
  afwa_cloud_opt         = 0, 1,
  afwa_therm_opt         = 0, 1,
  afwa_turb_opt          = 0, 1,
  afwa_buoy_opt          = 0, 1,
  afwa_hailcast_opt      = 0,
  afwa_ptype_ccn_tmp     = 268. 15,
  afwa_ptype_tot_melt    = 25,
/
```

The key variable here is **afwa_diag_opt**. It must be set to **1** for each domain to enable AFWA diagnostics for that domain. In the above example, a mother domain and a nest are running and we only want to run diagnostics on the nest.

The AFWA diagnostics suite is comprised of a number of packages that group like variables together in an attempt to limit the amount of unnecessary "extra" variables (e.g. for those who want *only* precipitation type variables or everything *but* turbulence and visibility). To turn on one of these packages, simply set its namelist option to **1** for the desired domain(s). WRFv3.6.1 comes with the following diagnostics packages and associated options (Section 3 will discuss these packages in more depth):

- Precipitation type - **afwa_ptype_opt** = 1
 - CCN temperature - **afwa_ptype_ccn_tmp** = <CCN temperature in Kelvin>
 - Total melting energy - **afwa_ptype_tot_melt** = <melting energy in J/kg>
- Severe weather - **afwa_severe_opt** = 1
 - Hailcast 1-D hail model - **afwa_hailcast_opt** = 1
- Vertically integrated liquid - **afwa_vil_opt** = 1
- Radar - **afwa_radar_opt** = 1
- Icing - **afwa_icing_opt** = 1
- Visibility - **afwa_vis_opt** = 1
- Cloud - **afwa_cloud_opt** = 1
- Thermal index - **afwa_therm_opt** = 1
- Turbulence - **afwa_turb_opt** = 1
- Buoyancy - **afwa_buoy_opt** = 1

b. *Timing controls*

Most diagnostics only need to be calculated on output time steps since they are merely snapshots of the current modeled environment. Calculating them in between time steps would be wasteful. However, one benefit of running inline diagnostics is the ability to gather useful information about rapidly evolving fields between output times, such as means, maximums, and minimums. These need to be calculated every time step, which means extra compute cost.

The diagnostics driver is called every time step, but because of the desire to save cost where possible, the “snapshot” variables are only calculated on output times. Two output streams control when these instantaneous variables are calculated: the main **history** stream and the **auxhist2** stream. Specifically, **history_interval** and **auxhist2_interval** are used to control the output frequency. The **auxhist2** stream allows the user to output diagnostics at a higher frequency than the **history** stream, which is outputting much more information and therefore has larger file sizes and takes longer to write. This can come into use with variables such as radar, for example.

Variables that need to be calculated every time step, such as means, maxes, and minimums, are reset after the **history** output time step. Currently, there is no similar reset for **auxhist2**, thus any mean, maximum, or minimum variable output on this stream will still be with respect to **history_interval**, and not **auxhist2_interval**. In practice, the **&time_control** might include something like this:

```

history_interval           = 0, 180,
io_form_auxhist2         = 5,
auxhist2_outname         = "radar_d<domain>. <date>. grb",
auxhist2_interval       = 0, 15,
frames_per_auxhist2     = 1, 1,

```

The **history_interval** and **auxhist2_interval** value of **0** for the mother domain indicates that we do not wish to output this domain at all. For the nest, the **auxhist2** stream will output any requested AFWA diagnostics to GRIB files called “radar_d<domain>.<date>.grb” every 15 minutes, while every 180 minutes the **history** stream will output any AFWA diagnostics and reset any means, maximums, and minimums. (For users desiring output in NetCDF, use **io_form_auxhist2** = 2).

c. Combining with other diagnostics

Some users may wish to combine AFWA diagnostics with some of the other diagnostics packages available in WRF. The pressure level diagnostics package is currently controlled by a separate namelist section. One could turn it on with the following:

```
&diags
  plev_diags           = 1,
  num_press_levels    = 5,
  press_levels        = 100000, 85000, 70000, 50000, 20000,
  use_tot_or_hyd_p    = 2,
  extrap_below_grnd   = 2,
  plev_mising         = 1e10,
```

It contains many other useful variables on pressure levels, but it outputs to a different I/O stream than the AFWA diagnostics, **auxhist23**. It may be desirable to combine AFWA diagnostics and pressure level diagnostics into the same file. To do this, one can either edit the Registry to add the desired stream for each variable (this requires a recompile), or take advantage of the real-time I/O stream feature available in WRF. For example, in the **&time_control** section of **namelist.input** one could have something like this

```
history_interval      = 86400, 60,
io_form_auxhist23    = 5,
auxhist23_outname     = "diagnostics_d<domain>. <date>. grb"
auxhist23_interval   = 86400, 60,
frames_per_auxhist23 = 1, 1,
iofiles_filename     = "var_list_d01.txt", "var_list_d02.txt",
ignore_iofiles_warning = .true.
```

Note that **auxhist23_interval** must be equal to **history_interval** (or **auxhist2_interval**) for the AFWA and pressure-level diagnostics to be called simultaneously. Here it is set to the same as **history_interval**. The **iofiles_filename** field tells the model to look for a file where we will be editing the I/O stream. For example, in the file called **var_list_d02.txt**, add the desired AFWA diagnostics to the **auxhist23** stream:

```
+ : h: 23: AFWA_CLOUD, AFWA_CLOUD_CEIL, AFWA_MSLP
```

Similarly, one can remove these variables from the **history** stream:

```
- : h: 0: AFWA_CLOUD, AFWA_CLOUD_CEIL, AFWA_MSLP
```

3. Description of Diagnostics

Many of the algorithms described herein were designed to provide probabilistic information to MEPS. This means that in order to use these variables appropriately more information is required about the cumulative distribution function (CDF) to which they contribute. Other variables are more straightforward in their application (such as CAPE, CIN, MSLP, and precipitable water) and can be taken at face value. Next, we describe how to use the Weibull distribution to create probabilistic information from an otherwise deterministic forecast; later, we expound upon the various packages outlined in Section 2a.

a. Weibull algorithm description

There are many environmental impacts due to weather that are caused by phenomena that are not explicitly resolved in numerical models. Despite this lack of resolution, information that exists in the model can be used to make a reasonable estimate about the occurrence of the unresolved phenomena. That information can be passed to interested users, but it comes with a degree of uncertainty due to the lack of explicit resolution.

It follows that if uncertainty exists, estimating the uncertainty could be very beneficial for decision making using risk management principles. The Weibull distribution allows for a relatively simple and flexible estimation of uncertainty that can be applied in a variety of ways to decision making. To model this uncertainty, the following three-variable Weibull distribution is chosen as a cumulative distribution function (CDF):

$$\text{CDF}(X) = 1 - e^{-\left(\frac{X-X_0}{\beta}\right)^\alpha} \quad (1)$$

This CDF determines the probability for a value to be less than or equal to any threshold X . The three key variables are X_0 which is a constant that determines where the distribution begins on the X -axis, α which determines where the bulk of the distribution lies, and β which determines the shape of the distribution. Usually, both X_0 and α will be held constant for each variable being predicted but may differ between variables; only β will change from grid point to grid point within a model run. This allows one output variable to describe the uncertainty, yet still enables flexibility in post-processing applications due to the relative ease in which a probability can be determined for any threshold X in Eqn. (1).

There are a number of useful things to know about the Weibull distribution. A value of $\alpha = 3.6$ is a close approximation to a Gaussian distribution and is used for some of algorithms in this document. The probability of the variable X being greater than the value of $\beta + X_0$ will always be approximately 37% regardless of the choice of α . Values of $\alpha < 1$ indicate variables that would be thought of as “rare” events, meaning that even though resolved model data may be indicating such an event is possible, its probability will still remain low. The following sections will note the values of α , β , and X_0 used in any MEPS algorithm designed to provide probabilistic information.

b. Default diagnostics (*afwa_diag_opt=1*)

As of version 3.6.1, there are two variables that come “free” when turning on AFWA diagnostics as they are used for multiple diagnostics package and currently are not associated with any one of them; they are as follows.

i. **AFWA_PWAT – Precipitable water (kg m^{-2})**

This is a utility variable that is used in the severe weather and visibility packages. It is the integration of water vapor in the column from the first eta level to the model top.

ii. **WSPD10MAX – Maximum 10 meter wind speed (m s^{-1})**

This is the maximum sustained model wind speed over the output interval (**history_interval**). This variable used to reside in the severe package, but has been moved outside to allow access to users running lower resolution simulations that do not require severe diagnostics but could otherwise benefit from maximum sustained winds.

WSPD1OMAX is used to parameterize surface wind gust using the Weibull distribution described in Eqn. (1). Over land, the following algorithm was developed for a surface wind gust estimate:

$$\alpha = 3.0 \quad (2)$$

$$\beta = X_0^{0.75} \quad (3)$$

$$X_0 = \mathbf{WSPD1OMAX} \quad (4)$$

The 0.75 in the exponent of Eqn. (3) causes a slow decrease in the gust factor as it gets larger, which approximates the observations found in Davis and Newstein (1968). Over water, the Weibull parameters are modified to take into account reduced vertical mixing due to roughness and heating:

$$\alpha = 1.0 \quad (5)$$

$$\beta = 1.25 \quad (6)$$

$$X_0 = \mathbf{WSPD1OMAX} \quad (7)$$

c. Severe weather diagnostics (*afwa_severe_opt=1*)

When turned on, the severe weather diagnostics package is called at every time step due to the rapidly evolving nature of severe weather, and outputs primarily maximum, or worst-case, fields between **hi story** output times. *Please note that this package was designed for a grid spacing of 4 km or less and is not recommended for coarser domains.* The following variables are calculated in the severe weather package; where applicable, the corresponding Weibull parameters also will be noted.

i. **W_UP_MAX** – Maximum updraft velocity (m s⁻¹)

This is a straightforward diagnostic of the maximum positive vertical velocity from the first model level to 400 hPa between **hi story** output times.

ii. **W_DN_MAX** – Maximum downdraft velocity (m s⁻¹)

This is like **W_UP_MAX**, but for minimum negative vertical velocity.

iii. **AFWA_HAIL** – Maximum hail diameter (mm)

The following algorithm is run at each time step to determine hail size potential. Model vertical velocity is employed to estimate how large of a hailstone could be supported by the updraft. Mid-level relative humidity is used to determine if dry air entrainment will lead to size sorting, enabling larger particles to get into the main updraft where hail growth can occur. A melting term reduces hail size based on how warm it is near the surface. Then, updraft helicity is used to estimate the tendency for the storm to be long-duration to allow hail size growth.

$$\text{Updraft} = (\text{Vertical Velocity [m s}^{-1}\text{]} / 1.4) 1.25 \quad (8)$$

$$\text{MidRH} = 3.5 \text{ km AGL RH [\%]} - 70; \text{ min of } 0 \quad (9)$$

$$\text{Melt} = 2 \text{ meter temperature [K]} - 288.15; \text{ min of } 0 \quad (10)$$

$$\text{Duration} = (2\text{-}5 \text{ km updraft helicity [m}^2 \text{ s}^{-2}\text{]} / 100) + 0.25 \quad (11)$$

$$\text{Hail [mm]} = (\text{Updraft} - \text{Melt} - \text{MidRH}) \times \text{Duration} \quad (12)$$

Finally, **AFWA_HAIL** is the maximum of Eqn. (12) between **hi story** output times. The Weibull parameters for the probability of maximum hail diameter less than or equal to X in Eqn. (1) are:

$$\alpha = 1.5 \quad (13)$$

$$\beta = 0.9 \times \mathbf{AFWA_HAIL} \quad (14)$$

$$X_0 = \mathbf{AFWA_HAIL} - \beta \quad (15)$$

iv. TCOLI_MAX – Maximum total column integrated ice (kg m⁻²)

One of two components to AFWA’s lightning algorithm, this is the maximum over the output interval (**history_interval**) of the summation of cloud ice, snow, and graupel over the total model column.

v. GRPL_FLX_MAX – Maximum graupel flux at -15 °C (g kg⁻¹ m s⁻¹)

The second component of AFWA’s lightning algorithm, this is the maximum over the output interval (**history_interval**) of graupel mixing ratio multiplied by vertical velocity at the -15°C level. Values of **GRPL_FLX_MAX** should range from around 25 in marginal lightning situations, to over 400 in situations with very frequent lightning.

Based on work by McCaul et al. (2009), for a 4 km domain outputting **TCOLI_MAX** and **GRPL_FLX_MAX** every hour, the probability of number of lightning strikes less than or equal to a threshold X per 16 sq. km per hour can be determined using the following Weibull curve parameters in Eqn. (1):

$$\alpha = 0.8 \quad (16)$$

$$\beta = (\text{GRPL_FLX_MAX} / 10.0) + (\text{TCOLI_MAX} - 7.0) / 10.0; \text{ Max of } 0.95 \quad (17)$$

$$X_0 = 0 \quad (18)$$

vi. LLWS_MAX – Maximum low-level wind shear (m s⁻¹)

This is the maximum value over the output interval (**history_interval**) of 0-2000 ft shear. Surface winds are taken from the **U10** and **V10** parameters that come from the various surface schemes available in WRF.

vii. AFWA_TORNADO – Maximum tornado wind speed (m s⁻¹)

This algorithm attempts to estimate the distribution of likely tornado wind speeds with a given storm. It is run at each time step in the model, but it is scaled linearly based on duration until 5 minutes have passed. An updraft helicity term is included to ensure a parent supercell is seen in the model. Low level buoyancy is used to estimate the likelihood of an occlusion downdraft that is warm and able to be ingested back into the updraft. Low level shear and mid-level RH are used due to their empirical correlation to tornado occurrence and intensity.

$$\text{Supercell} = (2\text{-}5 \text{ km updraft helicity [m}^2 \text{ s}^{-2}\text{]} - 25) / 50; (\text{min of } 0, \text{ max of } 1) \quad (19)$$

$$\text{LLbuoy} = (3000 - \text{LFC [m]}) / 1500; (\text{min of } 0, \text{ max of } 1) \quad (20)$$

$$\text{LLshear} = (0\text{-}2000 \text{ meter wind shear [m s}^{-1}\text{]} - 2) / 10; (\text{min of } 0, \text{ max of } 1) \quad (21)$$

$$\text{MidRH} = (90 - 3.5 \text{ km AGL RH [\%]}) / 30; (\text{min of } 0, \text{ max of } 1) \quad (22)$$

$$\text{Tornado [m s}^{-1}\text{]} = 50 \times \text{Supercell} \times \text{LLbuoy} \times \text{LLshear} \times \text{MidRH} \quad (23)$$

Finally, **AFWA_TORNADO** is the maximum of Eqn. (23) between **history** output times with a linear increase over the first five minutes that Tornado is greater than zero. The Weibull parameters for the probability of maximum tornado winds less than or equal to X in Eqn. (1) are:

$$\alpha = 1.0 \quad (24)$$

$$\beta = 0.5 \times \text{AFWA_TORNADO} \quad (25)$$

$$X_0 = \text{AFWA_TORNADO} - \beta \quad (26)$$

Given the low α value, the probability of exceedance for any threshold will be low, representing the uncertainty of getting a tornado to form in the first place.

d. *HAILCAST 1-d hail model (afwa_hailcast_opt=1, afwa_severe_opt=1)*

The release of WRFv3.6.1 includes an explicit 1-dimensional hailstone model called HAILCAST within the AFWA diagnostics suite (Adams-Selin, 2012).^{*} It is designed for use within high resolution simulations, in which updrafts are well resolved, to estimate maximum hail stone diameter. Currently, HAILCAST is wrapped within the severe weather package (**afwa_severe_opt**) as a separate option (**afwa_hailcast_opt**) because it can be rather expensive, especially in highly convective domains. *Please note that both of these options must be turned on to run HAILCAST.*

At every time step the HAILCAST hailstone driver is run for five initial hail embryo sizes varying from 10-50 μm in diameter at every point where an updraft has exceeded a minimum threshold of 10 m s^{-1} for over 15 minutes. The embryos are propagated explicitly by the updraft and undergo wet and dry growth, breakup, fallout, and melting. Finally, the mean and standard deviation of the maximum diameter of the five embryos between **history** output times is output from the model.

i. **AFWA_HAIL_NEWMEAN – HAILCAST hail diameter mean (mm)**

This is the mean of the maximum hail diameters from each of the five hail embryos after they have run through the HAILCAST model.

ii. **AFWA_HAIL_NEWSTD – HAILCAST hail diameter standard deviation (mm)**

This is the standard deviation of the maximum hail diameters from each of the five hail embryos after they have run through the HAILCAST model.

e. *Precipitation type diagnostics (afwa_ptype_opt=1)*

The precipitation type algorithm is calculated every model time step and is determined empirically, independent from the microphysics scheme. Its inputs include:

- CCN temperature (when cloud droplets will nucleate)
 - Determined by the **afwa_ptype_ccn_conc** namelist option (default value of 264.15 K)
 - Recommended range between 263.15 and 268.15 K
- Energy required to melt snow to rain
 - Determined by the **afwa_ptype_tot_melt** namelist option (default value of 50 J kg^{-1})
 - Recommended range between 10 and 50 J kg^{-1}
- Model total precipitation
- Model temperature and relative humidity vertical profiles
- Model incoming shortwave radiation

The algorithm itself is as follows:

1. Modify the 2 meter temperature (K) by adding the shortwave radiation (W m^{-2}) divided by 100.
2. If the modified 2 meter temperature is greater than 275.15 K, set type to rain.
3. Check the vertical profile to find highest cloud temperature (RH greater than 80%). If a cloud is found, but below it a dry (RH less than 70%) layer is found, reset and keep checking.
4. If the cloud top temperature is colder than **afwa_ptype_ccn_conc**, set type to snow. Otherwise, set to rain.
5. Check the vertical profile that the rain or snow is falling through.
 - a. If snow or ice pellets falls through a melting layer, integrate total melting energy.
 - b. If the integrated energy is higher than **afwa_ptype_tot_melt**, then set type to rain.

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- c. If the integrated energy is between 25-100% of **afwa_ptype_tot_melt**, and it subsequently falls through a sub-freezing layer, assume it partially melted and then re-froze into an ice pellet. Reset melting energy to zero.
- d. If as rain falls it encounters a temperature colder than **afwa_ptype_ccn_conc**, set type to ice pellets.
- e. Keep running these checks all the way to the ground and adjust types accordingly
- f. Once it gets to the ground, rain becomes freezing rain if the modified 2 meter temperature is less than 273.15.

All precipitation variables can be used as is, or they can provide further probabilistic information by substituting the following Weibull curve characteristics into Eqn. (1), using **AFWA_RAIN** as an example:

$$\alpha = 3.6 \quad (27)$$

$$\beta = 0.4 \times \text{AFWA_RAIN} \quad (28)$$

$$X_0 = \text{AFWA_RAIN} - \beta \quad (29)$$

The following variables are output by the precipitation type package.

i. AFWA_TOTPRECIP – Total simulation precipitation accumulation (mm)

This is the accumulation of precipitation from the convection and microphysics schemes (**RAINC** + **RAINNC**) over the entire simulation up to the current output time.

ii. AFWA_RAIN – Total simulation rain accumulation (mm)

This is the accumulation of rain over the entire simulation up to the current output time.

iii. AFWA_SNOW – Total simulation liquid equivalent snow accumulation (mm)

This is the accumulation of liquid equivalent snow over the entire simulation up to the current output time.

iv. AFWA_SNOWFALL – Total simulation snow accumulation (mm)

This is the accumulation of snowfall over the entire simulation up to the current output time. The algorithm estimates snowfall amounts based on density ratios that vary according to surface temperature in the following manner:

$$\text{Ratio} = (278.15 - \text{model 2-meter temperature [K]})^{0.4} \quad (30)$$

v. AFWA_ICE – Total simulation ice pellet accumulation (mm)

This is the accumulation of ice pellets over the entire simulation up to the current output time.

vi. AFWA_FZRA – Total simulation freezing rain accumulation (mm)

This is the accumulation of rain over the entire simulation up to the current output time.

f. Buoyancy diagnostics (afwa_buoy_opt=1)

The buoyancy diagnostics package provides some useful information that can be derived from the modeled atmospheric profile. In WRFv3.6 the buoyancy algorithm was calculated within the severe weather package at every time step, which proved to be too expensive for AFWA requirements. Also, these parameters are useful for coarser resolution simulations where the severe package is not able to produce meaningful information. Therefore, in WRFv3.6.1 it has been separated from the severe package and only runs on output time steps. The package runs a buoyancy routine for two parcels, a

surface-based and a most unstable. The routine lifts each parcel adiabatically up the model sounding and explicitly calculates buoyancy at each level. The following variables are output from the buoyancy package.

i. AFWA_CAPE – Surface-based CAPE (J kg^{-1})

This is the convective available potential energy (CAPE) of a parcel originating from the lowest model level.

ii. AFWA_CIN – Surface-based CIN (J kg^{-1})

This is the convective inhibition (CIN) of a parcel originating from the lowest model level.

iii. AFWA_CAPE_MU – Most unstable convective available potential energy (J kg^{-1})

This is the convective available potential energy (CAPE) of a parcel originating from the most unstable model level in the lowest 180 hPa using a stability criterion of highest mixing ratio.

iv. AFWA_CIN_MU – Most unstable convective inhibition (J kg^{-1})

This is the convective inhibition (CIN) of a parcel originating from the most unstable model level in the lowest 180 hPa using a stability criterion of highest mixing ratio.

v. AFWA_ZLFC – Surface-based LFC height (m)

This is the height of the level of free convection (LFC) of a surface-based parcel where buoyancy first becomes positive above the lifted condensation level (LCL).

vi. AFWA_PLFC – Surface-based LFC pressure (Pa)

This is the pressure of the level of free convection (LFC) of a surface-based parcel where buoyancy first becomes positive above the lifted condensation level (LCL).

vii. AFWA_LIDX – Surface-based lifted index (K)

This is the lifted index (LI) calculated as the simple difference between a surface-based parcel and ambient virtual temperature at 500 hPa. *Please note that a standardizing value of 273.15 K is added to **AFWA_LIDX** to accommodate AFWA post-processing requirements and should be subtracted to retrieve the correct LI.*

g. Thermal diagnostics (*afwa_therm_opt=1*)

The thermal diagnostics package calculates a handful of thermal indices that take into account other atmospheric parameters like moisture and wind to convey a sense of *perceived* thermal conditions. The package is only calculated at output time steps and outputs the following variables.

i. AFWA_HEATIDX – Heat index (K)

Heat index combines air temperature and relative humidity in an attempt to determine the *apparent temperature* perceived by a human body. The method approximates that used by the NOAA National Weather Service.

ii. AFWA_WCHILL – Wind chill (K)

Wind chill attempts to determine the apparent decrease in temperature perceived by a human body due to the flow of air over exposed skin. The only inputs to this diagnostic are wind and air temperature.

iii. **AFWA_FITS – Fighter index of thermal stress (K)**

The fighter index of thermal stress (FITS) gives guidance for hot-weather USAF operations. It is based on work by Stribley and Nunnely (1978) and is calculated as:

$$\text{FITS} = 0.8281 \times \text{Wet bulb temperature } [^{\circ}\text{C}] + 0.3549 \times \text{Dry bulb temperature } [^{\circ}\text{C}] + 5.08 \quad (31)$$

$$\text{AFWA_FITS [K]} = \text{FITS} + 273.15 \quad (32)$$

h. *Turbulence diagnostics (afwa_turb_opt=1)*

The turbulence package contains a Knapp Ellrod (1992) clear air turbulence algorithm and a four component low-level turbulence algorithm developed at AFWA. The following diagnostics are output from the turbulence package.

i. **AFWA_TURB – Knapp-Ellrod clear-air turbulence index (unitless)**

The Knapp-Elrond (1992) clear-air turbulence index is calculated using wind deformation information already available within the model diffusion scheme. The index is given by:

$$\text{AFWA_TURB} = \text{Vertical wind shear} \times (\text{Deformation} + \text{Convergence}) \quad (33)$$

An **AFWA_TURB** value of 4-8 corresponds to a clear-air turbulence pilot report of light to moderate, whereas a value from 8-12 would correspond to moderate, and higher than 12, severe. Currently there are eight hard-coded AGL layers comprising the vertical dimension of **AFWA_TURB**:

- 1,500-3,000 m
- 3,000-4,600 m
- 4,600-6,100 m
- 6,100-7,600 m
- 7,600-9,100 m
- 9,100-10,700 m
- 10,700-12,700 m

ii. **AFWA_LL TURB – Four ingredient low-level turbulence index (unitless)**

The low-level turbulence (LLT) algorithm calculates a turbulence index for the 0-1500 m AGL layer. It is an empirical convolution of four terms: a dynamic term, a thermodynamic term, a mountain wave term, and a trapped wave term.[†] This simple index requires further manipulation to make a direct comparison to pilot report classifications.

iii. **AFWA_LL TURBLGT – Probability of light low-level turbulence (%)**

This variable is derived from **AFWA_LL TURB** and is the probability of LLT meeting or exceeding the pilot report classification for light turbulence (maximum value capped at 90%).

iv. **AFWA_LL TURBMDT – Probability of moderate low-level turbulence (%)**

This variable is derived from **AFWA_LL TURB** and is the probability of LLT meeting or exceeding the pilot report classification for moderate turbulence (maximum value capped at 70%).

v. **AFWA_LL TURBSVR – Probability of severe low-level turbulence (%)**

This variable is derived from **AFWA_LL TURB** and is the probability of LLT meeting or exceeding the pilot report classification for severe turbulence (maximum value capped at 35%).

[†] For low-level turbulence algorithm questions, please email James McCormick: james.mccormick.10.ctr@us.af.mil.

i. *Radar diagnostics (afwa_radar_opt=1)*

The radar diagnostics package integrates what was originally a Read/Interpolate/Plot (RIP) routine, but was ported over to WRF for AFWA by NCAR's Research Application Laboratory (RAL). Refer to Stoelinga (2005) for documentation of the reflectivity scheme. The scheme includes the corrections and improvements mentioned in section 7 of Stoelinga (2005), including an adjustment for bright-banding, or the tendency for melting snowflakes to appear highly reflective.

Using the RIP radar reflectivity algorithm, the radar diagnostics package outputs the following variables.

i. REFD – Derived surface radar reflectivity (dBZ)

This is the output from the reflectivity algorithm at the lowest model level.

ii. REFD_COM – Derived composite radar reflectivity (dBZ)

This is the column maximum of the output from the reflectivity algorithm.

iii. ECHOTOP – Echo top height from derived reflectivity (m)

This is the highest level with derived reflectivity greater than 18 dBZ.

j. *Vertically integrated liquid diagnostics (afwa_vil_opt=1)*

The vertically integrated liquid water (VIL) diagnostics package was also ported to WRF for AFWA by NCAR RAL. It outputs the following variables.

i. VIL – Vertically integrated liquid water (kg m⁻²)

This is the vertical mass integration over the model column of rain and liquid equivalent snow and graupel.

ii. RADARVIL – Radar-derived vertically integrated liquid water (kg m⁻²)

This variable implements the RIP reflectivity output to diagnose vertically integrated liquid water.

k. *Icing diagnostics (afwa_icing_opt=1)*

The AFWA icing diagnostics package diagnoses and subdivides supercooled water mixing ratios into large (>50 μm) and small (<50 μm) droplet sizes (Adams-Selin & McCormick, 2013).[‡] Large droplets are responsible for the formation of clear icing, which can pose more of a hazard to aircraft than the rime icing formed by smaller droplets. Because droplet size distribution assumptions vary by microphysics scheme, the fraction of large supercooled cloud water drops will vary from scheme to scheme. As of this writing, the following microphysics options are supported:

- Eta (Ferrier)
- Thompson
- WSM5/6
- Morrison 2-moment
- WDM6

The following variables are output from this package.

[‡] For questions about icing diagnostics, please email Rebecca Adams-Selin: rebecca.selin.ctr@us.af.mil.

i. FZLEV – Freezing level (m)

This is the geopotential height of the 0°C isotherm or the terrain height, whichever is greater.

ii. ICINGBOT– Bottommost icing level (m)

This is the geopotential height at which icing mixing ratio first exceeds 1.E-5 kg kg⁻¹. This should never go below freezing level.

iii. ICINGTOP– Topmost icing level (m)

This is the geopotential height at which icing mixing ratio last exceeds 1.E-5 kg kg⁻¹. This should never go below **ICINGBOT**.

iv. QICING_LG_MAX– Column maximum large icing mixing ratio (kg kg⁻¹)

This is the column maximum large (>50 μm) supercooled droplet mixing ratio. *Please note that a full 3-D large icing field is also available, but not output. To output, add **QICING_LG** to the **history** or **auxhist2** stream within **registry.afwa** or via the real-time I/O stream (see Section 2c).*

v. QICING_SM_MAX – Column maximum small icing mixing ratio (kg kg⁻¹)

This is the column maximum small (<50 μm) supercooled droplet mixing ratio. *Please note that a full 3-D small icing field is available, but not output. To output, add **QICING_SM** to the **history** or **auxhist2** stream within **registry.afwa** or via the real-time I/O stream (see Section 2c).*

vi. ICING_LG – Column integrated total large icing (kg m⁻²)

This is the mass integration over the column of large (>50 μm) supercooled droplets; it can be thought of as supercooled large droplet VIL.

vii. ICING_SM – Column integrated total small icing (kg m⁻²)

This is the mass integration over the column of small (<50 μm) supercooled droplets; it can be thought of as supercooled small droplet VIL.

1. Visibility diagnostics (*awfa_vis_opt=1*)

Surface visibility is calculated using estimates of light extinction from rain, snow, and dust that are explicitly predicted in the model. Due to poor model performance with cloud water and cloud ice predictions near the surface, an empirical algorithm based on relative humidity is employed to estimate the threat of reduced surface visibility due to fog or haze.

The minimum visibility from hydrometeor, dust, and fog/haze calculations is used as a Weibull β value, and a prognostic Weibull α value is used if fog/haze visibility is lowest. The α term describes the shape of the Weibull curve, with a more Gaussian curve when absolute moisture is high, and a more exponential curve when absolute moisture is lower. The practical implication of this is to ensure higher probability of mid-range (3-5 mile) visibilities in warm hazy situations, and a more discrete good visibility/socked in fog delineation when absolute moisture is lower.

Visibility in meters due to hydrometeors is determined by:

$$\text{Extinction}_{\text{Hydro}} = 1.1 \times (\text{Rain} + \text{Graupel})^{0.75} + 10.36 \times \text{Snow}^{0.78} \quad (34)$$

$$\text{Visibility}_{\text{Hydro}} [\text{m}] = 3.912 / \text{Extinction}_{\text{Hydro}} \quad (35)$$

where Rain, Graupel, and Snow are mass concentrations in g m⁻³.

Visibility in meters due to dust obscuration is calculated assuming uniform spherical dust particles and a foreknowledge of the size distribution and density characteristics of the five dust bins used by the GOCART dust emission schemes. This is the same formulation that is used within the AFWA GOCART dust emission model, but can be applied to all GOCART dust packages.

$$\text{Extinction}_{\text{Dust}} = \sum_{i=1}^5 1.5 \times C_i / (\rho_i \times r_{\text{eff},i}) \quad (36)$$

$$\text{Vis}_{\text{Dust}} [\text{m}] = 3.912 / \text{Extinction}_{\text{Dust}} \quad (37)$$

where C_i is the mass concentration, ρ_i is the density, and $r_{\text{eff},i}$ is the effective radius of dust bin i .

Lastly, visibility in meters due to fog/haze is calculated as follows:

$$\text{RH} = \text{2-meter relative humidity} [\%] \quad (38)$$

$$\text{Wind} = \text{100-meter wind velocity} [\text{m s}^{-1}] \quad (39)$$

$$\text{Pwat} = \text{Precipitable water} [\text{mm}] \quad (40)$$

$$\text{Mix} = \text{2-meter mixing ratio} [\text{g kg}^{-1}] \quad (41)$$

$$\text{Vis}_{\text{Fog}} [\text{m}] = 1500 \times (105 - \text{RH}) \times (5 / \text{Mix}) \quad (42)$$

and an additional prognostic Weibull α value due to fog/haze is calculated as:

$$\alpha_{\text{Fog}} = 0.1 + (\text{Pwat} / 25) + (\text{Wind} / 3) + ((100 / \text{RH}) / 10) + (1 / \text{Mix}); \text{max of } 3.6 \quad (43)$$

As mentioned earlier, the minimum of the three visibility terms is taken as the visibility:

$$\text{Visibility} [\text{m}] = \text{Min} (\text{Vis}_{\text{Hydro}}, \text{Vis}_{\text{Dust}}, \text{Vis}_{\text{Fog}}) \quad (44)$$

The Weibull parameters to calculate visibility (m) less than a threshold X in Eqn. (1) are as follows:

$$\alpha = \begin{cases} \alpha_{\text{Fog}} & \text{Vis}_{\text{Fog}} < \text{Vis}_{\text{Dust}} \text{ and } \text{Vis}_{\text{Fog}} < \text{Vis}_{\text{Hydro}} \\ 3.6 & \text{otherwise} \end{cases} \quad (45)$$

$$\beta = \text{Visibility} \quad (46)$$

$$X_0 = 0 \quad (47)$$

The following variables are output from the visibility diagnostics package.

i. AFWA_VIS – Visibility at the surface (m)

This is the Visibility term from Eqn. (44), the minimum of the surface visibilities from hydrometeors, dust, and fog/haze. It can be used as a deterministic visibility, but can also be used as the Weibull β term for probabilistic use as in Eqn. (46).

ii. AFWA_VIS_ALPHA – Visibility Weibull α term (unitless)

This is the Weibull α term from Eqn. (45); it is either 3.6 or α_{Fog} if visibility reduction due to fog is lower than that due to hydrometeors or dust. It describes the shape of the Weibull curve defining the CDF of surface visibility. Values lower than 3.6 indicate a bias toward discrete fog type events.

iii. AFWA_VIS_DUST – Visibility at the surface due to dust (m)

This is the Vis_{Dust} term from Eqn. (37); it is the visibility at the surface due only to dust obscuration. It is only calculated for WRF-CHEM simulations that output the **DUST1,...,DUST5** variables, and employs the same algorithm as within the AFWA GOCART dust emissions scheme.

m. Cloud diagnostics (*afwa_cloud_opt=1*)

Total cloud coverage is predicted by looking at vertical profiles of relative humidity with respect to water, neglecting the lowest 125 meters, where model cloud mixing ratios are less trustworthy. The greater the depth of atmosphere with RH greater than 90%, the more cloud cover the algorithm will predict. This package calculates the following variables.

i. AFWA_CLOUD – Cloud fraction Weibull β value (fraction)

This is a Weibull β value that is used to determine the probability that cloud cover will or will not exceed a particular cloud fraction. It cannot be interpreted as a cloud fraction by itself, as it is allowed to exceed 1, but if restricted to a maximum value of 1, it can reasonably be interpreted as cloud fraction. (This is one of the rare instances within AFWA diagnostics where the diagnostic used as a Weibull β value cannot be used directly, without adjustment). The calculation is as follows:

$$\text{AFWA_CLOUD [fraction]} = \int_{125\text{ m}}^{\text{top}} ((\text{RH} - 90)/10) dz / 250 \quad (48)$$

The following Weibull values can be substituted into Eqn. (1) to predict the probability that cloud fraction will be less than a threshold cloud fraction X:

$$\alpha = 3.6 \quad (49)$$

$$\beta = \text{AFWA_CLOUD} \quad (50)$$

$$X_0 = 0 \quad (51)$$

ii. AFWA_CLOUD_CEIL – Cloud ceiling height (m)

This variable is the most likely cloud ceiling level *if a cloud exists*. In other words, this variable predicts where a cloud base would lie vertically, if a cloud were to exist in that column. It is determined to be at the lowest level where **AFWA_CLOUD** exceeds 0.8. Otherwise, it is set to the level of maximum RH.

The Weibull curve parameters for the *conditional* probability of cloud ceiling height less than some threshold X *were a cloud to exist*, are:

$$\alpha = 3.6 \quad (52)$$

$$\beta = \text{AFWA_CLOUD_CEIL} \quad (53)$$

$$X_0 = 0 \quad (54)$$

To calculate the *unconditional* probability of cloud ceiling less than a specified height X, the *conditional* probability of cloud ceiling less than X, derived from substituting Eqns. (52), (53), and (54) into Eqn. (1), must then be multiplied by the probability of cloud cover *exceeding* X = 0.8 from the cloud fraction Weibull CDF. This latter probability is found by substituting Eqns. (49), (50), and (51) into Eqn. (1) and subtracting the result from 1. So if the atmosphere is dry and the cloud cover probability is zero, then the *unconditional* probability of cloud ceiling height less than any X will also be zero.

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