# WRF-STILT Interface Description

Thomas Nehrkorn

Atmospheric and Environmental Research (AER), Inc.
131 Hartwell Avenue, Lexington, MA 02421-3126.
Phone: (781)-761-2288 FAX: (781)-761-2299
Net: `http://www.aer.com/`.

Internal AER Technical Memo

prepared under NASA contract NNH05CC42C

Date formatted: March 12, 2008

# Contents

# 1 Introduction

A technical description is provided of the interface between the Weather Research and Forecast (WRF) mesoscale model and the Stochastic Time-Inverted Lagrangian Transport (STILT) model. The STILT model is described in Lin et al. (2003) and references therein. This interface was written for version 2.1.1 of the Eulerian mass-coordinate (EM) dynamical core of WRF, which is part of the Advanced Research WRF (ARW) supported by the National Center for Atmospheric Research (NCAR) and described in detail in Skamarock et al. (2005, hereafter referred to as SkaKD). In the remainder of this document, any references to WRF are understood to mean the ARW.

An updated version of the interface for version 2.2 of the ARW WRF is also available.

Coupling of these two models requires a transformation of the WRF model output variables to those used in the STILT model, interpolation from the vertical WRF levels to those used in STILT, and proper treatment of the WRF staggered winds in STILT. In addition, the WRF model data must be reformatted to the input format used by STILT, the NOAA Air Resources Laboratory (ARL) format. The interface supports two of the output format choices of the WRF: netcdf and GRIB1.

Development of the interface made extensive use of existing software components. The WRF code was modified as needed to compute the required parameters, and the existing WRF capabilities for GRIB1 format output were modified for their output in GRIB1 format. Existing ARL software for reformatting of GRIB files to ARL format were adapted in the development of a custom-written WRF GRIB to ARL reformatter. Finally, specialized STILT input and preprocessing routines were developed for the WRF ARL-format data, and selected STILT modules were modified to properly handle the WRF grid structure.

In the following, we provide an overview of the model grids and variables of the WRF and STILT models, a description of the software and related configuration files. A discussion of the use of parameterized convective mass fluxes is provided in Section 4.

# 2 Model grids and variables

## 2.1 STILT model grids

The STILT model is based on the HYSPLIT model developed at ARL (Draxler and Hess, 1998, 1997). To minimize errors resulting from horizontal interpolation of model variables, the model is designed to perform all computation on the horizontal grid of the meteorological input dataset. Currently supported map projections are polar stereographic, Mercator, and Lambert conformal. By default the code assumes all model variables are located at the same mesh points, *i.e.* that there is no staggering of mass and momentum variables in the horizontal. Input datasets from models using staggered grids must thus be either interpolated to an unstaggered grid, or special handling must be implemented within the STILT code whenever staggered variables (usually the horizontal wind components) are interpolated to trajectory locations. The latter approach is taken in STILT for RAMS and WRF model input.

The STILT/HYSPLIT models use a $\sigma - z$ vertical coordinate, defined by equation (1) of Draxler and Hess (1997, hereafter DraH):

$$\sigma = \frac{Z_{top} - Z_{msl}}{Z_{top} - Z_{gl}} , \tag{1}$$

where $Z_{top}$ is the model top height, $Z_{msl}$ is the height of the model level (above mean sea level, MSL), and

$Z_{gl}$ is the height of the model terrain (above MSL). The above can be expressed equivalently as

$$\sigma = 1 - \frac{Z_{msl} - Z_{gl}}{Z_{top} - Z_{gl}} . \quad (2)$$

Unless otherwise specified, the STILT model uses a default set of vertical coordinates values in which the grid level index ($k$) and model level height above ground for a gridpoint at MSL are related through the quadratic relationship (equation (2) of DraH)

$$h = Z_{msl} - Z_{gl} = ak^2 + bk + c , \quad (3)$$

with the coefficients given by $a$ =30 m, $b$ =−25 m, and $c$ =5 m. The default value for $Z_{top}$ is 25 km. The default vertical coordinate values defined by Eq. (3) can be overridden in STILT in one of three ways:

1. specification of different values of $a$, $b$, and $c$ in a configuration file,
2. specification of different values of $h$ in a separate input file, or
3. use of the RAMS model levels, in the case of RAMS model input.

.

## 2.2 STILT model variables

This section provides a general decription of the types of atmospheric state variables used within STILT and in its meterological input module. A detailed listing is provided in Section 3.6.

The most important meteorological variables required for the trajectory calculations by STILT are vertical profiles of the horizontal and vertical wind components. The horizontal winds are assumed to be in units of $m/s$ and converted internally to grid lengths/minute, whereas the vertical velocity is converted from the meteorological input to its internal respresentation of $d\sigma/dt$. In addition, profiles of temperature, pressure, and humidity are needed and converted internally to pressure, virtual potential temperature, relative humidity, and air density. Variables at the surface needed for the computation of sigma-level profiles are the terrain height, pressure, temperature, horizontal wind, and surface roughness length.

Additional two-dimensional fields required from the meteorological input are: latent and sensible heat flux at the surface; the friction velocity $u^*$; the planetary boundary height; the soil moisture content; and the downward shortwave and longwave radiative fluxes. Coupling of the convective parameterization within RAMS or WRF with the convective flux parameterization within STILT requires additional variables described in Section 4.

## 2.3 WRF model grids

The computational grid of the WRF is a regularly spaced grid in one of several possible map projections (currently supported are the same set as those supported by STILT: polar stereographic, Mercator, and Lambert conformal). These grids may be nested, but each nest is output separately, and can be treated as a single, independent grid for the purpose of this discussion.

The vertical coordinate used by the WRF is a terrain-following pressure-sigma coordinate system based on the dry hydrostatic pressure ($p_{dh}$). It is defined by equation (2.11) of SkaKD as

$$\eta = \frac{p_{dh} - p_{dht}}{\mu_d} \text{ , where } \mu_d = p_{dhs} - p_{dht} . \quad (4)$$

Here $p_{dhs}$ and $p_{dht}$ are the dry hydrostatic pressure at the surface and the model top, respectively.

## 2.4 WRF wind and thermodynamic variables

The standard output provided by the WRF model includes instantaneous values of the grid relative horizontal wind components (in $m/s$) and geometric vertical velocity ($dz/dt$, in $m/s$) at the staggered grid locations of the Arakawa C-grid. The WRF-STILT interface provides the option to use velocity components, in which case only minor changes are required to the WRF model code. Because of the staggering of the horizontal wind components, map scale factors (see equation (2.22) of SkaKD) are required at the mass points as well as the u and v grid points.

The WRF model equations are formulated as perturbation equations with respect to a dry hydrostatic reference state at rest. Thermodynamic quantities available in the standard WRF model output include the (full) potential temperature, the base state and perturbation pressure, and the water vapor mixing ratio.

Additional WRF model variables are required by the WRF-STILT interface to permit computation of the WRF model level heights:

- the dry inverse density $\alpha_d$ is needed for the integration of the WRF hydrostatic equation (equation (2.30) of SkaKD)
$$\frac{\partial\Phi}{\partial\eta} = -\alpha_d\mu_d \tag{5}$$
- the base state and perturbation values of $\mu_d$.

## 2.5 WRF coupled wind variables

Aside from the accuracy of the meteorological fields, an important requirement for the meteorological input fields for any trajectory model is that they conserve mass. While the WRF (or other numerical models) will conserve mass internally to a high degree, this can no longer be guaranteed if the model variables are transformed and temporally and spatially interpolated (by model postprocessing and STILT preprocessing components). To minimize these problems, the WRF-STILT interface provides the option to make use of time-averaged values of the mass-coupled velocities used internally by WRF for the advection of passive scalars.

The time-averaged horizontal advection velocities ($U$, $V$) are defined by the equation following (2.22) in SkaKD:

$$U = u*\mu_d/m \;\; ; \qquad V = v*\mu_d/m \, , \tag{6}$$

where $u$, $v$ are the grid-relative wind components (in $m/s$), and $m$ is the map scale factor. A coupled vertical velocity is similarly defined as

$$\Omega = (\mu_d/m)\frac{d\eta}{dt} \, . \tag{7}$$

The time-stepping used by WRF for the slow (non-acoustic) modes is a third-order Runge-Kutta scheme. Acoustic tendencies are stepped on a shorter time step, using deviations from the last large time step values of the Runge-Kutta scheme. As is shown in Figure 3.1 of SkaKD, passive scalars are advected using values of $U$, $V$, and $\Omega$ that are time-averaged over the acoustic steps. It is these quantities that are further averaged over all large time steps between output times in the WRF-STILT interface.

# 3 Software Description

Implementation of the WRF-STILT interface required development and/or modification of three separate software packages: the WRF model, a separate GRIB to ARL format converter (WRFGRIB2ARL), and the STILT model. In this section, we give a brief description of each component, followed by a detailed discussion of the configuration files that can be modified by the user. The last subsection (Section 3.6) provides a mapping from the variable names used in the ARL format file (and the STILT meteorological input module) to the variable names in the WRF code.

## 3.1 WRF model code modifications

If the option to use standard wind components is used, no changes are required to the source code of the WRF model. However, some changes are required to control and configuration files. If GRIB format WRF output is to be used, the namelist file must specify history output in the GRIB1 output. In addition, two configuration files of the WRF model need to be modified:

- the Registry file (Section 3.5.1), which is used within the WRF software framework to control the storage and I/O of model variables, and
- the gribmap file (Section 3.5.2), which controls the output and encoding of WRF model variables in the GRIB1 format output files.

If time-averaged mass-coupled advective velocities are used, several changes are required to WRF EM dynamical core routines, for the computation and output of the time-averaged quantities. These are documented in in-line comments in the modified WRF code.

## 3.2 WRFGRIB2ARL converter

A WRF GRIB to ARL reformatter was written to convert the WRF output files generated by the GRIB1 I/O module of WRF to the ARL format required by the meteorological input module of STILT. A number of specialized GRIB to ARL converters exist for different operational model and analysis output files, and we made extensive use of the existing GRIB decoding and ARL encoding software contained in these converters.

In its default configuration, the converter is configured to read a single GRIB file (one per time period) and generate a single ARL format output file. The ARL files for the different time periods can then be combined using the unix `cat` command. By default, the WRF variables output on the mass points, and the x- and y-stagger points, are all output to the same file, using the grid specification for the mass points in the ARL header. To accomodate the additional row or column of the staggered variables, all fields are dimensioned by the dimensions of the mass grid extended by an extra row and column. The option exists to output the staggered fields to separate output files, and provide the appropriate grid specifications in the headers of the individual ARL files. However, the current version of the STILT ingest module does not support this option. The ARL format provides for the output of different variables at different vertical levels, and the option exists to make use of this file format for the output of mass and wind level variables. However, the current version of the STILT ingest does not support this option, and by default all levels (other than the surface) contain the same variables. The mass level variables are listed in the output as if they were located at the next higher wind level.

The $\eta$ values of the vertical levels are specified in separate plain text configuration files for the mass and wind levels. The converter software contains a script (`make_levelfile.pl`) to automatically generate these files by generating and parsing an inventory of one of the GRIB input files. A hand-edited configuration file (`var_sample`, see Section 3.5.3) is used to specify details of the GRIB decoding and ARL encoding for each variable. Execution of the converter (`wrfgrib2arl`) is controlled by command-line arguments. A help message is displayed if no arguments are specified.

### 3.3 WRFNC2ARL converter

A WRF netcdf to ARL reformatter was written to convert the WRF output files generated by the netcdf I/O module of WRF to the ARL format required by the meteorological input module of STILT. The software is quite similar to that of the WRFGRIB2ARL converter, it provides for similar options. The only difference in usage is that the $\eta$ values of the vertical levels do not need to be specified in separate plain text configuration files (they are obtained directly from the input netcdf files by the converter), and differences in the format of the (`var_sample`, see Section 3.5.3).

### 3.4 STILT code modification

The STILT source code primarily required modifications in its meteorological input module (`metinp`), and in the interpolation of the input profiles to the STILT model levels (`prfwrf`). Additional changes, which are not described in detail here, were required throughout a number of modules to account for the horizontal and vertical staggering of the wind components, and the treatment of time-averaged rather than instantaneous model values. Both of these aspects were quite similar to existing provisions for RAMS model input and have been commented accordingly within the source code.

The `metinp`module was modified to recognize the WRF model output (keying on the model ID tag in the input file), and to process the required and optional WRF model fields listed in Section 3.6. Base state and perturbation quantities of pressure and $\mu_d$ are combined to full values in this module.

Vertical interpolation from WRF to STILT model levels is performed in `prfwrf`. The height above terrain of the STILT model levels ($h^m$) is first computed using Eq. (1):

$$h_k^m = Z_{msl,k} - Z_{gl} = (1 - \sigma_k)(Z_{top} - Z_{gl}) \ . \tag{8}$$

The corresponding height above ground for the input WRF mass model levels is obtained by upward integration of Eq. (5)

$$\Delta z_k = h_k - h_{k-1} = -\frac{1}{g}\mu_d \bar{\alpha}_d \Delta\eta_k \ , \tag{9}$$

where $\Delta\eta_k$ is the spacing of the WRF mass levels, and $\bar{\alpha}_d$ is the layer-average value of $\alpha_d$, computed from the mass level values using equation (3.28) of SkaKD. The layer thicknesses $\Delta\eta^w$ are computed from the wind-level $\eta^w$ values specified in the ARL file input from

$$\Delta\eta_k^w = \begin{cases} \eta_1^w - 1 & \text{if } k = 1 \\ \eta_k^w - \eta_{k-1}^w & \text{if } k > 1 \end{cases} \ .$$

The WRF mass level model variables are then interpolated linearly in height from the WRF mass levels to the STILT model levels ($h^m$).

The staggering of the WRF vertical velocities in the vertical is preserved within STILT by interpolation from the WRF wind levels to staggered vertical levels in $\sigma$. Their height above ground ($h^w$) is defined through the recursive relation

$$h_k^w = \begin{cases} 0 & \text{if } k = 1 \\ h_{k-1}^m + \left(h_{k-1}^m - h_{k-1}^w\right) & \text{if } k > 1 \end{cases} . \tag{10}$$

For coupling using the instanantaneous values of the standard wind components, no variable transformation are required for the horizontal winds beyond the standard unit conversions. Conversion from geometric vertical velocity ($w = dz/dt$) to the sigma vertical velocity ($d\sigma/dt$) use the general relation between geometric vertical velocity and vertical velocity in a terrain-following coordinate system (see, for example, eq (1-53) of Haltiner and Williams, 1980):

$$w = (\frac{\partial z}{\partial t})_\sigma + \mathbf{V} \cdot \nabla_\sigma z + \frac{\partial z}{\partial \sigma} , \tag{11}$$

which result in

$$\frac{d\sigma}{dt} = \frac{1}{Z_{top} - Z_{gl}} (\sigma \mathbf{V} \cdot \nabla Z_{gl} - w) . \tag{12}$$

The first term on the right, which involves the slope of the model terrain, is usually neglected (for example, in equation (8) of DraH97).

For coupled velocities, the grid-relative horizontal wind components are recovered from Eq. (6). For the vertical velocity, the coupled eta vertical velocity must first be converted to $w$ before the application of Eq. (12). Using the hydrostatic assumption in Eq. (11), we obtain

$$w = \frac{-\alpha_d}{g} (\eta \mathbf{V} \cdot \nabla \mu_d + \mu_d \frac{d\eta}{dt}) .$$

Substitution into Eq. (12) results in

$$\frac{d\sigma}{dt} = \frac{1}{Z_{TOP} - Z_{gl}} \left[ \mathbf{V} \cdot (\sigma \nabla Z_{gl} + \frac{\eta\alpha}{g} \nabla \mu_d) + \frac{\alpha}{g} \Omega \right] . \tag{13}$$

The first term on the right can be neglected, since it consists of two terms that largely cancel: the horizontal gradients of the terrain and surface pressure.

## 3.5 Configuration files

### 3.5.1 WRF: Registry.EM

The Registry is used at compile time to automatically generate a large amount of code for the declaration of actual and dummy arguments in subroutine calls, and the generation of calls to I/O routines. The format of the file is documented in in-line comments within the file itself. The minimum required changes for this file are the inclusion of the following additional variables in the history file output (designated by the letter "h" in the I/O specification in the Registry file):

- **MUU:** Value of $\mu_d$ (in *Pa*) at u grid points
- **MUV:** Value of $\mu_d$ (in *Pa*) at v grid points

- **MUT:** Value of $\mu_d$ (in *Pa*) at mass grid points
- **UST:** Friction velocity $u^*$ (in $m/s$)

If time-averaged mass-coupled velocities are used, more variables need to be allocated storage and added to the history output:

- **AVGFLX_RUM:** Time-averaged value of $U$ (in $Pam/s$)
- **AVGFLX_RVM:** Time-averaged value of $V$ (in $Pam/s$)
- **AVGFLX_WWM:** Time-averaged value of $\Omega$ (in $Pa/s$)

In addition, storage needs to be allocated for additional variables that are not output to the history file:

- **AVGFLX_COUNT:** Counter for time-averaged coupled velocities

#### 3.5.2 WRF: gribmap.txt

The `gribmap.txt` file is a plain text file (this file is only needed if WRF output is in the GRIB1 format). Each line contains the specification for a single GRIB variable code. It consists of up to five colon-separated fields that specify the

- GRIB variable code number
- GRIB variable name
- GRIB variable description
- WRF output variable name(s)
- Precision (decimals)

The variable code number is encoded in the GRIB file and used by the WRFGRIB2ARL converter to identify the different variables. The GRIB variable name and description are only used in inventory listings by GRIB decoders. The WRF output variable name(s) are used by the WRF GRIB I/O module to link variable entries in the Registry file to the gribmap entry. The final field specifies how many digits are to be preserved in the GRIB encoding.

More details on the entries required in the current WRF-STILT interface are provided in Section 3.6.

#### 3.5.3 Converter configuration file var_sample

This plain text configuration file determines which variables from the WRF are output, and specifies details of their de- and encoding. Following a header section, the file contains a single line for each variable. The contents of the file depends on whether the WRFGRIB2ARL or WRFNC2ARL converter is used. The first 4 columns are the same for both converters:

- a 4-character variable name, enclosed in single quotes
- a 1-character xy-staggering indicator, one of ('x', 'y', or ' '), case-insensitive
- a 1-character z-staggering indicator, one of ('z', or ' '), case-insensitive

- an integer dimensionality indicator, either 2 or 3 (for 2d/3d fields)

The WRFGRIB2ARL converter file contains the additional columns:

- an integer variable code (GRIB code table 2)
- an integer level type (GRIB code table 3)
- an integer level value (ignored for 3d variables, or if specified as -99)
- a floating point conversion factor to be applied to the data before output

In the case of the WRFNC2ARL converter file the additional columns are:

- the character variable name corresponding to the variable label in the netcdf file, enclosed in single quotes
- a floating point conversion factor to be applied to the data before output
- a floating point offset to be added to the data before the conversion factor is applied

Examples of file entries for the default configuration are shown in Section 3.6.

#### 3.5.4 STILT

Execution of the STILT model is controlled by two configuration files:

**SETUP.CFG:** namelist file controlling various numerical aspects of the trajectory computation, and

**CONTROL:** plain text input file controlling the receptor locations, time period, and meterological input file names.

For a close matching of input model and internal STILT vertical levels, an optional additional plain text configuration file was added (**ZSG_LEVS.IN**). The first line of this file contains control information specifying: the number of vertical levels to be used in STILT; the level index of the surface layer; and the model top ($Z_{top}$, in m). Following an arbitrary number of header lines terminated by a line beginning with the string "ENDHEADER", the values of $h_k^w$ (for a gridpoint at MSL) are specified, one per line. These values are computed off-line from an analysis of the WRF model output, *e.g.* as the average value of geopotential height at the WRF mass levels over all sea-level grid points. The value for $Z_{top}$ must be larger than the maximum value of $h_k^w$, *e.g.* the maximum value $h_m^w$.

### 3.6 Variable mapping from STILT to WRF

If the WRFNC2ARL converter is used, the variable names specified in the `var_sample` file directly relates the STILT parameter codes to the WRF array names as specified in the `Registry` file. In the case of the WRFGRIB2ARL converter, the information relating WRF variables to STILT parameter codes is contained in three separate configuration files. A parser (`wrf-stilt-params.pl`) is available to analyze the three configuration files desribed above and generate a mapping between the ARL-format variable names ingested by STILT, and the variable names used in the WRF codes.

The following provides an edited version of the parser output, for the variables used in both the wind component and momemtum flux coupling. For each variable, three lines show the entry in the

**var_sample file:** variable name, xy- and z-staggering (if any), dimensionality (2 or 3), grib variable code number, vertical coordinate type code number, vertical coordinate value (-99 if ignored), and conversion factor;

**gribmap.txt file:** variable name and description for GRIB decoding, WRF output variable names, GRIB precision

**Registry.EM file:** WRF variable name, dimension specification, type of variable, type of staggering (if any), WRF output variable name, description, and units.

**MSFT:**
```
'MSFT' ' '    ' '   2     189        1    -99    1.0
MAPFAC_M:Map Scale Factor [dimensionless]:MAPFAC_M:7
msft : ij : misc : - : MAPFAC_M : Map scale factor on mass grid :
```

**MSFU:**
```
'MSFU' 'X'    ' '   2     190        1    -99    1.0
MAPFAC_U:Map Scale Factor [dimensionless]:MAPFAC_U:7
msfu : ij : misc : X : MAPFAC_U : Map scale factor on u-grid :
```

**MSFV:**
```
'MSFV' 'Y'    ' '   2     191        1    -99    1.0
MAPFAC_V:Map Scale Factor [dimensionless]:MAPFAC_V:7
msfv : ij : misc : Y : MAPFAC_V : Map scale factor on v-grid :
```

**ALT0:**
```
'ALT0' ' '    ' '   3     132     119    -99    1.0
ALT:inverse dry density [m3 kg-1]:ALT:8
alt : ikj : dyn_em : - : alt : inverse density : m3 kg-1
```

**MUBA:**
```
'MUBA' ' '    ' '   2     139        1    -99    1.0
MU_BASE:Base-state dry air mass in column [Pa]:MUB:2
mub : ij : dyn_em : - : mub : base state dry air mass in column : Pa
```

**MUPE:**
```
'MUPE' ' '    ' '   2     140        1    -99    1.0
MU_PERT:Perturbation dry air mass in column [Pa]:MU:2
mu : ijb : dyn_em : - : mu : perturbation dry air mass in column : Pa
```

**THET:**
```
'THET' ' '    ' '   3      13     119    -99    1.0
POT:Potential temp. [K]:TH2,THZ0,T:4
t : ikjb : dyn_em : -  : t :
  perturbation potential temperature (theta-t0) : K
```

**PRES:**
```
'PRES' ' '    ' '   3     142     119    -99    0.01
P_BASE:Base-state pressure [Pa]:PB:2
pb : ikj : dyn_em : - : pb : BASE STATE PRESSURE  : Pa
```

**PPRE:**
```
'PPRE' ' '    ' '   3       1     119    -99    0.01
PRES:Pressure [Pa]:P,PSFC:2
p : ikj : dyn_em : - : p : perturbation pressure : Pa
```

**SPHU:**
```
'SPHU' ' '    ' '   3      53     119    -99    1.0
MIXR:Humidity mixing ratio [kg/kg]:QVAPOR,Q2,QVG:6
qv : ikjftb : moist : - : QVAPOR : Water vapor mixing ratio : kg kg-1
```

```
SHTF: 'SHTF' ' '    ' '   2     155       1    -99    1.0
    GFLUX:Ground heat flux [W/m^2]:HFX:4
    HFX : ij : misc : - : HFX : UPWARD HEAT FLUX AT THE SURFACE : W m-2

USTR: 'USTR' ' '    ' '   2     167       1    -99    1.0
    UST:U* IN SIMILARITY THEORY [m/s]:UST:4
    UST : ij : misc : - : UST : U* IN SIMILARITY THEORY : m s-1

LHTF: 'LHTF' ' '    ' '   2     121       1    -99    1.0
    LHTFL:Latent heat flux [W/m^2]:LH:4
    LH : ij : misc : - : LH : LATENT HEAT FLUX AT THE SURFACE : W m-2

SHGT: 'SHGT' ' '    ' '   2       8       1    -99    1.0
    DIST:Geometric height [m]:HGT:4
    ht : ij : misc : - : HGT : Terrain Height : m

PRSS: 'PRSS' ' '    ' '   2       1       1    -99    0.01
    PRES:Pressure [Pa]:P,PSFC:2
    PSFC : ij : misc : - : PSFC : SFC PRESSURE : Pa

T02M: 'T02M' ' '    ' '   2      11     105      2    1.0
    TMP:Temp. [K]:T2,TSK:2
    T2 : ij : misc : - : T2 : TEMP at 2 M : K

U10M: 'U10M' ' '    ' '   2      33     105     10    1.0
    UGRD:u wind [m/s]:U,U10,UZ0:3
    U10 : ij : misc : - : U10 : U at 10 M : m s-1

V10M: 'V10M' ' '    ' '   2      34     105     10    1.0
    VGRD:v wind [m/s]:V,V10,VZ0:3
    V10 : ij : misc : - : V10 : V at 10 M : m s-1

HPBL: 'HPBL' ' '    ' '   2     221       1    -99    1.0
    HPBL:Planetary boundary layer height [m]:PBLH:2
    PBLH : ij : misc : - : PBLH : PBL HEIGHT : m

SOLW: 'SOLW' ' '    ' '   2     144     112     10    1.0
    SOILW:Volumetric soil moisture [fraction]:SMOIS:4
    SMOIS : ilj : - : Z : SMOIS : SOIL MOISTURE : m3 m-3

DSWF: 'DSWF' ' '    ' '   2     204       1    -99    1.0
    DSWRF:Downward short wave flux [W/m^2]:SWDOWN:3
    SWDOWN : ij : misc : - : SWDOWN :
      DOWNWARD SHORT WAVE FLUX AT GROUND SURFACE : W m-2

DLWF: 'DLWF' ' '    ' '   2     205       1    -99    1.0
    DLWRF:Downward long wave flux [W/m^2]:GLW:3
    GLW : ij : misc : - : GLW :
      DOWNWARD LONG WAVE FLUX AT GROUND SURFACE : W m-2
```

The wind-component coupling just requires the wind components in the horizontal and vertical:

**UWND:** :

```
 'UWND' 'X'    ' '   3     33     119    -99    1.0
UGRD:u wind [m/s]:U,U10,UZ0:3
u : ikjb : dyn_em : X : U : x-wind component : m s-1
```

**VWND:** :

```
 'VWND' 'Y'    ' '   3     34     119    -99    1.0
VGRD:v wind [m/s]:V,V10,VZ0:3
v : ikjb : dyn_em : Y : V : y-wind component : m s-1
```

**DZDT:** :

```
 'DZDT' ' '    'Z'   3     40     119    -99    1.0
DZDT:Geometric vertical velocity [m/s]:W:5
w : ikjb : dyn_em : Z : w : z-wind component : m s-1
```

For a coupling using time-averaged momentum flux variables, some additional variables are needed for decouplingof the velocities:

**MUU0:** :

```
 'MUU0' ' '    ' '   2    154       1    -99    1.0
MUU:Total dry air mass in column on u-grid[Pa]:MUU:2
muu : ij : dyn_em : - : muu : total dry air mass in column, u-grid : Pa
```

**MUV0:** :

```
 'MUV0' ' '    ' '   2    157       1    -99    1.0
MUV:Total dry air mass in column on v-grid[Pa]:MUV:2
muv : ij : dyn_em : - : muv : total dry air mass in column, v-grid : Pa
```

**UWND:** :

```
 'UWND' 'X'    ' '   3    194     119    -99    1.0
AVGFLX_RUM:hist-time-averaged mu-coupled u [Pa m s-1]:AVGFLX_RUM:
avgflx_rum : ikj : dyn_em : X : avgflx_rum :
 hist-time-averaged mu-coupled u : Pa m s-1
```

**VWND:** :

```
 'VWND' 'Y'    ' '   3    195     119    -99    1.0
AVGFLX_RVM:hist-time-averaged mu-coupled v [Pa m s-1]:AVGFLX_RVM:
avgflx_rvm : ikj : dyn_em : Y : avgflx_rvm :
 hist-time-averaged mu-coupled v : Pa m s-1
```

**WWND:** :

```
 'WWND' ' '    'Z'   3     196     119    -99    1.0
AVGFLX_WWM:hist-time-averaged mu-coupled eta-dot [Pa s-1]:AVGFLX_WWM:5
avgflx_wwm : ikj : dyn_em : Z : avgflx_wwm :
 hist-time-averaged mu-coupled eta-dot : Pa s-1
```

# 4 Coupling of convective mass fluxes

STILT provides three options for treating atmospheric convection for trajectory calculations:

1. No convection,
2. "Extreme" convection, in which complete vertical mixing throughout the entire unstable layer is assumed at each meterological input time, and
3. Grell convection, in which the convective fluxes computed within the Grell scheme of the meteorological model are used to parameterize the effects on the particle trajectories.

In our development of the WRF-STILT interface for convective fluxes, we made use of the software developed by Saulo Freitas (personal communication, 2005) for the RAMS-STILT coupling.

## 4.1 Convective fluxes output by WRF

In the WRF model, the Grell-Dévényi scheme (Grell and Dévényi, 2002) is implemented for deep convection only (shallow convection is disabled). It uses a 144-member ensemble of parameterizations, using all combinations obtained by using 3 different values of precipitation efficiency, 3 different values for a numerical parameter related to the cloud base mass flux normalization, and 16 different closure assumptions. Within the Grell-Dévényi scheme, all computed convective fluxes are normalized by the cloud base mass flux. The normalized fluxes are then averaged over the ensemble members, and finally dimensionalized by the ensemble-averaged cloud base mass flux.

The Grell-Dévényi is a mass-flux scheme, in which the grid-cell average of the updraft mass flux profile is given by equation (2) of Grell and Dévényi (2002):

$$m_u(z,\lambda) = m_b(\lambda)\eta_u(z,\lambda)$$

where $\lambda$ denotes an ensemble type, $m_b$ is the mass-flux at cloud base, and $\eta_u$ is the normalized updraft mass flux profile. Similarly, the downdraft mass flux is given by equation (A.18) of Grell (1993):

$$m_d(z,\lambda) = m_o(\lambda)\eta_d(z,\lambda)$$

where $m_o$ is the mass flux at the originating level of the downdraft, which is related to the cloud base mass flux through a parameter ($\varepsilon$) related to the precipitation efficiency (1-$\beta$) and the total condensation in the updraft ($I_1$) and evaporation in the downdraft ($I_2$) through equation (A.24) of Grell (1993):

$$m_o(\lambda) = \varepsilon(\lambda)m_b(\lambda) = \frac{\beta(\lambda)I_1(\lambda)m_b(\lambda)}{I_2(\lambda)}\ .$$

The vertical profiles of the normalized up- and downdraft mass fluxes are controlled by the fractional entrainment and detrainment rates computed in `cup_enss` and `cup_dd_ms`, which are then used in subroutine `cup_dellas` to arrive at the final values of entrainment and detrainment rates, using additional assumptions about entrainment and detrainment at the top and bottom of the up- and downdrafts. The entrainment and detrainment mass fluxes are used within subroutine `cup_dellas` for the computation of convectively induced tendencies of the environment. Details of this computation, and the mass budget of the convective fluxes, are shown in Figure B1 of Grell (1993). The routine includes an internal consistency check for mass conservation. We implemented changes to this routine to store (normalized) values of the up- and downdraft mass fluxes and entrainment rates. Further changes were needed in subroutine `cup_output_ens` for the computation and storage of dimensionalized mass fluxes summed over all ensemble members.[1]

### 4.2 Convective fluxes within STILT

For Grell convection, STILT uses vertical profiles of the mass flux within the updrafts and downdrafts, and the entrainment of mass from the environment into the up- and downdrafts (and detrainment into the environment from the up- and downdrafts). It is assumed that the up- and downdraft mass fluxes (in $kgm^{-2}s^{-1}$) are given at the staggered model levels ($h^w$), while the entrainment and detrainment fluxes (also in $kgm^{-2}s^{-1}$) are defined at mass levels ($h^m$), representing the change in up- or downdraft mass flux over the layer depth due to entrainment and detrainment. The grid-cell averages of up- and downdraft mass fluxes at cloud base are converted to a fractional coverage, using an assumed convective vertical velocity scale. Vertical profiles of up- and downdraft vertical velocity are then derived from the flux profiles and the fractional coverage of the up- and downdrafts. The vertical profiles of the up- and downdraft mass fluxes, and their changes due to entrainment and detrainment, are used to compute the probability of individual particles being located within the environment or an up- or downdraft.

To support use of WRF-generated convective mass fluxes, changes were needed in the computation of the vertical levels (in program `hymodelc`) passed to the Grell convection subroutine (`cgrell`), since the existing RAMS implementation assumed the fluxes were available at the staggered vertical grid of the RAMS model data. In addition, the vertical interpolation routine for WRF input data (`prfwrf`) had to be augmented to support a remapping of the mass fluxes to the STILT model levels. As was the case for the vertical velocity, the wind-level up- and downdraft mass fluxes are interpolated to the staggered STILT levels ($h^w$), while the entrainment and detrainment fluxes are redistributed to the STILT layers. The entrainment and detrainment fluxes are optionally readjusted after the vertical interpolation to ensure mass conservation within a prescribed tolerance.

### 4.3 Mapping from ARL-format to WRF variable names

The following provides the linkage for the convective mass fluxes between the variable names used in the ARL-format file and the variable names used within the WRF model code (in the same format as in Section 3.6).

**CFU1:** :

```
'CFU1' ' '    'Z'   3    187    119    -99    1.0
```

[1] These changes were implemented in a version of the Grell scheme code that was also modified to allow reordering of the internal arrays for improved computational efficiency on non-vector computer architectures (Nehrkorn and Modica, 2005).

```
CFU1:AVERAGE updraft mass flux from GD-scheme [kg m-2 s-1]:CFU1:8
avgflx_cfu1 : ikj : misc : Z : CFU1 :
 AVERAGE updraft mass flux from GD-scheme : kg m-2 s-1
```

**CFD1:** :

```
 'CFD1' ' '    'Z'   3     197     119    -99    1.0
CFD1:AVERAGE downdraft mass flux from GD-scheme [kg m-2 s-1]:CFD1:8
avgflx_cfd1 : ikj : misc : Z : CFD1 :
 AVERAGE downdraft mass flux from GD-scheme : kg m-2 s-1
```

**DFU1:** :

```
 'DFU1' ' '    ' '   3     198     119    -99    1.0
DFU1:AVERAGE detrainment from updraft from GD-scheme [kg m-2 s-1]:DFU1:8
avgflx_dfu1 : ikj : misc : - : DFU1 :
 AVERAGE detrainment from updraft from GD-scheme : kg m-2 s-1
```

**EFU1:** :

```
 'EFU1' ' '    ' '   3     199     119    -99    1.0
EFU1:AVERAGE entrainment into updraft from GD-scheme [kg m-2 s-1]:EFU1:8
avgflx_efu1 : ikj : misc : - : EFU1 :
 AVERAGE entrainment into updraft  from GD-scheme : kg m-2 s-1
```

**DFD1:** :

```
 'DFD1' ' '    ' '   3     200     119    -99    1.0
DFD1:AVERAGE detrainment from downdraft from GD-scheme [kg m-2 s-1]:DFD1:8
avgflx_dfd1 : ikj : misc : - : DFD1 :
 AVERAGE detrainment from downdraft from GD-scheme : kg m-2 s-1
```

**EFD1:** :

```
 'EFD1' ' '    ' '   3     201     119    -99    1.0
EFD1:AVERAGE entrainment into downdraft from GD-scheme [kg m-2 s-1]:EFD1:8
avgflx_efd1 : ikj : misc : - : EFD1 :
 AVERAGE entrainment into downdraft  from GD-scheme : kg m-2 s-1
```

## 5 References

Draxler, R. R. and G. D. Hess, 1997: Description of the HYSPLIT_4 modeling system. Technical Memorandum ERL ARL-224, NOAA, Silver Spring, MD, 25 pp.. Available from http://www.arl.noaa.gov/data/web/models/hysplit4/win95/arl-224.pdf.

———, 1998: An overview of the HYSPLIT_4 modeling system for trajectories, dispersion, and deposition. *Australian Meteorological Magazine*, 47, 295–308.

Grell, G. A., 1993: Prognostic evaluation of assumptions used by cumulus parameterizations. *Mon. Weather Rev.*, **121** (**3**), 764–787.

Grell, G. A. and D. Dévényi, 2002: A generalized approach to parameterizing convection combining ensemble and data assimilation techniques. *Geophys. Res. Lett.*, **29** (**14**), 1693, doi:10.1029/2002GL015 311.

Haltiner, G. J. and R. T. Williams, 1980: *Numerical Prediction and Dynamic Meteorology*. 2d ed., Wiley, New York.

Lin, J. C., C. Gerbig, S. C. Wofsy, A. E. Andrews, B. C. Daube, K. J. Davis, and A. Grainger, 2003: A near-field tool for simulating the upstream influence of atmospheric observations: The stochastic time-inverted Lagrangian transport model (STILT). *J. Geophys. Res.*, **108** (**D16**), 4493, 10.1029/2002JD003 161.

Nehrkorn, T. and G. Modica, 2005: WRF module optimization study. *Joint WRF/MM5 Users' Workshop*, NCAR, Boulder, CO, available from http://www.mmm.ucar.edu/wrf/users/supports/workshop.html.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang, and J. G. Powers, 2005: A description of the advanced research WRF version 2. Technical Note 468+STR, MMM Division, NCAR, Boulder, CO, 88 pp.. Available from http://www.mmm.ucar.edu/wrf/users/docs/arw_v2.pdf.