WRF Data Assimilation System

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WRFDA System – Outline

- *Introduction*
- Compiling the code
- WRFDA software structure
- Computing overview

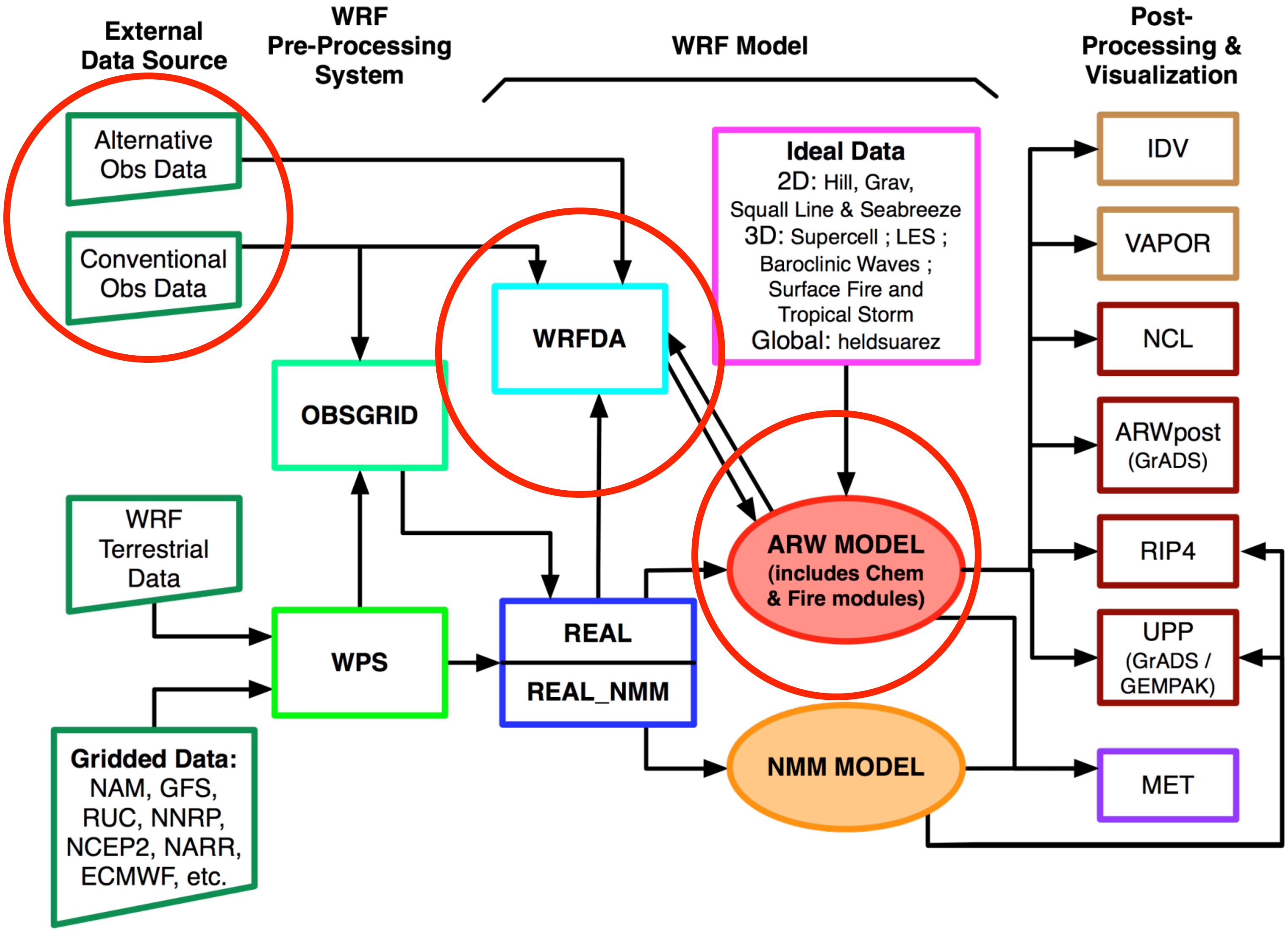
Introduction – What is WRFDA?

- A data assimilation system for the WRF Model (ARW core)
  - 3D- and 4D-VAR, FGAT, Ensemble, and Hybrid methods
- Designed to be flexible, portable and easily installed and modified
  - Open-source and public domain
  - Can be compiled on a variety of platforms
  - Part of the WRF Software Framework
- Designed to handle a wide variety of data
  - Conventional observations
  - Radar velocity and reflectivity
  - Satellite (radiance and derived data)
  - Accumulated precipitation

Introduction – What does WRFDA do?

- WRFDA takes a first guess of the atmospheric state, and combines that information with model error and observation information through one of several assimilation methods and background error options to produce a best guess of the atmospheric state at the given time

WRFDA in WRF Modeling System


External Data Source
WRF Pre-Processing System
WRF Model
Post-Processing & Visualization
Alternative Obs Data
Conventional Obs Data
WRFDA
OBSGRID
Ideal Data
2D: Hill, Grav, Squall Line & Seabreeze
3D: Supercell ; LES ; Baroclinic Waves ; Surface Fire and Tropical Storm
Global: heldsuarez
IDV
VAPOR
NCL
ARWpost (GrADS)
RIP4
UPP (GrADS / GEMPAK)
MET
WRF Terrestrial Data
WPS
REAL
REAL_NMM
ARW MODEL (includes Chem & Fire modules)
NMM MODEL
Gridded Data: NAM, GFS, RUC, NNRP, NCEP2, NARR, ECMWF, etc.

WRF Model review

- real.exe creates wrfinput_d* and wrfbdy_d01
  - wrfinput_d01 file contains the 3d-initial condition state for the parent domain
  - wrfbdy_d01 contains the lateral boundary conditions for the parent domain
  - For multiple domains, you will have wrfinput_d02, wrfinput_d03, etc., which are the initial conditions for domain 2, domain 3, etc., respectively. Boundary conditions for these files are taken from the parent domains
- wrf.exe creates wrfout_d* files
  - wrfout_d##_YYYY_MM_DD:mm:ss contains one or more 3d forecast states for domain ## starting at the indicated date/time

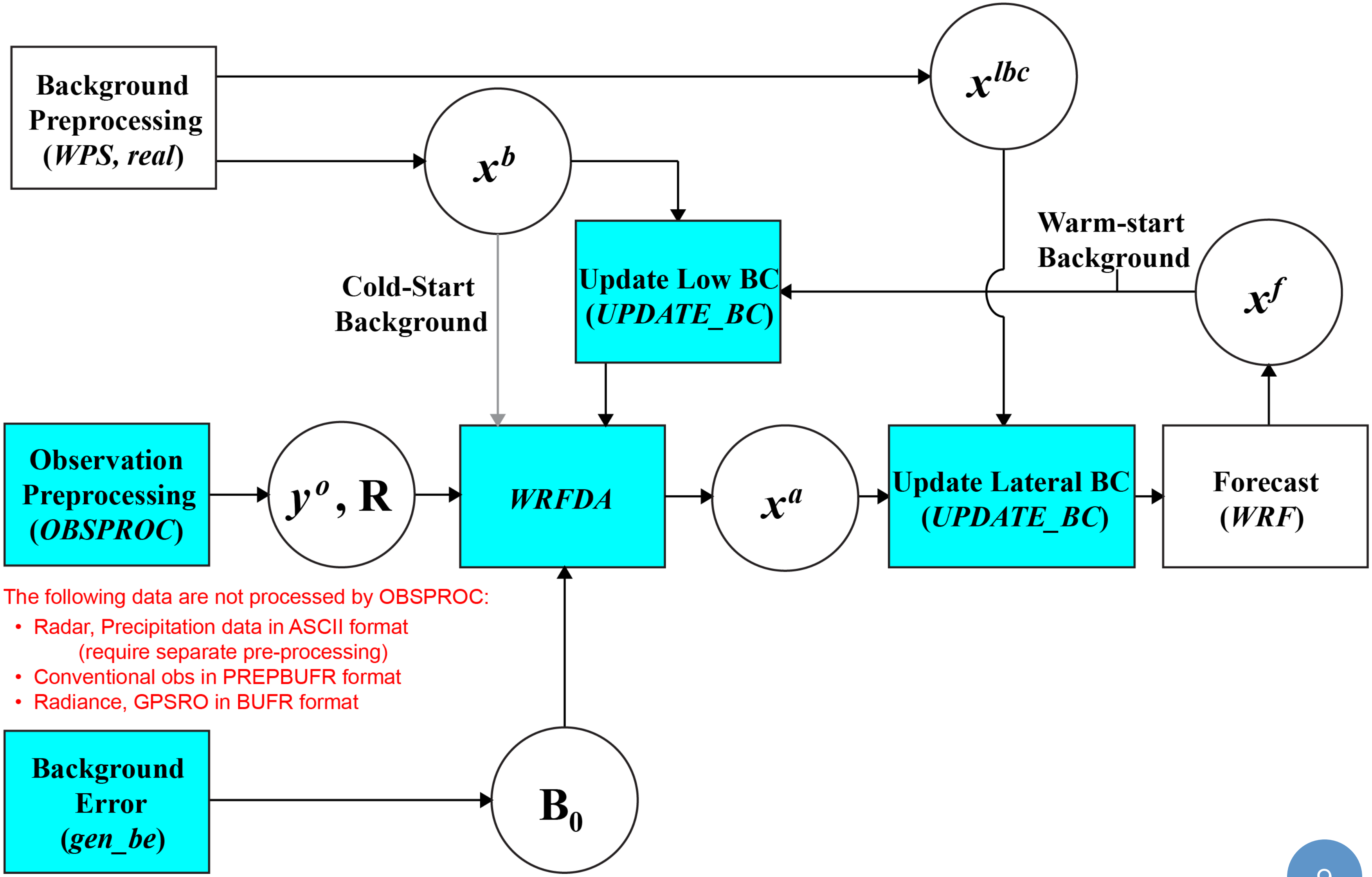
WRFDA in WRF Modeling System

- WRFDA takes a single WRF file (either wrfinput* or wrfout*) and creates a single output file (wrfvar_output)
  - This wrfvar_output file is the updated “best guess” of the atmospheric state after data assimilation
  - wrfvar_output is in the same format as wrfinput files, so can be used to initialize a WRF forecast
  - WRFDA can only use wrfout files which have a single time dimension (In WRF namelist: `frames_per_outfile=1`)
- To perform data assimilation on multiple domains or multiple times, you must run WRFDA multiple times with the appropriate input files

Cycling mode

- Because WRFDA can take WRF forecast files as input, the system can naturally be run in cycling mode
- WRFDA initializes a WRF forecast, the output of which is fed back into WRFDA to initialize another WRF forecast
- Requires boundary condition updating

WRFDA in the WRF Modeling System


Background Preprocessing (*WPS, real*)
x^{lbc}
x^b
Update Low BC (*UPDATE_BC*)
Warm-start Background
x^f
Cold-Start Background
Observation Preprocessing (*OBSPROC*)
y^o, R
WRFDA
x^a
Update Lateral BC (*UPDATE_BC*)
Forecast (*WRF*)
Background Error (*gen_be*)
B_0

The following data are not processed by OBSPROC:

- Radar, Precipitation data in ASCII format (require separate pre-processing)
- Conventional obs in PREPBUFR format
- Radiance, GPSRO in BUFR format

Blue: Supported by WRFDA team

WRFDA System – Outline

- Introduction
- *Compiling the code*
- WRFDA software structure
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Compiling – What is needed?

- WRFDA has similar system requirements to WRF
  - Can be run on a wide variety of UNIX and Linux-based systems
  - Linux/Mac, desktops/laptops, clusters with UNIX-based OS
- WRFDA computational requirements depend on your task
  - Running a small 3DVAR case may take less than 1GB of RAM
  - Large 4DVAR cases may require hundreds of GB
- A supported C and Fortran compiler
  - ifort/icc
  - gfortran/gcc
  - pgf90/pgcc
- Some have known problems; see http://www2.mmm.ucar.edu/wrf/users/wrfda/known-problems.html#compilers

Compiling – What is needed?

- Similar to WRF, there are required and optional libraries
  - netCDF C/fortran libraries are required, and must be downloaded and built by the user
    - http://www.unidata.ucar.edu/downloads/netcdf/index.jsp
  - MPI libraries (e.g. MPICH) are required for running WRFDA in parallel
  - BUFR libraries are required for reading PREPBUFR or radiance BUFR files, but they are included in WRFDA and built automatically

Compiling – What is needed?

- Similar to WRF, there are required and optional libraries
  - For radiance assimilation, a radiative transfer model is needed:
    - CRTM, the Community Radiative Transfer Model, is included with the WRFDA source code
    - RTTOV is provided by EUMETSAT/NWP SAF, and must be downloaded and built separately
      - https://nwpsaf.eu/deliverables/rtm/rtm_rttov11.html
  - New in version 3.8: AMSR2 radiance files in HDF5 format
    - HDF5 libraries are maintained by The HDF5 Group, and must be downloaded and built separately
      - https://www.hdfgroup.org/HDF5/

Compiling – Getting the source code

- Visit the WRFDA download website:
  - http://www2.mmm.ucar.edu/wrf/users/wrfda/download/get_source.html
- Click "New Users" and fill out the registration form, (registration is free), or
- Click "Returning users" and enter your email if you have previously registered to download a WRF product
- Download the latest tar file (Version 3.8)
- Unzip (`gunzip WRFDA_V3.8.tar.gz`) and un-tar (`tar -xvf WRFDA_V3.8.tar`) the code package
- You should see a directory named "WRFDA"; this is the WRFDA source code

WRFDA Directory structure

```
arch
clean
compile
configure
dyn_em
dyn_exp
external
frame
inc
main
Makefile
phys
README.DA
README.io_config
Registry
run
share
test
tools
var
```

build scripts

README file with information about WRFDA

Contains `registry.var`

WRFDA source code directory

Legend:
Blue – directory
Green – script file
Gray – other text file

WRFDA/var Directory structure

build ← *Executables built here*

convertor

da ← *WRFDA main source code contained here*

external ← *Source code for external libraries (CRTM, BUFR, etc.)*

gen_be ← *GEN_BE source code*

graphics

Makefile

obsproc ← *OBSPROC source code*

README.basics
README.namelist
README.radiance } *More README files with useful information*

run ← *Useful runtime files (mostly for radiance)*

scripts

test ← *Data for tutorial cases*

Legend:
Blue – directory
Green – script file
Gray – other text file

WRFDA/var/da Directory structure

Main WRFDA Program (driver): `da_main`

WRFDA Subroutines (mediation layer)

```
da_4dvar
da_control
da_etkf
da_define_structures
da_dynamics
da_grid_definitions
da_interpolation
da_minimisation
da_physics
da_setup_structures
da_varbc
da_vtox_transforms
```

Observation Types

```
da_airep
da_airsr
da_bogus
da_buoy
da_geoamv
da_gpspw
da_gpsref
da_metar
da_mtgirs
da_pilot
da_polaramv
da_profiler
da_pseudo
da_qscat
da_radar
da_radiance
da_rain
da_satem
da_ships
da_sound
da_ssmi
da_synop
da_tamdar
```

Compiling – Preparing the environment

- As mentioned before, some libraries are required for WRFDA, and some are optional depending what you are using WRFDA for
  - netCDF is required; you should set an environment variable to specify where the netCDF libraries are built on your system:
  - `setenv NETCDF full_path_for_NETCDF`
- If you plan on doing radiance assimilation, you will need CRTM or RTTOV. WRFDA can be built with either or both
  - The CRTM source code is included in the WRFDA package, use `setenv CRTM 1` to build it
  - To use RTTOV, set an environment variable specifying where RTTOV is built on your system:
  - `setenv RTTOV full_path_for_RTTOV`

Compiling – Preparing the environment

- If you plan on assimilating AMSR2 data, you will need to link to the HDF5 libraries
  - Set an environment variable specifying where HDF5 is built on your system:
  - `setenv HDF5 full_path_for_HDF5`
- To build the code faster, if your computer has the gnu make utility, you can set the environment variable J to build the code in parallel
  - `setenv J "-j 4"` (will build on 4 processors)
  - Note that this is different from compiling the code to *run* in parallel

Compiling – Building the WRFDA code

- Two scripts must be run to build the code:
- `configure` asks for some information about your machine and how you want to build the code, and generates a `configure.wrf` file
- `./configure wrfda`

```
> ./configure wrfda
checking for perl5... no
checking for perl... found /usr/bin/perl (perl)
Will use NETCDF in dir: /usr/local/netcdf-3.6.3-gfortran
Will use HDF5 in dir: /usr/local/hdf5-1.8.15-gcc
PHDF5 not set in environment. Will configure WRF for use without.
Will use 'time' to report timing information
$JASPERLIB or $JASPERINC not found in environment, configuring to build without grib2 I/O...
------------------------------------------------------------------------
Please select from among the following Linux x86_64 options:

  1. (serial)   2. (smpar)   3. (dmpar)   4. (dm+sm)   PGI (pgf90/gcc)
  5. (serial)   6. (smpar)   7. (dmpar)   8. (dm+sm)   PGI (pgf90/pgcc): SGI MPT
  9. (serial)  10. (smpar)  11. (dmpar)  12. (dm+sm)   PGI (pgf90/gcc): PGI accelerator
 13. (serial)  14. (smpar)  15. (dmpar)  16. (dm+sm)   INTEL (ifort/icc)
 ... ... ...
```

- Select the option that is best for your purposes

Compiling – Building the WRFDA code

- Two scripts must be run to build the code:
- `compile` compiles all the code for the settings you specified

```
./compile all_wrfvar >& compile.wrfda.log
```

- Depending on your machine and what options you have selected, compilation can take less than 5 minutes up to an hour. For example, gfortran compiles WRFDA quite quickly, while intel compilers take longer to build (but the executables may run faster)

Compiling – review compiled code

- When the compilation script is completed, you should see the message “build completed:” followed by the date and time.
- The script does not automatically check to make sure all executables were successfully built; you will need to check manually
- There should be 44 executables built all together: 43 in the WRFDA/var/build directory, and WRFDA/var/obsproc/obsproc.exe
- In all likelihood, you will not use most of these directly: the majority of them are called by scripts for various diagnostic packages

Compiling – review executables

- These are the executables you will most likely be using:
- da_wrfvar.exe
  - The main WRFDA executable: this program will perform the actual data assimilation and output a WRF-formatted wrfvar_output file
- obsproc.exe
  - The executable for OBSPROC, the observation pre-processor for text-based observation formats
- da_update_bc.exe
  - The executable for UPDATE_BC; used for updating boundary conditions after assimilation and during cycling runs

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- Introduction
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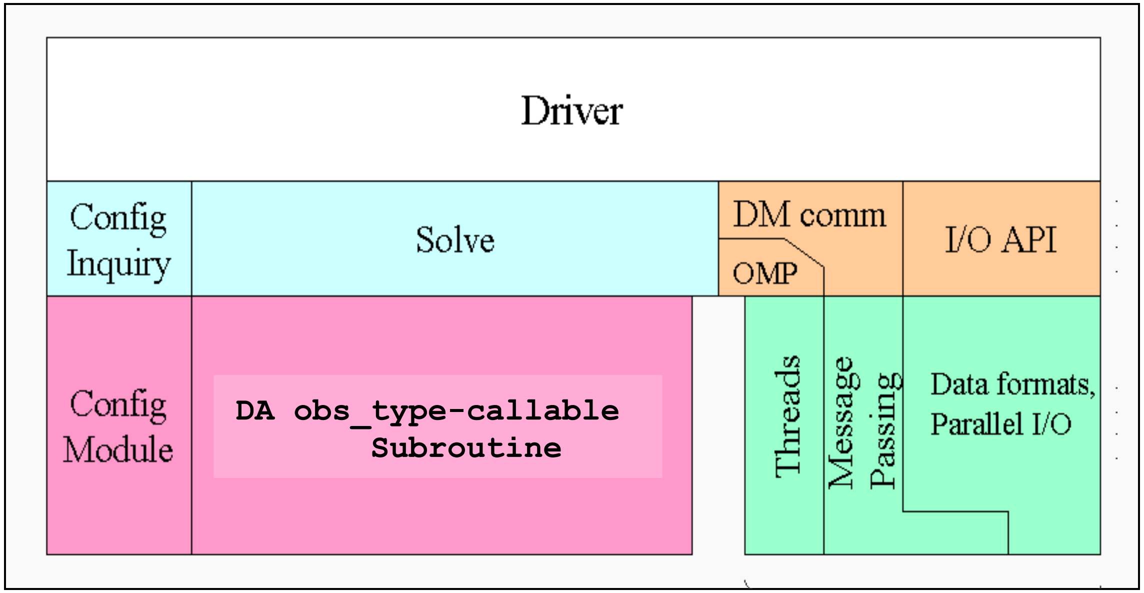
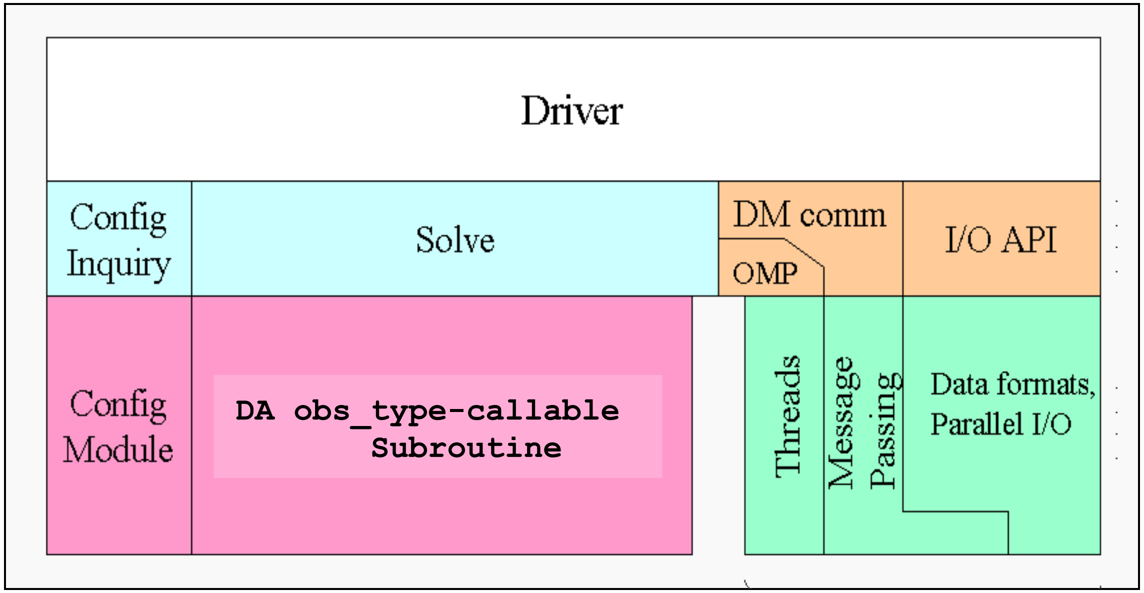
- *WRFDA software structure*
- Computing overview

WRFDA Software – Architecture



- Hierarchical software architecture
  - Insulate scientists' code from parallelism and other architecture/implementation-specific details
  - Well-defined interfaces between layers, and external packages for communications, I/O.

WRFDA Software – Architecture



Registry.wrfvar

- Registry: an “Active” data dictionary
  - Tabular listing of model state and attributes
  - Large sections of interface code generated automatically
  - Scientists manipulate model state simply by modifying Registry, without further knowledge of code mechanics
  - **registry.var** is the main dictionary for WRFDA
  - registry.var is combined at compile time with Registry.EM_COMMON.var and others to produce Registry.wrfvar, which contains all of the registry definitions used by WRFDA

WRFDA Software – Architecture

registry.var

Variable type

Variable name

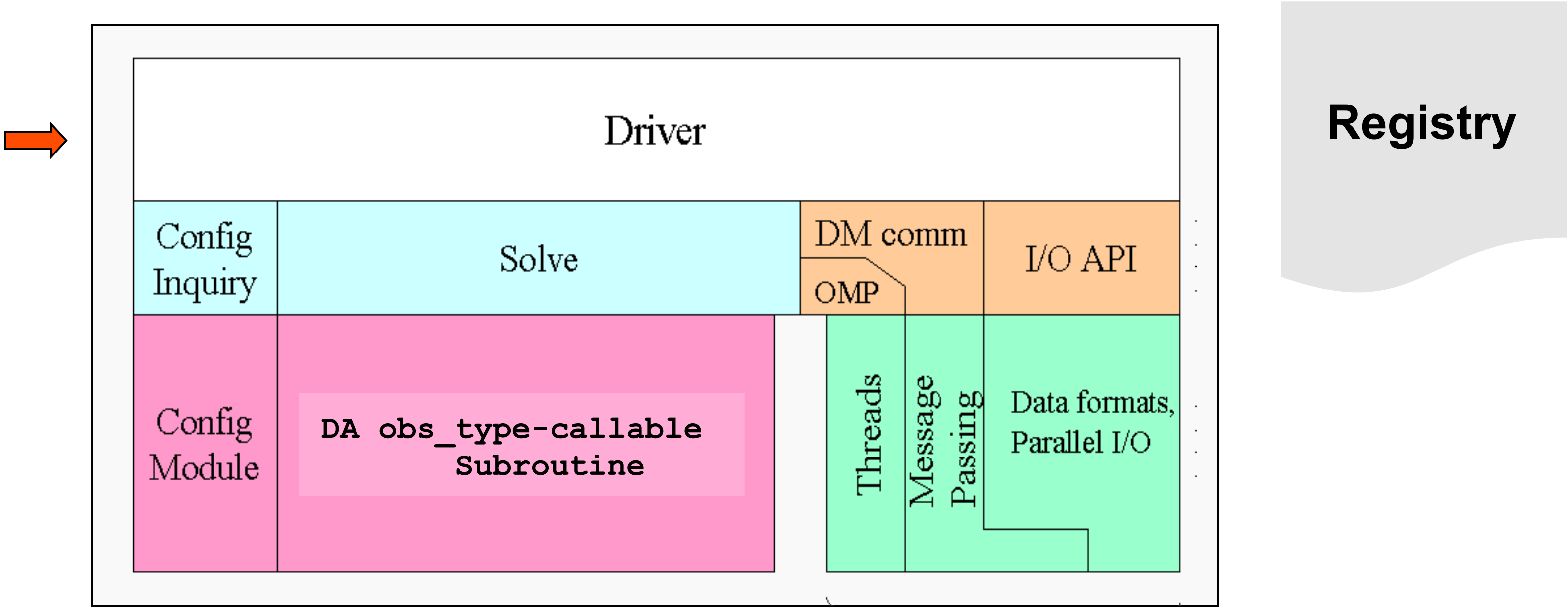
Namelist name

Variable size

Default value

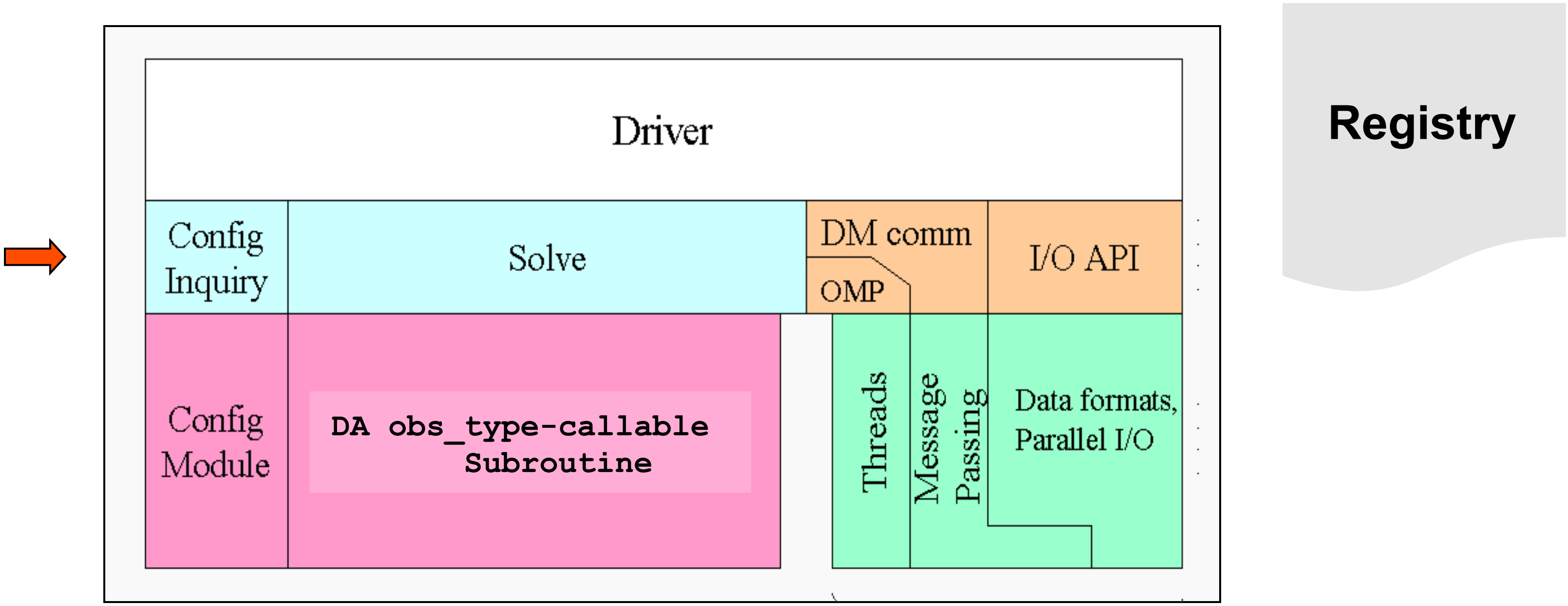
```
rconfig   integer   rttov_emis_atlas_ir      namelist,wrfvar14  1   0         - "rttov_emis_atlas_ir"       ""   ""
rconfig   integer   rttov_emis_atlas_mw      namelist,wrfvar14  1   0         - "rttov_emis_atlas_mw"       ""   ""
rconfig   integer   rtminit_print            namelist,wrfvar14  1   1         - "rtminit_print"             ""   ""
rconfig   integer   rtminit_nsensor          namelist,wrfvar14  1   1         - "rtminit_nsensor"           ""   ""
rconfig   integer   rtminit_platform         namelist,wrfvar14  max_instruments -1      - "rtminit_platform"       ""
rconfig   integer   rtminit_satid            namelist,wrfvar14  max_instruments -1.0    - "rtminit_satid"          ""
rconfig   integer   rtminit_sensor           namelist,wrfvar14  max_instruments -1.0    - "rtminit_sensor"         ""
rconfig   integer   rad_monitoring           namelist,wrfvar14  max_instruments 0       - "rad_monitoring"         ""
rconfig   real      thinning_mesh            namelist,wrfvar14  max_instruments 60.0    - "thinning_mesh"          ""
rconfig   logical   thinning                 namelist,wrfvar14  1   .true.    - "thinning "                 ""   ""
rconfig   logical   read_biascoef            namelist,wrfvar14  1   .false.   - "read_biascoef"             ""   ""
rconfig   logical   biascorr                 namelist,wrfvar14  1   .false.   - "biascorr"                  ""   ""
rconfig   logical   biasprep                 namelist,wrfvar14  1   .false.   - "biasprep"                  ""   ""
rconfig   logical   rttov_scatt              namelist,wrfvar14  1   .false.   - "rttov_scatt"               ""   ""
rconfig   logical   write_profile            namelist,wrfvar14  1   .false.   - "write_profile"             ""   ""
rconfig   logical   write_jacobian           namelist,wrfvar14  1   .false.   - "write_jacobian"            ""   ""
rconfig   logical   qc_rad                   namelist,wrfvar14  1   .true.    - "qc_rad"                    ""   ""
rconfig   logical   write_iv_rad_ascii       namelist,wrfvar14  1   .false.   - "write_iv_rad_ascii"        ""   ""
rconfig   logical   write_oa_rad_ascii       namelist,wrfvar14  1   .false.   - "write_oa_rad_ascii"        ""   ""
rconfig   logical   write_filtered_rad       namelist,wrfvar14  1   .false.   - "write_filtered_rad"        ""   ""
rconfig   logical   use_error_factor_rad     namelist,wrfvar14  1   .false.   - "use_error_factor_rad"      ""   ""
rconfig   logical   use_landem               namelist,wrfvar14  1   .false.   - "use_landem"                ""   ""
rconfig   logical   use_antcorr              namelist,wrfvar14  max_instruments .false.  - "use_antcorr"       ""   "
rconfig   logical   use_mspps_emis           namelist,wrfvar14  max_instruments .false.  - "use_mspps_emis"    ""   "
rconfig   logical   use_mspps_ts             namelist,wrfvar14  max_instruments .false.  - "use_mspps_ts"      ""   "
```

WRFDA Software – Architecture



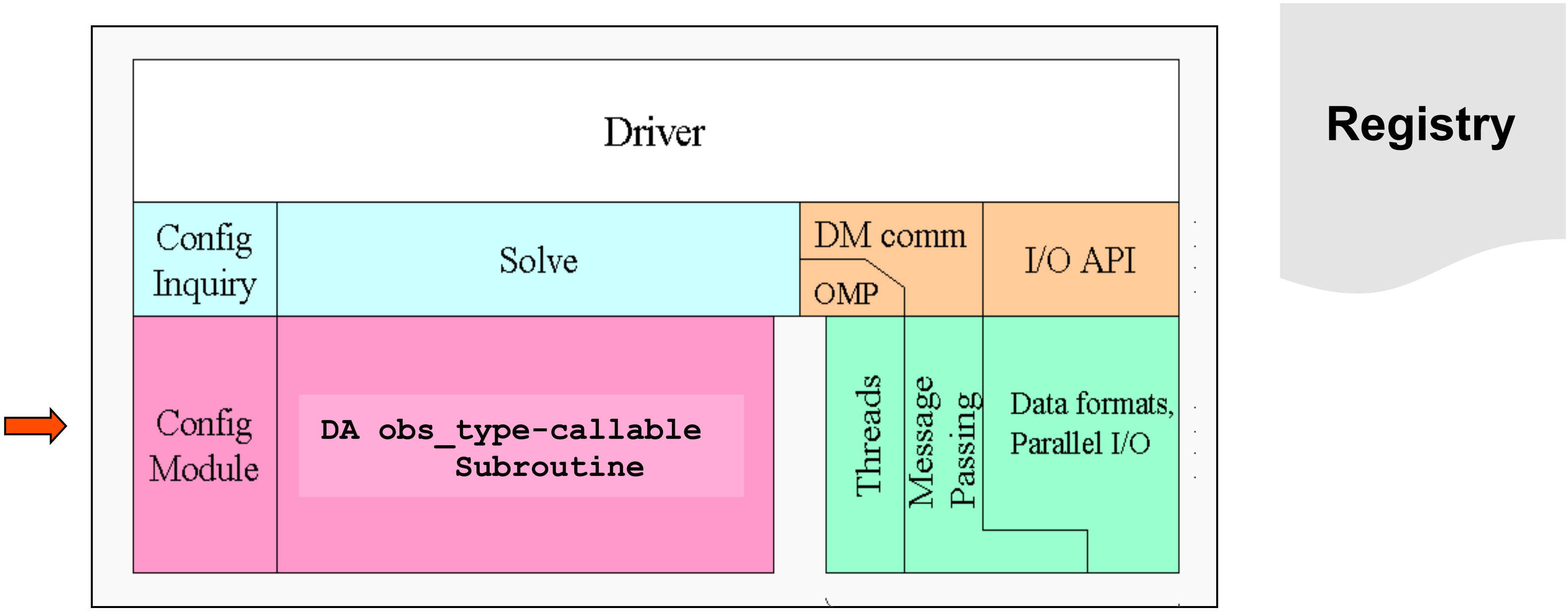
- Driver Layer
  - **Domains**: Allocates, stores, decomposes, represents abstractly as single data objects

WRFDA Software – Architecture



- Minimization/Solver Layer
  - Minimization/Solver routine, choose the function based on the namelist variable, 3DVAR, 4DVAR, FSO or Verification, and choose the minimization algorithm.

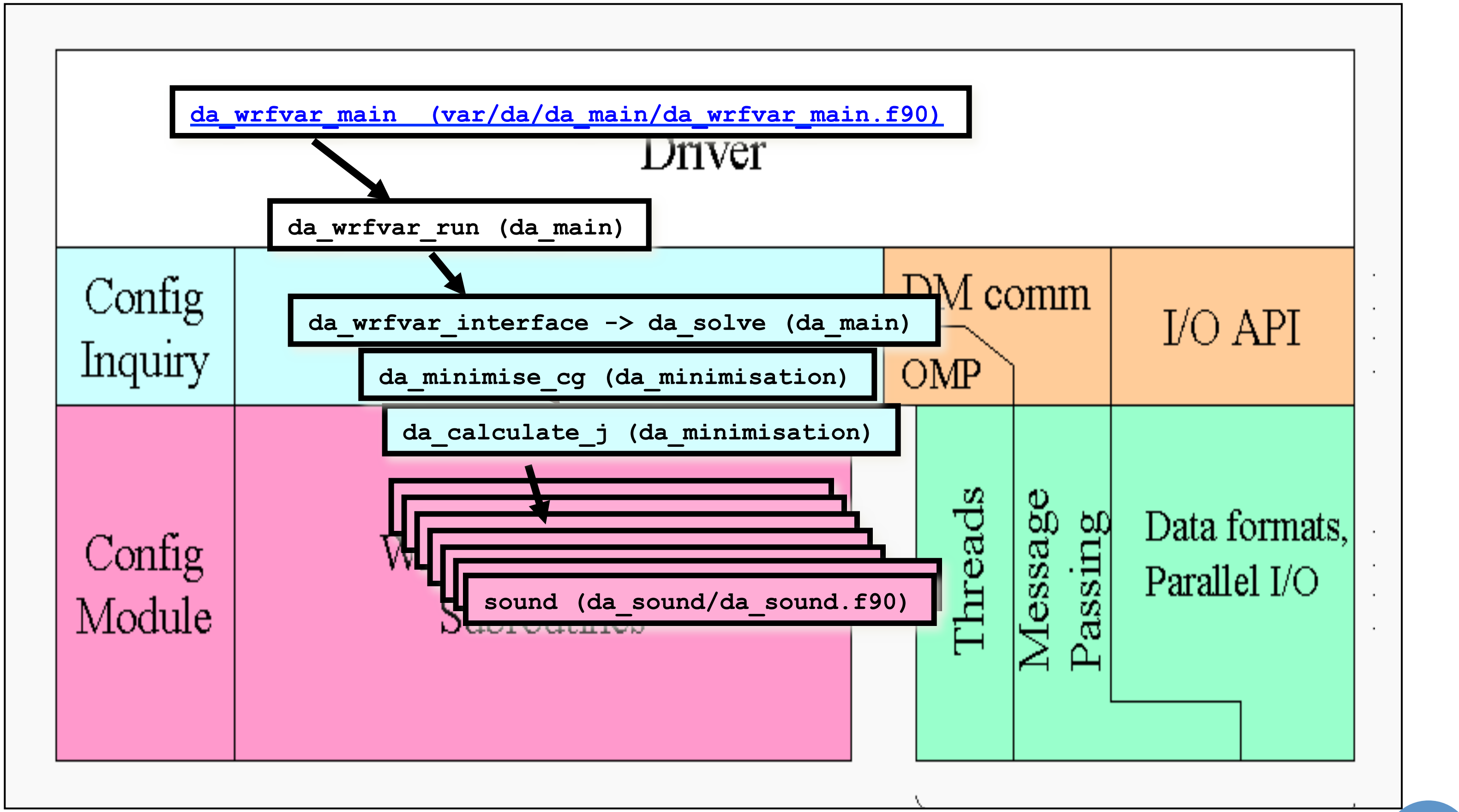
WRFDA Software – Architecture



- Observation Layer
  - **Observation interfaces**: contains the gradient and cost function calculation subroutines for each type of observations.

Call Structure Superimposed on Architecture

da_sound.f90(da_sound)


da_wrfvar_main (var/da/da_main/da_wrfvar_main.f90)
Driver
da_wrfvar_run (da_main)
Config Inquiry
da_wrfvar_interface -> da_solve (da_main)
da_minimise_cg (da_minimisation)
DM comm
OMP
I/O API
da_calculate_j (da_minimisation)
Config Module
sound (da_sound/da_sound.f90)
Threads
Message Passing
Data formats, Parallel I/O

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- Introduction
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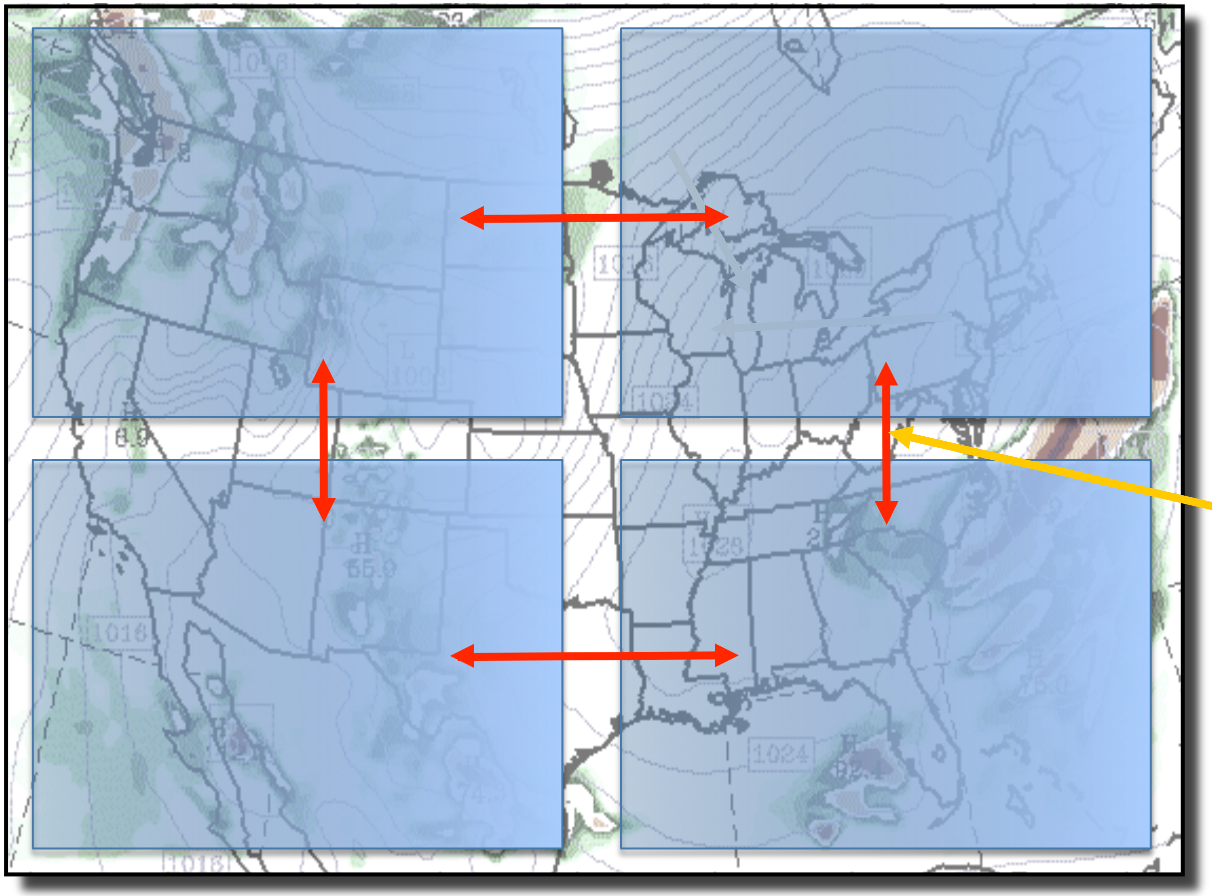
- WRFDA software overview
- *Computing overview*

WRFDA Parallelism

- WRFDA can be run serially or as a parallel job
- WRFDA uses ***domain decomposition*** to divide total amount of work over parallel processes
- The decomposition of the application over processes has two levels:
  - The ***domain*** is broken up into rectangular pieces that are assigned to MPI (distributed memory) processes. These pieces are called ***patches***
  - The ***patches*** may be further subdivided into smaller rectangular pieces that are called ***tiles***, and these are assigned to ***shared-memory threads*** within the process.
- *However, WRFDA does not support shared memory parallelism! So distributed memory is what I will cover here.*

Parallelism in WRFDA: Multi-level Decomposition



Inter-processor communication

Distributed Memory Communications

When Needed?

Communication is required between patches when a horizontal index is incremented or decremented on the right-hand-side of an assignment.

Why?

On a patch boundary, the index may refer to a value that is on a different patch.

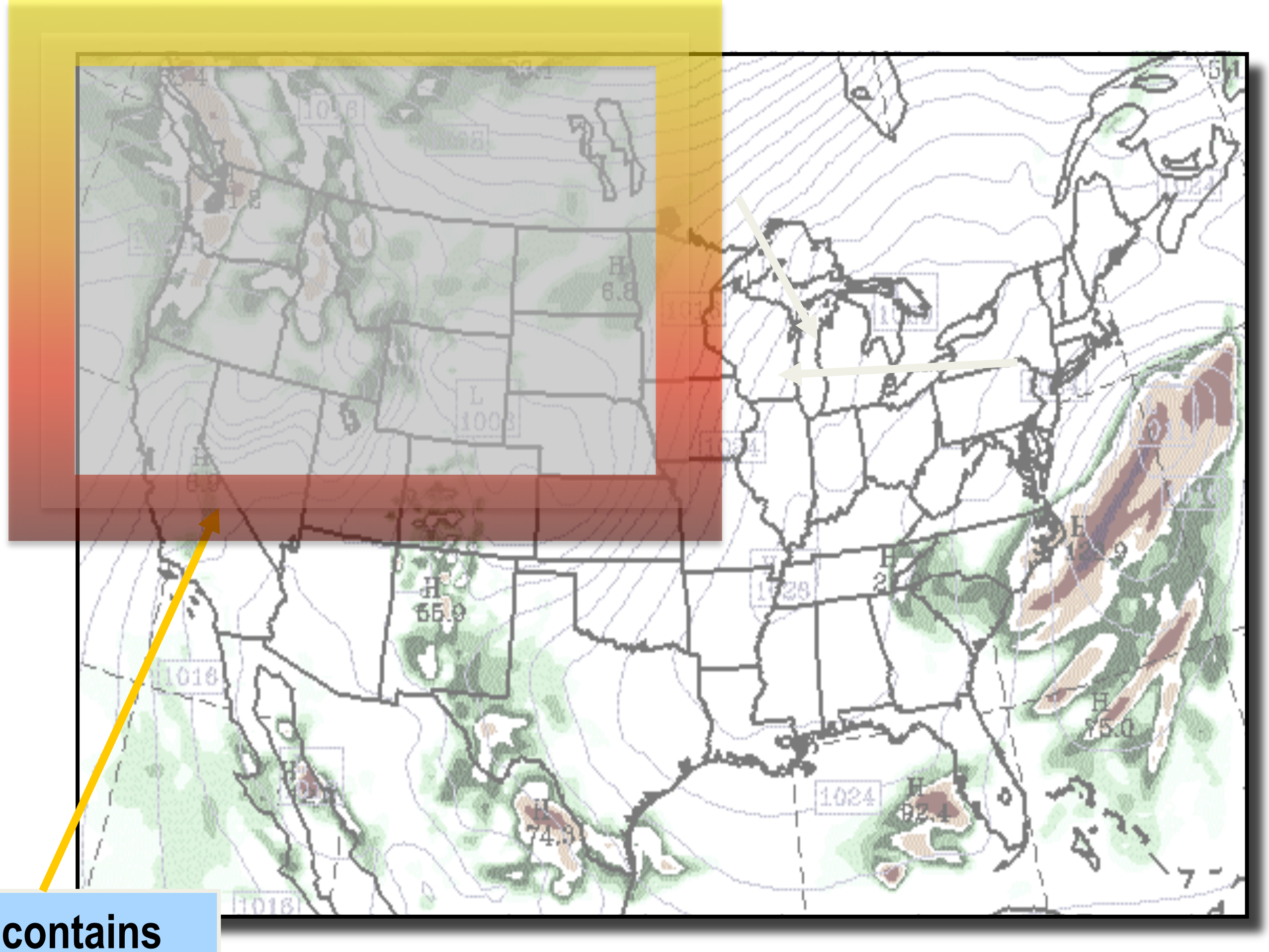
Following is an example code fragment that requires communication between patches

Signs in code

Note the tell-tale +1 and –1 expressions in indices for rr, H1, and H2 arrays on right-hand side of assignment.

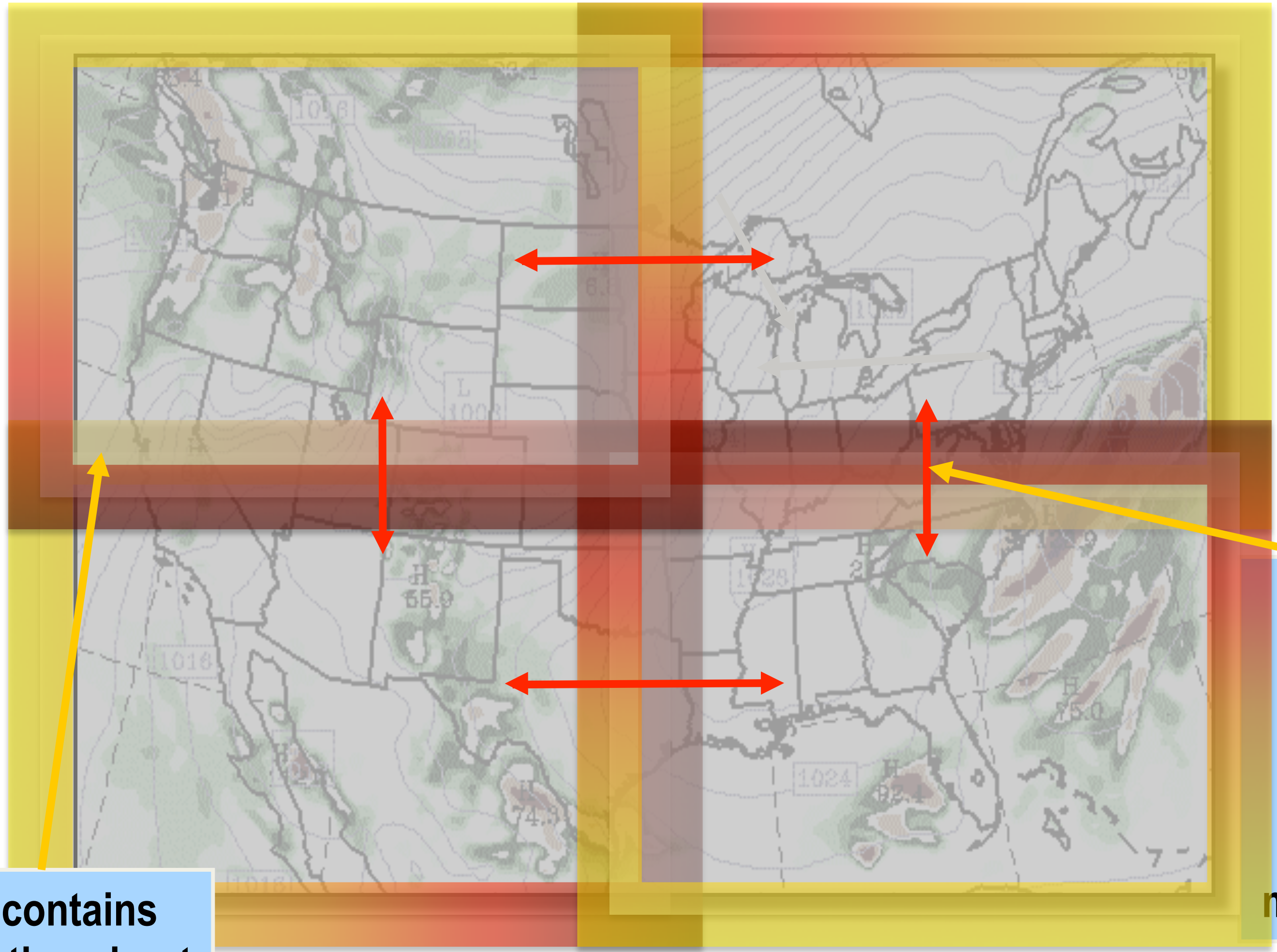
These are *horizontal data dependencies* because the indexed operands may lie in the patch of a neighboring processor. That neighbor's updates to that element of the array won't be seen on this processor.

Distributed Memory Communications



Halo (contains information about adjacent patch)

Distributed Memory Communications



Halo (contains information about adjacent patch)

Inter-processor communication

(Halos update from adjacent patch after each minimization step)

Grid Representation in Arrays

- Increasing indices in WRFDA arrays run
  - West to East (X, or I-dimension)
  - South to North (Y, or J-dimension)
  - Bottom to Top (Z, or K-dimension)
- Storage order in WRFDA is IJK , but for WRF, it is IKJ (ARW) and IJK (NMM)
- Output data has grid ordering independent of the ordering inside the WRFDA model

Grid Representation in Arrays

- The extent of the logical or *domain* dimensions is always the "staggered" grid dimension. That is, from the point of view of a non-staggered dimension (also referred to as the ARW “mass points”), there is always an extra cell on the end of the domain dimension
- In WRFDA, the minimization is on A-grid (non-staggered grid). The wind components will be interpolated from A-grid to C-grid (staggered grid) before they are output, to conform with standard WRF format

Summary

- WRFDA
  - is designed to be an easy-to-use data assimilation system for use with the WRF model
  - is designed within the WRF Software Framework for rapid development and ease of modification
  - is compiled in much the same way as WRF
  - can be run in parallel for quick assimilation of large amounts of data on large domains

Appendix – WRFDA Resources

- WRFDA users page
  - http://www2.mmm.ucar.edu/wrf/users/wrfda
  - Download WRFDA source code, test data, related packages and documentation
  - Lists WRFDA news and developments
- Online documentation
  - http://www2.mmm.ucar.edu/wrf/users/docs/user_guide_V3/users_guide_chap6.htm
  - Chapter 6 of the WRF Users' Guide; documents installation of WRFDA and running of various WRFDA methods
- WRFDA user services and help desk
  - wrfhelp@ucar.edu

Appendix – WRFDA History

- Developed from MM5 3DVar beginning around 2002, first version (2.0) released December 2003
- 4DVAR capability added in 2008, made practical with parallelism starting with Version 3.4 (April 2012)
- Developed and supported by WRFDA group of the Mesoscale and Microscale Meteorology Lab of NCAR
- Requirements emphasize flexibility over a range of platforms, applications, users, performance
- Current release WRFDA v3.8 (April 2016)
- Shares the WRF Software Framework