Multi-sensor Advection Diffusion nowCast (MADCast) for cloud analysis and short-term prediction

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Multi-sensor Advection Diffusion nowCast (MADCast) for cloud analysis and short-term prediction

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Abstract: A new approach designed for the analysis and short-term forecasting of clouds, called Multi-sensor Advection-Diffusion nowCast (MADCast), has been implemented within the Weather Research and Forecasting (WRF) model and data assimilation platforms. In this approach, profiles of cloud fractions are retrieved from multiple infrared sensors using the Multivariate Minimum Residual (MMR) scheme. These profiles are then projected to the grid of the numerical weather prediction model, which is used to dynamically transport and diffuse the clouds in three dimensions.
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1. **INTRODUCTION**

The initialization of clouds in Numerical Weather Prediction (NWP) models is a difficult problem that has recently received increased scrutiny. Current data assimilation methods are challenged by the high spatio-temporal variability of clouds, strong non-linearities in the radiative transfer calculation, and non-Gaussian error distributions. Furthermore, even with the new generation of satellite sensors, clouds are fundamentally under-observed and the initialization process needs to rely on ancillary information to determine the non-observed cloud variables. However, the usual balance equations defined at synoptic scale are not applicable for convection-permitting scales and model balance via ensembles of forecasts is affected by systematic model errors. For these reasons, NWP prediction is usually outperformed by simple advection methods in the first hours of forecast (*i.e.* nowcasting, Guillot E. M. et al., 2012).

This document describes first the methodology developed and then shows how this new scheme is implemented in the different modelling system component programs such as the Weather Research and Forecasting model (WRF), the Community Radiative Transfer Model (CRTM) and the Gridpoint Statistical Interpolation system (GSI, Kleist et al., 2009) or the WRF Data Assimilation system (WRFDA, Barker et al., 2012). Finally, it explains how to setup a test case and to evaluate the results.

2. **METHODOLOGY**

The Multi-sensor Advection Diffusion nowCast (MADCast) system is a novel approach for cloud nowcasting based on cloud fraction retrieval using multiple infrared satellite sensors, a simplified version of the WRF model and data assimilation. The three main components are shown in Figure 1 and detailed in this section.
Figure 1. Flowchart of the MADCast system, which is composed of three main steps: first, it retrieves vertical profile of cloud fraction by pixel from various InfraRed (IR) sensors, then it combines them to perform a single gridded analysis of cloud fraction, and finally a forecast is launched and cycling is allowed.

2.1 Cloud fraction retrieval

The fundamental piece of the system is the Multivariate Minimum Residual (MMR) scheme proposed by Auligné (2014a,b). This process has been implemented in a data assimilation system and the three main steps leading to cloud fraction retrieval are explained below:

1. Comparison of satellite infrared radiance observations with their equivalents from a numerical model output (WRF) using the Community Radiative Transfer Model (CRTM) under clear sky hypothesis.
2. A data assimilation system (GSI or WRFDA) is used to compute the departures between the observations and their model equivalent (hereinafter simply called departures). These departures are calculated for multiple channels sensitive to different altitudes in the atmosphere.
3. Application of the MMR scheme to solve a variational problem for every satellite field-of-view individually and to retrieve a cloud profile (similarly to a 1DVar approach). The retrieval process is fast and properly constrained due to the simple representation of the cloud via a vertical stack of thin, opaque blackbody clouds. The control variable is hence reduced to the cloud fraction at every vertical level.
2.2 3-D Multi sensor approach

The next component of the nowcasting system is the interpolation of the cloud columns from the satellite fields-of-view to the model grid points. The footprint of a satellite measurement depends on its scan angle (Figure 2). Therefore, the interpolation from the observation locations onto the NWP model grid handles these parameters and it is currently implemented for AIRS and IASI instruments. Figure 3 shows an example of the interpolation of IASI retrievals to the WRF model grid with a 15 km resolution.

Specific procedures are also used to optimally combine the information from sounders (with high vertical accuracy but low horizontal resolution) with imagers (with low vertical accuracy and high horizontal resolution). These procedures are perfectible, yet they produce reasonable results. The resulting product is a three-dimensional gridded field of cloud fraction that fits precisely the measurements for a combination of infrared satellite instruments. The MMR scheme has been implemented successfully for several satellite infrared instruments onboard polar-orbiting and geostationary platforms, including AIRS, IASI, CrIS, MODIS, GOES-Imager, and GOES-Sounder. A validation of the results has been conducted with synthetic and real data, inter-comparison between instruments, and independent observations such as CloudSat (Xu et al., 2014).

![Figure 2](image)

*Figure 2. (a) Size of the interpolation radius as a function of scan angle for IASI. (b) Example of IASI fields of view on the edge of the swath. The 4x4 pixel matrix explains the shape of the curve in (a).*
2.3 Forecast and rapid update cycling

The forecasting component of the system is constructed via the WRF dynamical core. This provides dynamical transport and diffusion of clouds over time. Technically, the WRF model is run without any physics, treating the 3-D gridded cloud fraction as a dynamical tracer. This approach is faster than a full NWP model implementation while preserving acceptable skills for short-term forecasts in situations without significant changes in the cloud thermo-dynamical structure.

The last component of the cloud nowcasting system is the implementation of a rapid-update cycling (currently every hour). In observation-rich areas, new information is overwriting the latest forecast whereas unobserved regions remain unchanged. This procedure ensures that the system is always using the most recent information. The age of the information is recorded and transported in time (as an additional tracer) to allow for optimal combination of forecast data with new observations. Each updated state becomes in turn the initial point for a new forecast, which will not suffer from the usual model spin-down problems since clouds are treated as tracers and they do not interact with the model physics. Figure 4 shows the sum of cloud fraction over the model vertical levels over the Continental United States (CONUS) domain at 15 km resolution. The analysis resulted from a combination of GOES, AIRS and IASI sensors. Diffusion tends to smooth the cloud fields with forecast lead-time and in this example the lack of accurate lateral boundary conditions is noticeable.
Figure 4. Forecast of vertically integrated cloud fraction (in %) from the WRF model at a) $t+0h$, b) $t+1h$, c) $t+3h$ and d) $t+6h$. 
3. IMPLEMENTATION

The MMR algorithm, the basis of the MADCast system, was implemented in both GSI and WRFDA. It does not require additional input data files, other than the files regularly needed by GSI and WRFDA. In output, it creates two new additional 3-dimensional fields (cloud fraction and cloud fraction age) that are written out in the WRF files, otherwise generated as output of GSI or WRFDA. As such, its application is transparent to GSI and WRFDA users. Some changes are needed in the WRF community model, so that WRF can recognize those new fields as tracers. The modified WRF model will then be able to transport the retrieved cloud fraction and its age to the next analysis time during the forecast.

3.1 Processing of all-sky radiances from multiple sensors

The current MADCast system has the capability to ingest all-sky radiances from the following instruments:

- AIRS, IASI, CrIS provided by the National Centers for Environmental Prediction operational (NCEP) in BUFR format.
- MODIS from Aqua and Terra provided by NASA in HDF format
- GOES-imager from GOES-13 and GOES-15 provided by NASA in NetCDF format.
- FY-2D VISSR, Himawari-7 MTSAT-2, METEOSAT-10 SEVIRI through AFWA proprietary feed in binary format.

For GSI purposes, file pre-processors have been developed to convert MODIS and GOES data into BUFR files.

3.2 Modification of the Community Radiative Transfer Model (CRTM)

The JCSDA CRTM version 2.1.3 code has been modified to compute cloud overcast radiances. A new array was appended to the CRTM internal data structure and logic for the computation of radiances with an overcast cloud (i.e. an opaque black cloud) at each model level during the radiative transfer calculations was added. The modifications do not significantly increase the computational cost of the radiative transfer calculations in GSI. Comparisons between the modified CRTM and the Radiative Transfer for TIROS Operational Vertical Sounder (RTTOV) radiative transfer code, which already contains similar changes, show same performances. Table 1 lists the modified routines in CRTM and the nature of these modifications.
### Table 1. Description of the implementation of the Overcast radiances computation in CRTM2.1.3 code.

<table>
<thead>
<tr>
<th>Modifications in the CRTM2.1.3</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRTM_RTSolution_Define.f90</td>
<td>The type CRTM_RTSolution_type includes a new allocatable array Overcast to pass the overcast radiances as output arguments.</td>
</tr>
<tr>
<td>RTV_Define.f90</td>
<td>The Overcast array is defined in the RTV_type structure that holds forward variables across FWD, Tangent Linear, and Adjoint calls.</td>
</tr>
<tr>
<td>Emission_Module.f90</td>
<td>The overcast radiances are computed and stored temporary in the RTV%Overcast array. (CRTM_Emission routine)</td>
</tr>
<tr>
<td>Common_RTSolution.f90</td>
<td>The function Assign_Common_Output fills the RTSolution optional structure with Overcast radiances of the table RTV%Overcast</td>
</tr>
</tbody>
</table>

#### 3.3 Cloud Analysis

**a) Implementation in GSI**

All the methods specific to the Multivariate Minimum Residual scheme are gathered in the new Fortran module *ncar_cldfra_mod.f90* and presented in Table 2. The MMR scheme, encapsulated in the *da_cloud_detect* Fortran routine, performs the minimization to retrieve the cloud fraction profiles for each instrument field-of-view by using the following successive steps:

1. Convert observed brightness temperature to radiance using CRTM2.0 conversion interface for all the channels. The ratio between overcast radiance and observed radiance is computed and used during the minimization process.
2. Initialize the cloud fraction profile with the model first-guess if the flag *lcldfra_warm* is activated.
3. Use the solver *inria_n2qn1*. At each iteration, the routine *da_cloud_sim* simulates the cloudy radiance from the cloud fraction profile, and computes the cost function and its gradient.
4. Interpolate the resulting cloud profile onto the model grid.

This process is iterated for all pixels of all InfraRed (IR) sensors as described in Figure 5. The order of the sensors, in the loop, defined in the namelist section *&OBS_INPUT*, affects the results as the new solution overwrites the previous. The IR sensors have a different spectral (number of channels) and horizontal resolution. For specific application, it may be important to define an order that can benefit the analysis with the best horizontal or vertical resolution as the last sensor information will overwrite the previous.
Figure 5. Flowchart of the cloud fraction retrieval process, which is performed in an iterative way over the pixels of all the available sensors. First, the MMR scheme computes observed, modelled and overcast radiance by pixel of a sensor. Then, from a first guess defined in cloud fraction, it minimizes a cost function defined in terms of radiance to ultimately interpolate the analysis onto the horizontal grid, thus filling out the gap between pixels.

When the flag `incar_cldfra` is activated in the namelist, the regular quality check for satellite radiances is bypassed and GSI will stop after the calculations of the innovations. The GSI `setuprad.f90` routine then reads the overcast radiances from the
modified CRTM code and applies the MMR scheme. Table 3 gathers the key modifications to implement the MMR scheme in the GSI code.

<table>
<thead>
<tr>
<th>Content of the module ncar_cldfra_mod.f90</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>init_ncar_cldfra</td>
<td>Read cloud fraction variable name available in a first guess meteorological file</td>
</tr>
<tr>
<td>interp_to_grid_simple</td>
<td>The cloud fraction retrieval from each pixel is attributed to the four neighbouring grid points</td>
</tr>
<tr>
<td>interp_to_grid_fill</td>
<td>The cloud fraction retrieval from each pixel is interpolated to the model grid by accounting for gaps between neighbouring pixels.</td>
</tr>
<tr>
<td>da_cloud_sim</td>
<td>Simulate the cloudy radiance as a linear combination of overcasts and clear radiances</td>
</tr>
<tr>
<td>inria_n2qn1</td>
<td>Interface to the constrained version of the m1qn3 minimizer. The use of n2qn1 code requires a license from INRIA, France.</td>
</tr>
<tr>
<td>da_cloud_detect</td>
<td>Define and encapsulate all MMR scheme to retrieve cloud fraction</td>
</tr>
<tr>
<td>read_afwa_binary_check, read_afwa_binary_header, read_afwa_binary_data</td>
<td>Specific readers of radiance data provided by AFWA in binary format.</td>
</tr>
</tbody>
</table>

*Table 2. Description of the content of new the Fortran module ncar_cldfra_mod.f90.*

<table>
<thead>
<tr>
<th>Key Modification in the GSI code src/main/</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>setuprad.f90</td>
<td>Call the MMR cloud retrieval scheme</td>
</tr>
<tr>
<td>wrwrfmassa.F90, read_wrf_mass_guess.F90, wrf_netcdf_interface.F90</td>
<td>Implemented I/O interfaces for cloud tracers. The wrwrfmassa routine updates the age of the cloud fraction retrievals. In addition, the tracer definition need to be added in the anavinfo table</td>
</tr>
<tr>
<td>crtm_interface.f90</td>
<td>Added arguments in call_crtm to pass the grid i/j locations and overcast radiances that are needed in cloud detection procedure</td>
</tr>
<tr>
<td>gsimod.F90</td>
<td>Added namelist variable lncar_cldfra for switching on the MMR cloud detection capability</td>
</tr>
<tr>
<td>read_svissr_afwa.f90, read_mt2img_afwa.f90, read_seviri_afwa.f90</td>
<td>New reader from the AFWA binary files</td>
</tr>
</tbody>
</table>

*Table 3. Implementation of the MMR scheme in GSI.*
b) Implementation in WRFDA

The MMR scheme has been implemented in WRFDA: when the flag `use_clddet_mmr` is activated, the quality check for satellite radiances is bypassed.

The tracers representing the cloud fraction are defined in the WRFDA registry `Registry.wrfvar` by adding one line per sensor:

```
state real tr_air  ikjftb tracer 1 - irhusdf=(bdy_interp:dt) "tr_air" "tr_air of the cloud fraction for air"
state real age_air  ikjftb tracer 1 - irhusdf=(bdy_interp:dt) "age_air" "age_air for air"
(...)
state real tr_cldfra  ikjftb tracer 1 - irhusdf=(bdy_interp:dt) "tr_cldfra" "tr_cldfra for cloud fraction combination"
state real age_cldfra  ikjftb tracer 1 - irhusdf=(bdy_interp:dt) "age_cldfra" "age_cldfra for cloud fraction combination"
```

Note: the WRF tracers defined in section 3.4 and the WRFDA tracers have to match.

In the architecture of the WRFDA code, the directory `var/da/da_radiance` gathers most of the methods to process the radiances. The MMR scheme is encapsulated in the `da_cloud_detect.inc`. The Overcast radiances are implemented in WRFDA as an array within the innovation vector defined for each instrument. Table 4 summarizes the key modifications done in the WRFDA code.

<table>
<thead>
<tr>
<th>Key Modifications in the WRFDA code done in the directory var/da/da_radiance</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>da_get_innov_vector_crtm.inc</td>
<td>Compute the Overcast radiance</td>
</tr>
<tr>
<td>interp_to_grid.inc</td>
<td>Identical to GSI</td>
</tr>
<tr>
<td>inria_n2q1n1.inc</td>
<td>Identical to GSI</td>
</tr>
<tr>
<td>da_cloud_detect.inc</td>
<td>Identical to GSI</td>
</tr>
</tbody>
</table>

*Table 4. Implementation of the MMR scheme in WRFDA code.*
3.4 WRF forecast

WRF is used as a dynamical core to advect and diffuse the cloud fraction retrieval computed at analysis time. Each satellite needs the definition of two tracers: its own cloud fraction retrieval, and the associated “age” of the last update. The modifications are done in WRF to define these tracers.

Passive tracers can be conveniently added in WRF using the registry file. For example, a tracer corresponding to the contribution of the AIRS sensor to the total cloud fraction tr_airs and the tracer carrying this cloud fraction’s age age_airs are added to the WRF registry file Registry.EM:

\[
\begin{align*}
\text{state real tr_airs ikjfth tracer 1 - irhusdf=(bdy_interp:dt) "tr_airs" "tr_cldfra for airs"} \\
\text{state real age_airs ikjfth tracer 1 - irhusdf=(bdy_interp:dt) "age_airs" "age of the cloud fraction for airs"}
\end{align*}
\]

Those additions need to be repeated for each sensor. The list of those sensors with the names of the corresponding WRF tracer variables is given in Table 5. Notice the additional variable tr_cldfra, which combines contributions of each sensor into one single cloud fraction array.

\[
\begin{align*}
\text{state real tr_cldfra ikjfth tracer 1 - irhusdf=(bdy_interp:dt) "tr_cldfra" "tr_cldfra for combination"} \\
\text{state real age_cldfra ikjfth tracer 1 - irhusdf=(bdy_interp:dt) "age_cldfra" "age of the cloud fraction for combination"}
\end{align*}
\]

Variables have been added in the routine dyn_em/start_em.F in order to update each of the new tracers (one for each sensor). The following lines show the corresponding statements for the AIRS and combined cloud fraction tracers:

\[
\begin{align*}
\text{tracer(:,:,P_tr_airs) = grid%tracer(:,:,P_tr_airs)} \\
\text{tracer(:,:,P_age_airs) = grid%tracer(:,:,P_age_airs)} \\
\text{tracer(:,:,P_tr_cldfra) = grid%tracer(:,:,P_tr_cldfra)} \\
\text{tracer(:,:,P_age_cldfra) = grid%tracer(:,:,P_age_cldfra)}
\end{align*}
\]
4. EXPERIMENT SET-UP

The following sections explain how to install, set-up and run MADCast with GSI and WRFDA.

4.1 Software Installation

Apart from the code changes described in section 3.4, no specific compilers or libraries, other than those normally needed to install GSI (http://www.dtcenter.org/com-GSI/users/) or WRFDA (http://www2.mmm.ucar.edu/wrf/users/wrfda) and WRF and documented in their respective User’s Guide, are needed. The MADCast distribution also contains post-processing and graphics scripts. Applications of those scripts require the installation of the NCAR Common Language (NCL) and the NetCDF Operators (NCO) operators. Those packages are freely available from respectively: http://www.ncl.ucar.edu/ and http://nco.sourceforge.net/.

4.2 Input

As mentioned, the MADCast system uses the same input gridded data as GSI (or WRFDA) and WRF. Those files are a WRF input file: wrfinput_d01, a WRF boundary file: wrfbdy_d01, and GSI (and WRFDA) background error statistical file. The GSI and WRFDA User’s Guide and Tutorials explain how to download the airsbufr, iasibufr and crisbufr BUFR files. The GOES and the MODIS observation files can be obtained from the National Aeronautics and Space Administration (NASA).

Additional radiances files available at AFWA in binary format can also be used. Those files are svissr, seviri and img_mt2.

4.3 Output

Cloud fraction retrievals are appended to the regular output of the GSI (and WRFDA) analysis as new 3-dimensional fields. Table 5 provides the names of those additional fields. There are 2 fields per type of assimilated radiance: one for the cloud fraction (in percentage) and one for the cloud fraction’s age (defined in number of assimilation cycles). The total cloud fraction that results from the combination of all the sensors is stored in the tr_cldfra fields, with its age in the age_cldfra field.

Remark 1: The name of the variables that are added into the WRF registry (section 3.4) should exactly match the names of the variable listed in Table 5.

Remark 2: When the MADCast is initialized for the very first time from WRF WPS, and not from GSI (and WRFDA), the fields listed in Table 5 need to be appended to the WRF input file created by WPS. NCO operators can be used or a NCL script tracer_update.ncl is provided to append and reset those variables to a WRF input file.
Cloud fraction retrieval of MMR | Tracer value | Age value
---|---|---
Combined solution | tr_cldfra | age_cldfra
AIRS | tr_airs | age_airs
CRIS | tr_cris | age_cris
GOES sounder | tr_goesnr | age_goesnr
GOES imager | tr_img | age_img
IASI | tr_iasi | age_iasi
MODIS | tr_modis | age_modis
SVISSR (AFWA binary format) | svissr | age_svissr
SEVIRI (AFWA binary format) | seviri | age_seviri
Himawari-7 MTSAT-2 (AFWA binary format) | img_mt2 | age_img_mt2

Table 5. Nomenclature of the names of the additional 3-dimensional fields that results from the GSI and WRFDA cloud fraction calculations. Those fields are appended to the regular output file.

4.4 Namelist

a) GSI Namelist

New options have been added to the GSI namelist to activate the MMR. A new record &NCAR_APPS has been created. Table 6 describes the new namelist entries that make up the namelist record.

<table>
<thead>
<tr>
<th>Namelist parameters &amp;ncar_apps</th>
<th>Value by default</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>lnclr_cldfra</td>
<td>.true.</td>
<td>Turning on MMR cloud detection</td>
</tr>
<tr>
<td>lcldfra_warm</td>
<td>.true.</td>
<td>Warm-starting cloud fraction from the previous sensor or analysis cycle</td>
</tr>
<tr>
<td>lconstr</td>
<td>.true.</td>
<td>Use a background constraint in the cloud fraction retrieval, with increased penalty for very high clouds (above 150hpa)</td>
</tr>
<tr>
<td>c_f</td>
<td>real</td>
<td>Scale factor for the penalty</td>
</tr>
<tr>
<td>lboun_n2qn1</td>
<td>.true.</td>
<td>Apply bounds for the n2qn1 minimizer to insure that cloud fraction stays within [0-1]</td>
</tr>
<tr>
<td>lfill_gap</td>
<td>.true.</td>
<td>Filling horizontal gaps between satellite pixels during the interpolation to the model grid</td>
</tr>
<tr>
<td>afwa_source</td>
<td>.false.</td>
<td>Using SEVIRI/MTSAT2-imager/FY2 data from AFWA binary files</td>
</tr>
<tr>
<td>afwa_source_goesimg</td>
<td>.false.</td>
<td>Using GOES imager data from AFWA binary files</td>
</tr>
</tbody>
</table>

Table 6. Description of the GSI namelist &ncar_apps controlling the MMR algorithm.
**Remark:** When radiances from more than one sensor are used, the order in which the satellite data are assimilated is important. This order will follow the order of the indexation of the variable *dfile* in the namelist &OBS INPUT record. In the example below, radiances from IASI firstly from the METOP-A satellite, then from the METOP-B satellite, will be assimilated before the AIRS radiances.

\[
dfile(06)='iasibufr', \quad dtype(06)='iasi', \quad dplat(06)='metop-a', \quad dsis(06)='iasi616_metop-a', \quad dval(06)=0.0, \quad dthin(06)=1, \quad dsfcalc(06)=1, \\
dfile(07)='iasibufr', \quad dtype(07)='iasi', \quad dplat(07)='metop-b', \quad dsis(07)='iasi616_metop-b', \quad dval(07)=0.0, \quad dthin(07)=1, \quad dsfcalc(07)=1, \\
dfile(08)='airsbufr', \quad dtype(08)='airs', \quad dplat(08)='aqua', \quad dsis(08)='airs281SUBSET_aqua', \quad dval(08)=0.0, \quad dthin(08)=1, \quad dsfcalc(08)=1, \
\]

Files that are not present in the working directory at run time will be skipped.

The ancillary parameter file *anavinfo* will provide GSI with the information it needs to recognize the variables related to MMR. The nomenclature of file *anavinfo* follows the naming convention of Table 5. Below is an excerpt of a *anavinfo* file.

<table>
<thead>
<tr>
<th>!var</th>
<th>level</th>
<th>crtm_use</th>
<th>desc</th>
<th>orig_name</th>
</tr>
</thead>
<tbody>
<tr>
<td>tr_cldfra</td>
<td>39</td>
<td>0</td>
<td>tracer_cldfra</td>
<td>tr_cldfra</td>
</tr>
<tr>
<td>tr_iasi</td>
<td>39</td>
<td>0</td>
<td>tracer_airs</td>
<td>tr_iasi</td>
</tr>
<tr>
<td>tr_airs</td>
<td>39</td>
<td>0</td>
<td>tracer_airs</td>
<td>tr_airs</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>age_cldfra</td>
<td>39</td>
<td>0</td>
<td>age_cldfra</td>
<td>age_cldfra</td>
</tr>
<tr>
<td>age_iasi</td>
<td>39</td>
<td>0</td>
<td>age_iasi</td>
<td>age_iasi</td>
</tr>
<tr>
<td>age_airs</td>
<td>39</td>
<td>0</td>
<td>age_airs</td>
<td>age_airs</td>
</tr>
</tbody>
</table>

For each instrument listed in file *anavinfo*, the channels to be used must be activated in file *satinfo*. See the GSI User’s guide for a description of the *satinfo* table. In addition, cloud fraction will be retrieved only for the sensors that are listed in Table 5 and present in the GSI gridded input data file *wrfinput_d01*.

**b) WRFDA Namelist**

New parameters have been added in the section &wrfvar14 of the WRFDA namelist as shown in Table 7.

<table>
<thead>
<tr>
<th>Namelist parameters &amp;wrfvar14</th>
<th>Value by default</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>use_clldet_mmr</td>
<td>.true.</td>
<td>Turning on MMR cloud detection</td>
</tr>
<tr>
<td>clldfra_warm</td>
<td>.true.</td>
<td>Warm-starting cloud fraction from the previous sensor or analysis cycle</td>
</tr>
<tr>
<td>use_constr</td>
<td>.true.</td>
<td>Use a background constraint in the cloud fraction retrieval, with increased penalty for very high clouds (above 150hpa)</td>
</tr>
<tr>
<td>c_f</td>
<td>real</td>
<td>Scale factor for the penalty</td>
</tr>
</tbody>
</table>

Table 7. Description of the WRFDA namelist parameters controlling the MMR algorithm.
In the muti-sensor approach, the sensors are processed in the order specified in the WRFDA namelist:

```wrfvar14
rtminit_nsensor = 3,
rtminit_platform = 10, 9, 4,
rtminit_satid = 2, 2, 13,
rtminit_sensor = 16, 11, 22,
```

In this example, IASI is read first, then AIRS and finally GOES.

5. VERIFICATION

Scripts and programs to conduct verification on the cloud analysis and forecast are provided. Those scripts allow verifications based on GOES cloud retrievals from NASA and surface ground station. Figure 6 presents the main components of the verification procedure. Those components are described in the next sub-sections.

![Flowchart of MADCast post-processing system. The 3-D cloud fraction verification is performed by matching a cloud mask determined from GOES imager satellite data with a cloud mask of WRF determined from the model output. Comparisons of irradiance are done at the location of the SURFRAD/ISIS ground station network.](image)

Technical Note 18/21
5.1 Cloud fraction

Analysis and forecast verifications are performed by comparing 2-D cloud masks derived from GOES NASA retrievals with the WRF model output. As both are defined on a different mesh grid at different resolution, they first must be interpolated on the same horizontal regular latitude-longitude grid. Then, the cloud mask for the GOES NASA retrievals is estimated from the cloud top pressure. The cloud mask for the WRF model is directly evaluated by defining a threshold on the cloud fraction integrated over the vertical levels. Finally, statistical scores are computed by matching the observed and modelled masks as shown in Figure 7 (Schaefer, J. T., 1990). Note that the threshold of cloud fraction that defines the mask for the model has a consequence on the bias rate.

Statistic definition:

<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Forecast</td>
<td>Yes</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>C</td>
<td>D</td>
</tr>
</tbody>
</table>

Hit rate (POD): \( A / (A+C) \)
False alarm rate: \( B / (B+D) \)
Threat score (TS): \( A / (A+B+C) \)
Bias: \( (A+B) / (A+C) \)
True skill score (TSS) \( \text{POD - POFD} \)

Figure 7. (a) Example of scores calculated from the regridded observed and modelled cloud masks over a single 6-hour forecast. Maps of contingency table for (b) \( t+0h \), and (c) \( t+6h \).
5.2 Solar irradiance

Figure 8 overlays time-series of analysed, forecasted and observed surface irradiance at a SURFRAD station in Penn State University. This output is available at every SURFRAD and ISIS station. The model simulation combines a clear-sky radiative transfer calculation of the Global Horizontal Irradiance (GHI) with the WRF RRTMG scheme with a very simple cloud attenuation module using the cloud fraction field as input. In addition, variables such as direct and diffuse irradiance are available through this verification.

![Figure 8. Time series of 10-min averaged Global Horizontal Irradiance (GHI) at Penn State University SURFRAD station (UTC time) for observations (black), model analysis (blue), the 2-h forecast (green), and 5-h forecast (orange). The red line shows the clear sky model simulation.](image)

6. CONCLUSIONS

This document describes the methodology and the different components of the MADCast system, designed for cloud nowcasting. This novel approach computes cloud fraction retrieval using the MMR scheme implemented in the GSI and WRFDA data platforms. The CRTM code has been modified to compute overcast (cloudy) radiance and the WRF model is used as a dynamical core to forecast cloud evolution. The cloud analysis benefits from the synergy of multiple infrared instruments, combining imagers and sounders. The system is designed to conserve the vertical information from the sounders while using the high spatial and temporal resolution of the imagers. Global coverage can be achieved with this system. The description of the code modifications and the parameters to drive the MMR scheme are presented in details to help the new user running MADCast system either with GSI or WRFDA. The MADCast system has been tested in “near real time” during a four-month period in which hourly cycle analyses were conducted. A suite of verification tools has been presented to evaluate the accuracy of the results.
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References:


