Wave DA at NOAA

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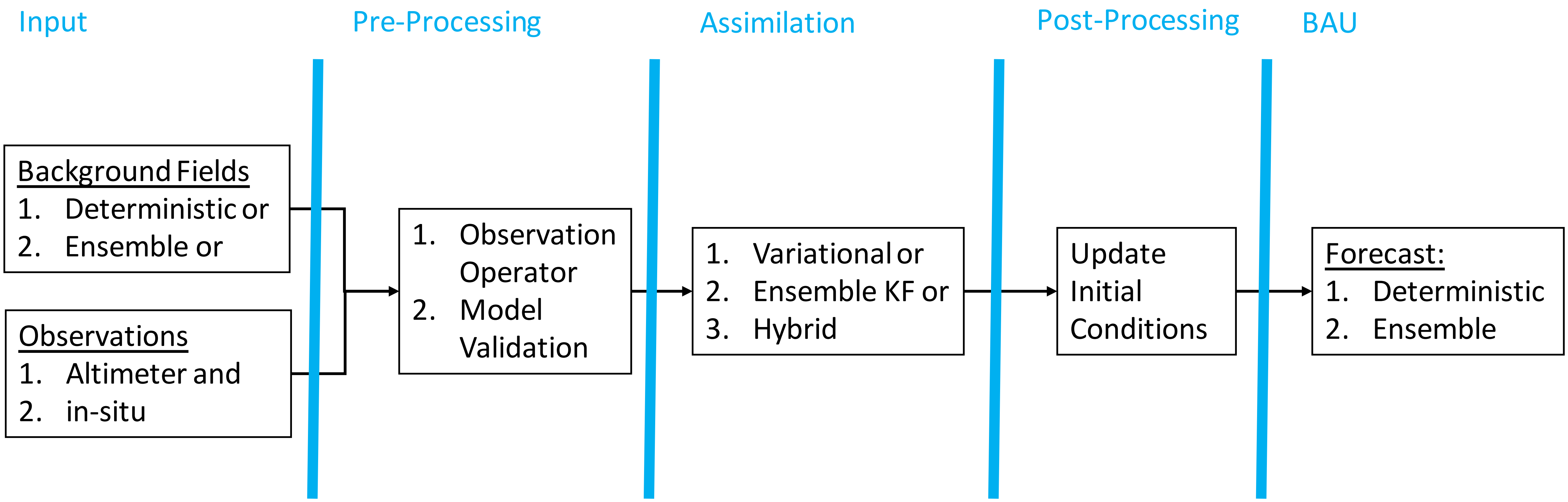
Requirements for Wave DA at NWS

- **Objective**: Provide analysis in global and regional scales for the operational wave models and guidance at the NWS
- **Approach**: Minimum changes/updates to (any) forward wave model and to existing data assimilation systems at NWS.
- **Algorithmic Implementation**: The existing –mainly GSI and LETKF – assimilation systems at NOAA are leveraged and customized to accommodate the needs for the wave DA.
- **Input data**: Mainly Significant Wave Height

Conceptual Flowchart of Wave DA suite

The arsenal of developed wave DA tools



Characteristics: Modular architecture, Machine independent when possible.

Wave DA Inputs

Requirements:
1. No (to limited) changes to the operational models
2. Standardization of the process

<u>Background Fields:</u>
1. grib2 format → I/O module :: **grib2_ww3_io.f90**

WMO standards, user friendly (for the most of the cases), any variable(s), time/date/cycle, **f**, etc.

2. grib2 format is used throughout the DA.

<u>Observations:</u>
1. BUFR / prepBUFR (observation format at the operational data tanks) → Importing module :: **read_obs.f90**

WMO standards, basic QC, temporal window, definition of the spatial domain, spatial average

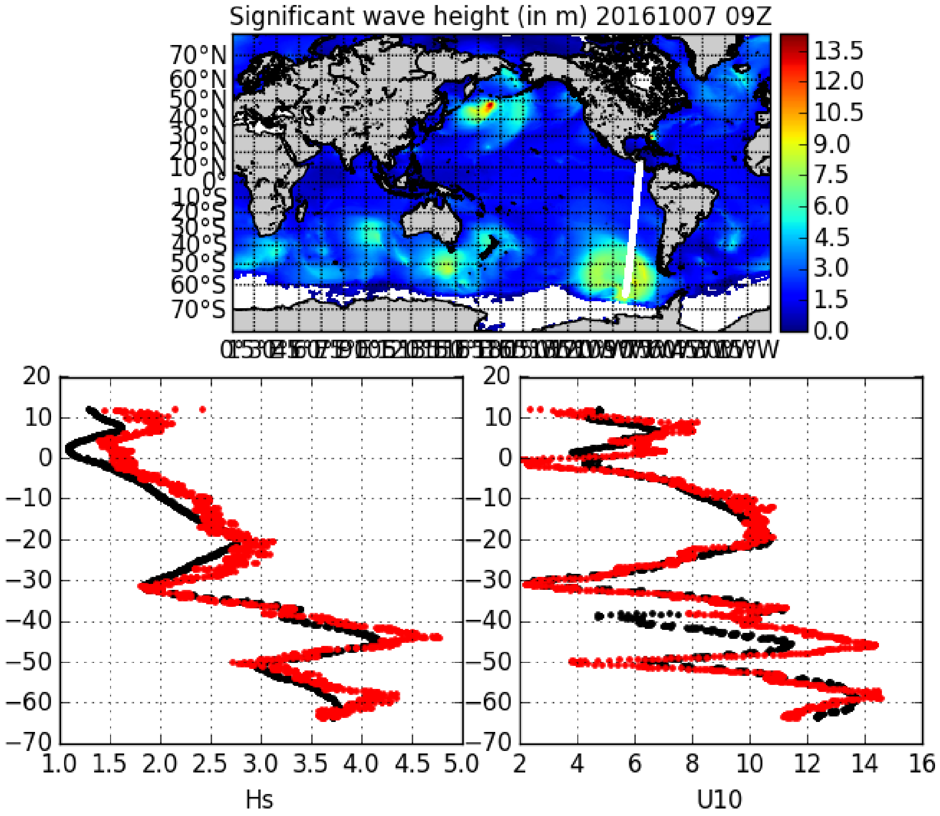
2. Compatible with Jason-2, -3, CS2, Saral/Altika, Sentinel-3, any wave observations at prepBUFR.

Observation Operators and Validation

The observation operator transforms the analysis control variable into the equivalents of each observed quantity at observation location and time.

Program: **ObsOpWaves**

1. Compatible with any variable that could be included to the model output;
2. Appropriate operator for each variable;
3. Operates on multiple prognostic/diagnostic variables at the same time;
4. Compatible with multiple observation sources;
5. Multiple flags available: Obs QC, SuperObs, debugging, verbose.
6. Outputs – Flat Files:
    A. Error statistics of the requested variables (Module **Error_Statistics.f90**)
    B. Collocated Data (binary and text format)



Variational Assimilation

Definition: $J(\boldsymbol{x}) = (\boldsymbol{x} - \boldsymbol{x}_n^b)^T \boldsymbol{B}^{-1} (\boldsymbol{x} - \boldsymbol{x}_n^b) + (\boldsymbol{y} - \boldsymbol{H}\boldsymbol{x}_n^b)^T \boldsymbol{R}^{-1} (\boldsymbol{y}_i - \boldsymbol{H}_k \boldsymbol{x}_n^b)^b$

Time Independent : 2D-Var, e.g. Hs(*x*,*y*)
4D-Var, e.g. *N*(*x*,*y*,*f*,*ϑ*)

~~Time Dependent : 3D-Var, e.g. Hs(*x*,*y*,*t*)
5D-Var, e.g. *N*(*x*,*y*,*f*,*ϑ*,*t*)~~

Based on the Community Gridpoint Statistical Interpolation (GSI) system (www.dtcenter.org/com-GSI/users/). GSI started as atmospheric DA system, still strongly coupled with WRF.

Tens of Developers ➔ Many features and capabilities (e.g. Includes Var, ENKF and Hybrid)
Almost 2 decades old ➔ Limited Flexibility, e.g. Global vs Regional systems

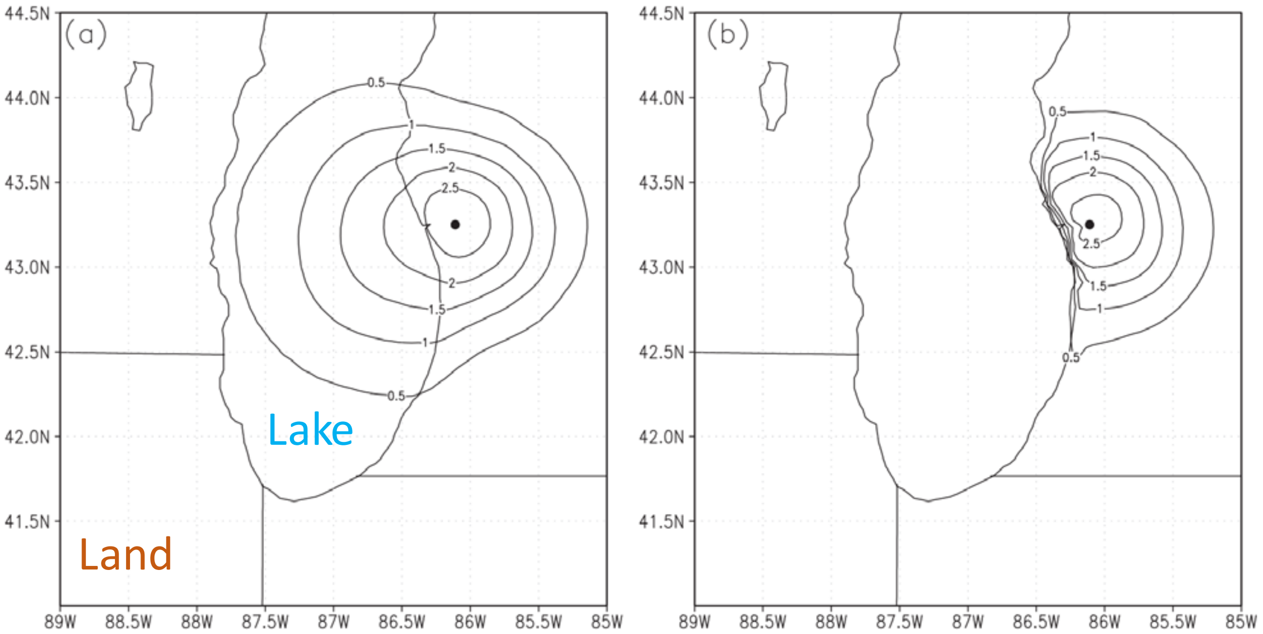
Significant wave height is the first non-atmospheric parameter to be included, providing 2D-var analysis.

Several subroutines have been added: I/O, Weighting, Handling the boundaries

Public release: Limited documentation, not all the source code is included nor the fix files.

Sea/Land

The autocovariance function is of Gaussian form, with structure functions chosen to follow the underlying terrain field



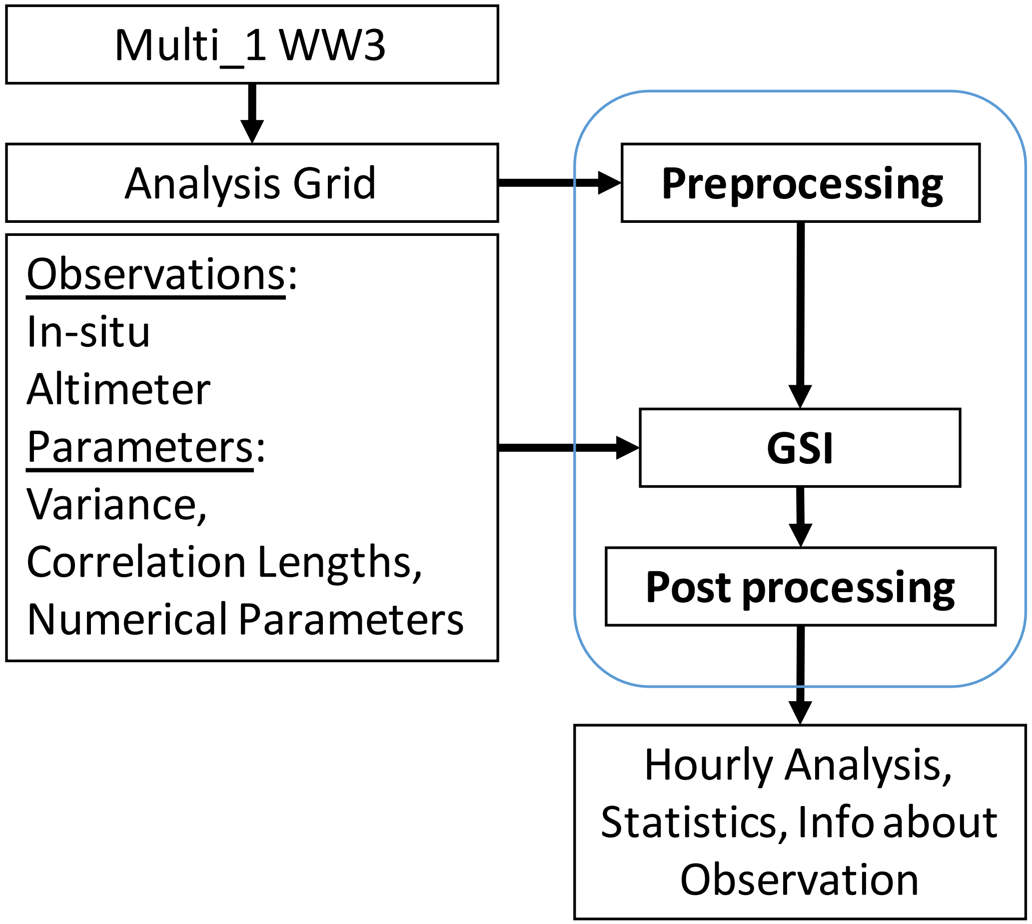
Pondeca et al. 2011

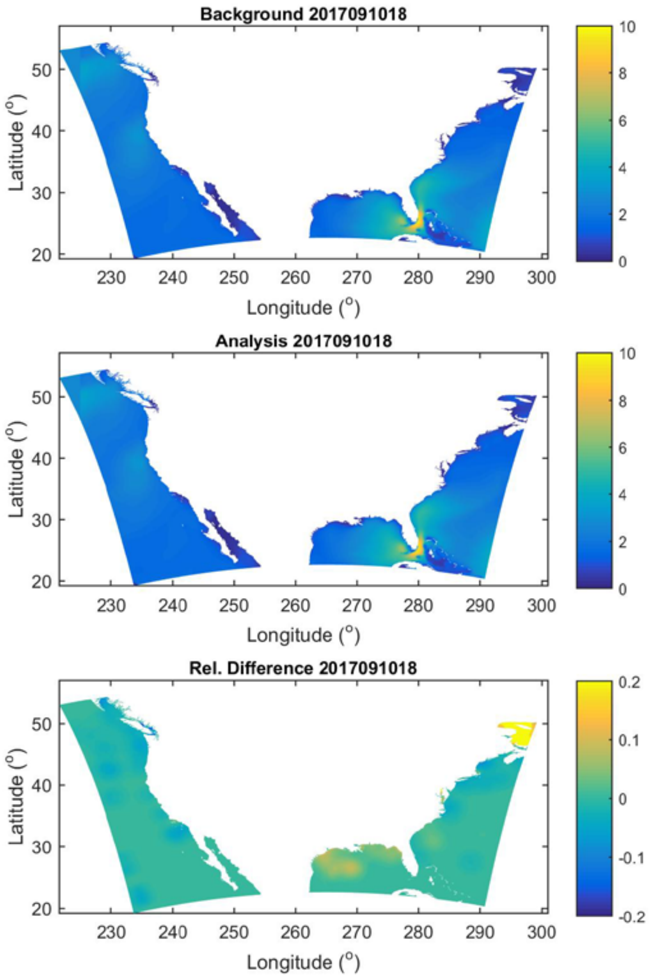
$$C(\Delta\mathbf{x}) = \sigma_o^2 \exp\left(-\frac{1}{2}\Delta\mathbf{x}^{\mathrm{T}}\mathbf{S}^{-1}\Delta\mathbf{x}\right)$$

$$\mathbf{S}^{-1} = \frac{\mathbf{I}}{L_h^2} + \frac{1}{L_f^2}(\nabla H)(\nabla H)^{\mathrm{T}}$$

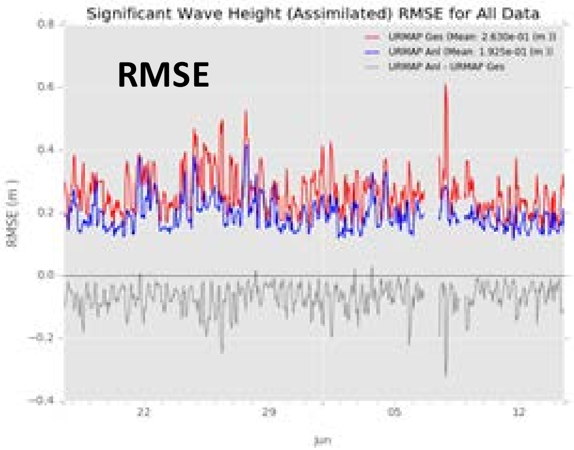
σ_o : Variance,
L_h : Spatial Correlation Scale,
L_f : Function Correlation Scale

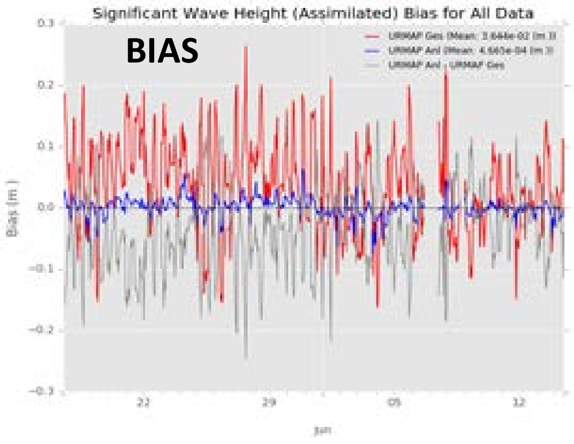
URMA : GSI Application for H_s





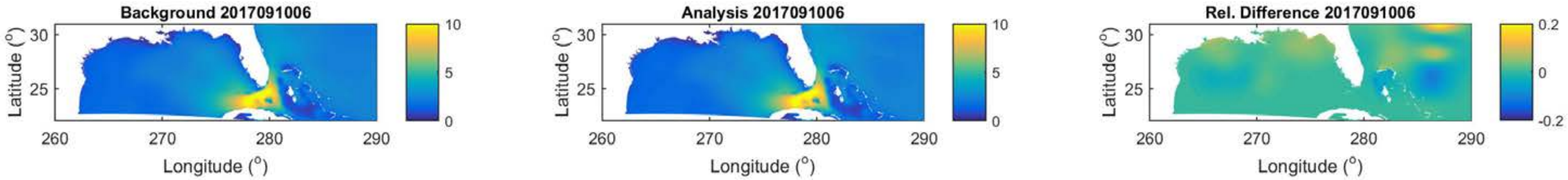
H_s Analysis for CONUS



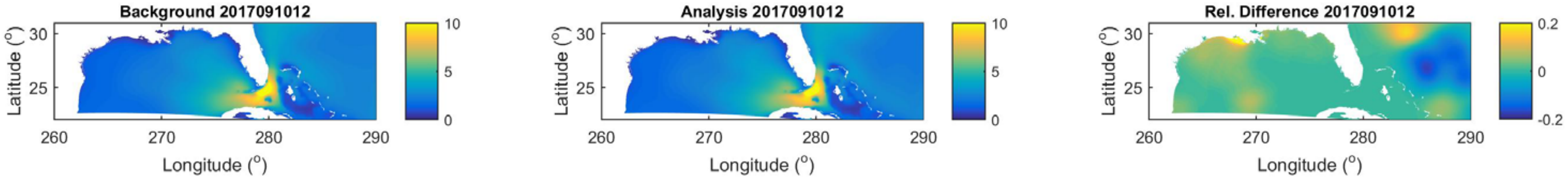


Backgound // **Analysis**

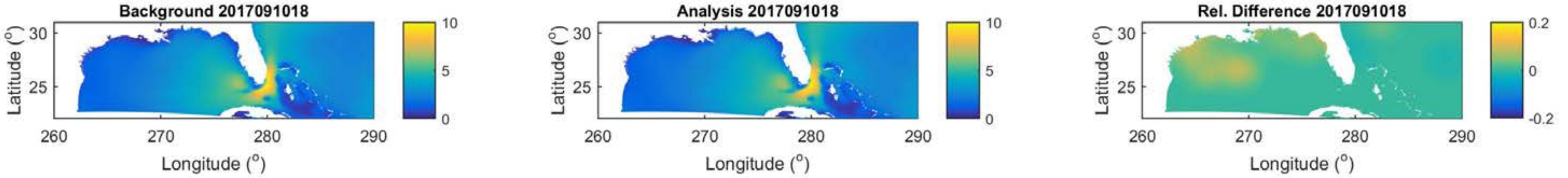
IRMA Landfall - 6h



IRMA Landfall



IRMA Landfall + 6h



Ensemble Kalman Filter

Definition: $x^a_{t,m}$= X^b_t w^a_t+$\overline{\boldsymbol{x}}^b$, when $\boldsymbol{W} = [(\mathrm{m}-1)\mathrm{I}+\boldsymbol{P_A}]^{1/2}$ and $\boldsymbol{P_A} = [(\mathrm{m}-1)\mathrm{I}+Y^T R^{-1} Y]^{-1}$

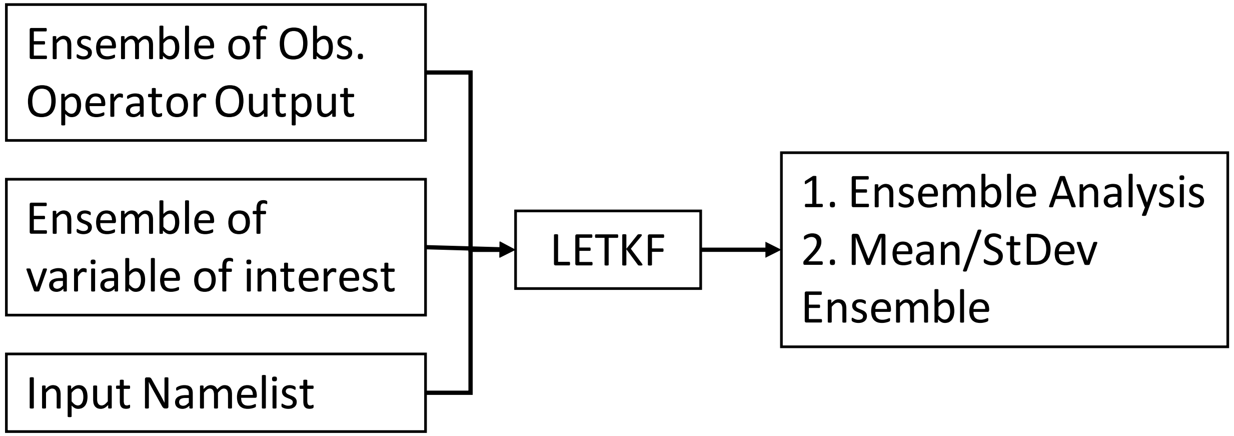
EnKF is computationally intense and there are several approaches; at NCEP the Local Ensemble Transform Kalman Filter (Hunt et al 2007). The basis for the LETKF-Waves was the LETKF-OCEAN by S. Penny.

Major advantages:

- The problem is solved locally, simultaneously and point-to-point independently
- Computationally efficient because each model grid point is simultaneously assimilated
- No model dependency, but for the waves, a significant portion of the LETKF code has been rewritten
- Easily expandable to N-dimensions (e.g., wave spectra)

LETKF-WAVES

The LETKF- H_s is built on top of existing prediction systems using modular design



input.nml

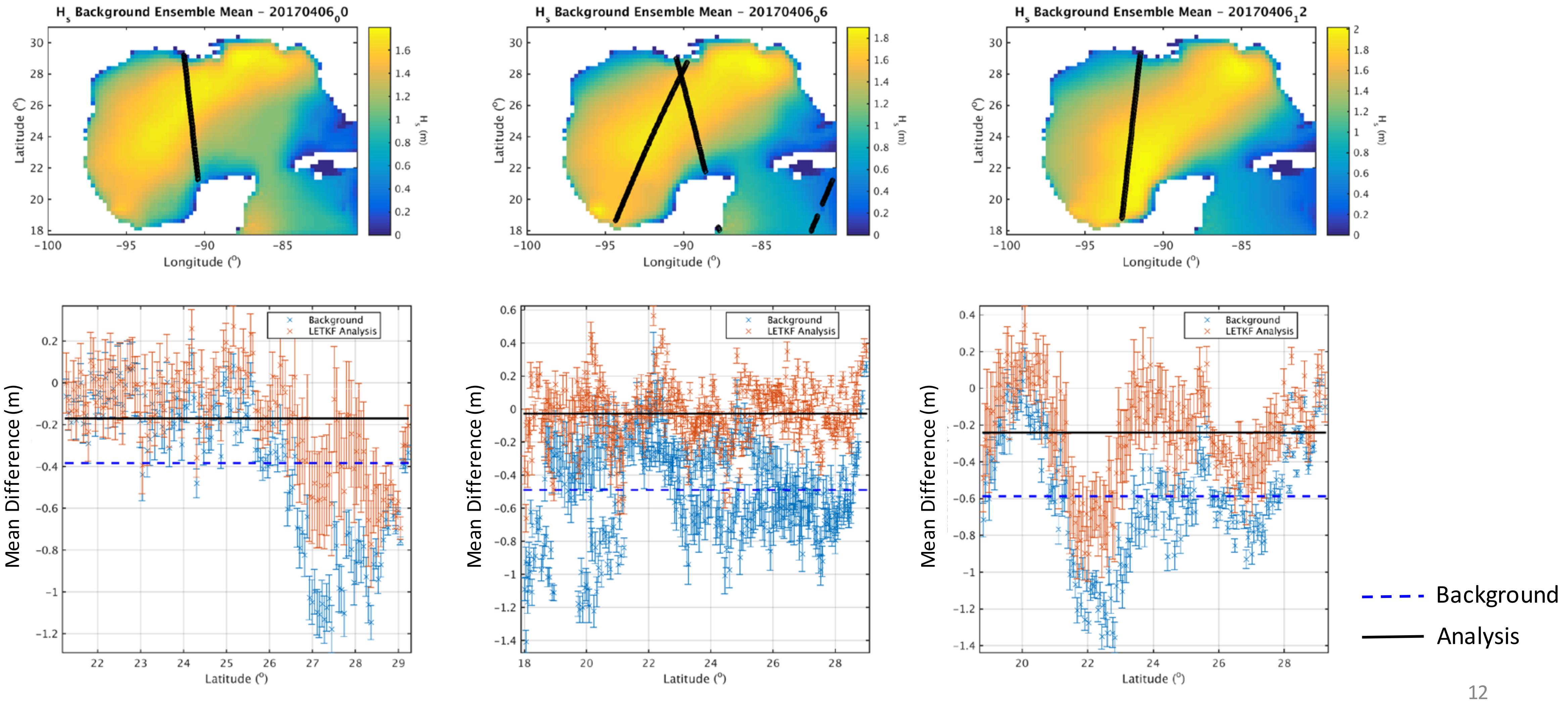
```
&params_model_nml
 pathdata = './',
 cyc = 00,
 f_number = 6
/
&params_letkf_nml
 doHTSGW = .true.
 dodebug = .true.
 nslots = 1,
 nbslot = 1,
 sigma_obs = 200.0d3,
 sigma_obs0 = 200.0d3,
 gross_error = 3.0d0,
 cov_infl_mul = 1.0d0,
 sp_infl_add = 0.d0,
 localization_method = 0
 DO_NO_VERT_LOC = .true.
/
```

Path of Analysis
Cycle
Prediction Time

Number of Analysis Parameters
Number of timesteps
Min/ Max Correlation Length
Gross Error
Two types of inflation
Selection of localization Method
Spectral Analysis

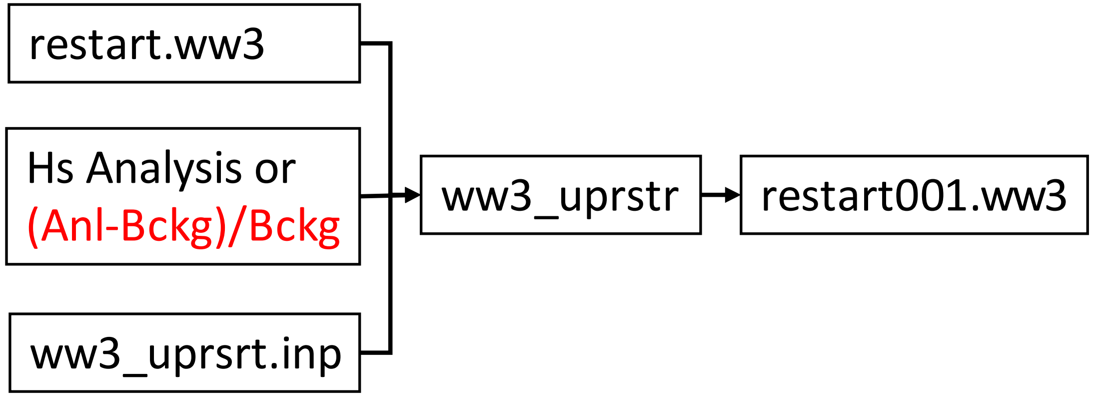
LETKF-Waves expects specific filenames

LEKTF-Hs Analysis at GOM



Updating the WW3 Restart Files

New WAVEWATCH III auxiliary program: **ww3_uprstr**



ww3_uprstr.inp is similar to any ww3_*.inp

```
! -------------------------------------------------------------------- $
!$ WAVEWATCH III Update Restart input file                              $
!$ -------------------------------------------------------------------- $
!$
!$ Time of Assimilation ----------------------------------------------- $
!$ - Starting time in yyyymmdd hhmmss format.
!$
!$ This is the assimilation starting time and has to be the same with
!$ the time at the restart.ww3.
!
!   20170801 060000 $20050828 090000
!$
!$ Choose algorithm to update restart file
!$  UPDN for the Nth approach
!$  The UPDN*, with N<2 the same correction factor is applied at all the gri
!$   UPD0C:: Option 0C  All the spectra are updated with a constant
!$           fac=(HsBckg-HsAnl)/HsAnl.
!$           Expected input: PRCNTG, as defined at fac
!$   UPD0F:: Option 0F  All the spectra are updated with a constant
!$           fac=HsAnl/HsBckg.
!$           Expected input: PRCNTG, as defined at fac
!$   UPD1 :: Option 1   The fac(x,y,frq,theta), is weighted according to
!$           the % of energy at each spectral bin.
!$           Expected input: PRCNTG, as defined at UPD0F
!$   UPDN, with N>1 each gridpoint has its own update factor.
!$   UPD2 :: Option 2   The fac(x,y,frq,theta), is calculated at each grid p
!$           according to HsBckg and HsAnl
!$           Expected input the Analysis field, grbtxt format
!$   UPD3 :: Option 3   The update factor is a surface with the shape of
!$           the background spectrum.
!$           Expected input the Analysis field, grbtxt format
!$   UPD4 :: Option 4  The generalization of the UPD3. The update factor
!$           is the sum of surfaces which are applied on the background
!$           spectrum
!$           Expected input: the Analysis field, grbtxt format and the
!$           functions(frq,theta) of the update to be applied.
!   UPD5
!$
!$ PRCNTG is input for option 1 and it is the percentage of correction
!$applied  to all the gridpoints (e.g. 1.)
!   1.0
!$
!$ Name of the file with the difference between background and analysis $
!$ suffix .bin for binary files, .txt for text files and .grbtxt for    $
!$ text out of grib2 file.                                               $
!$
!   correction.grbtxt
!$
!$ Name of the file with the SWH analysis from the DA system            $
!$ suffix .grbtxt for text out of grib2 file.Optional                   $
!$
!   anl.grbtxt
!$
!$ -------------------------------------------------------------------- $
!$ WAVEWATCH III EoF ww3_uprstr.inp
```

Date

Method

Update Factor

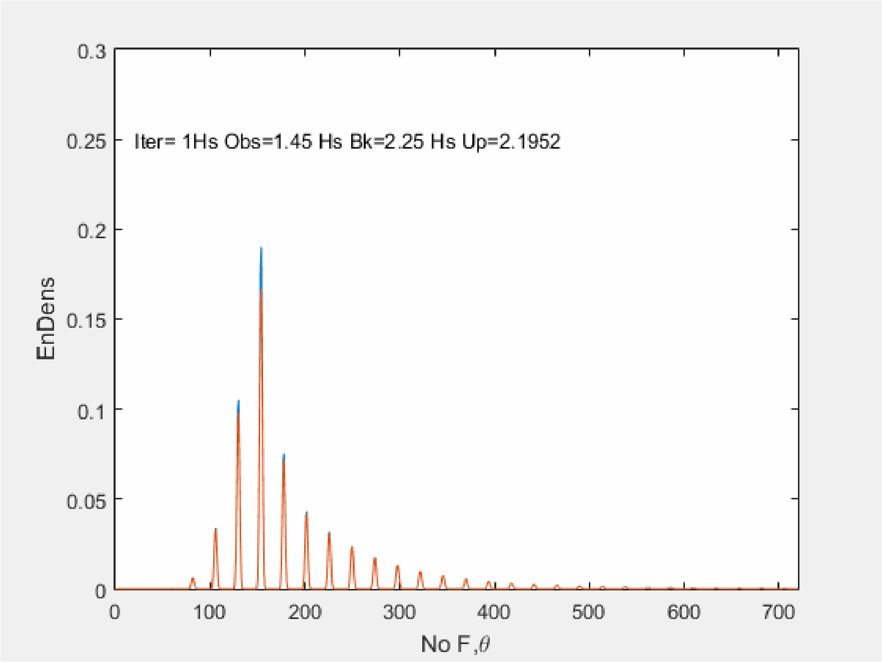
Correction File

Analysis File

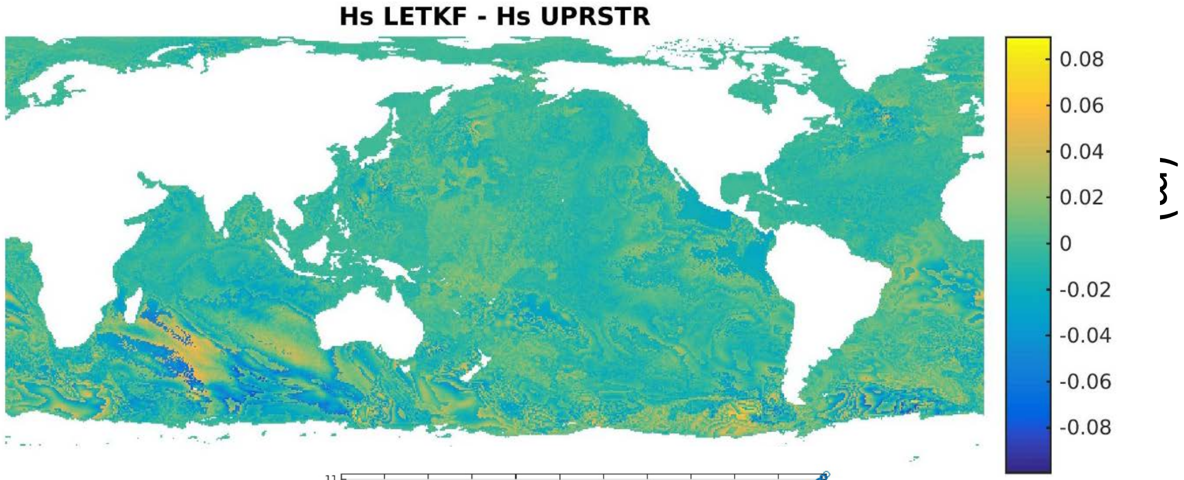
ww3_uprstr :: UPD3 algorithm

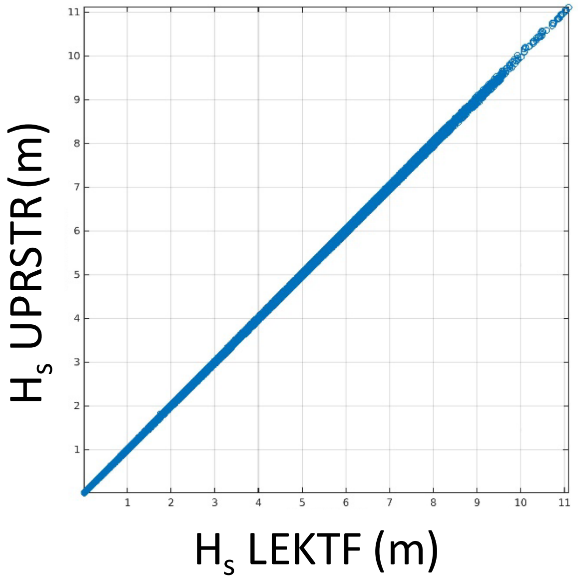
Model Operator: From diagnostic to prognostic

The shape of the restart.ww3 spectra is retained and the Hs correction is redistributed to (f, ϑ) that have already energy, proportionally to the N(f, ϑ) of the background.



Verification of UPD3



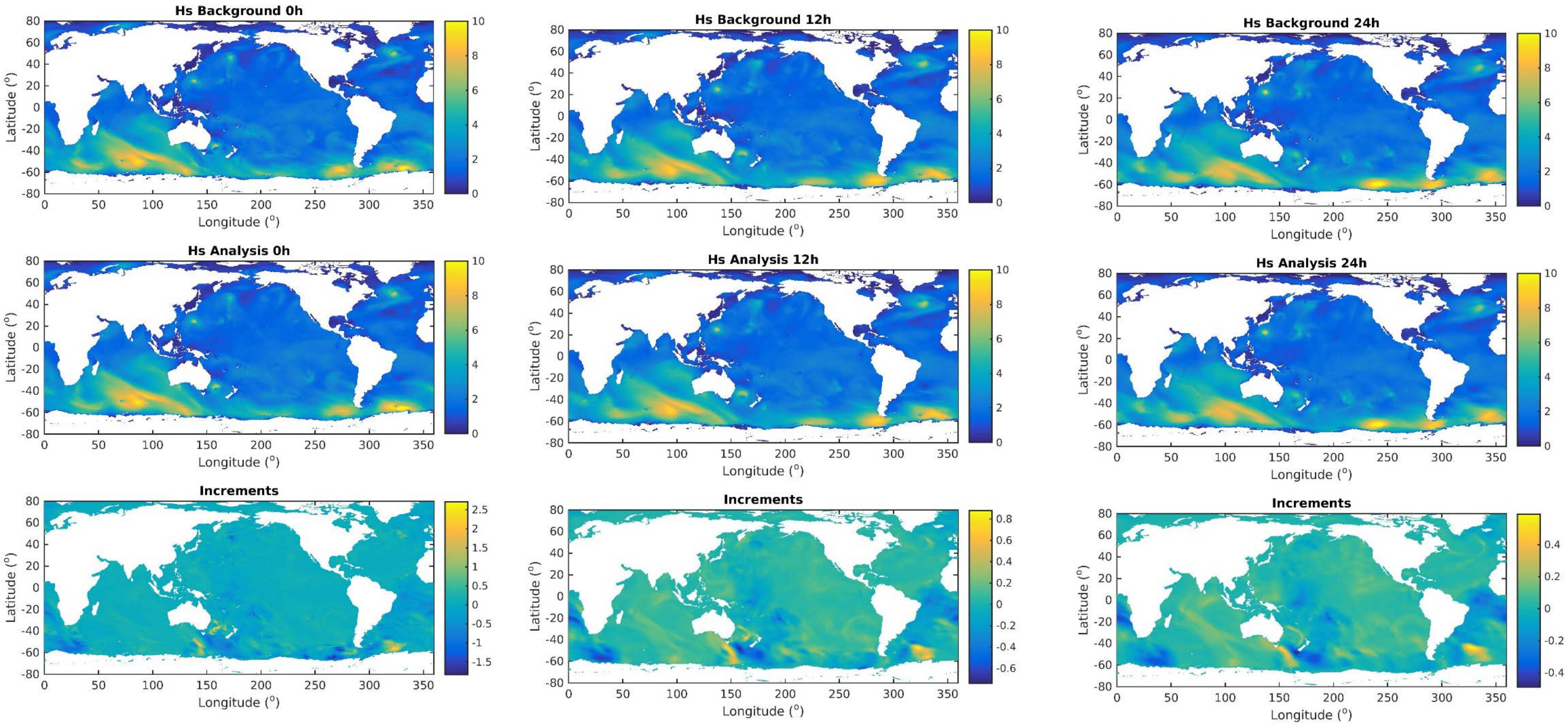


Preliminary Results

Without DA

With DA

Increments

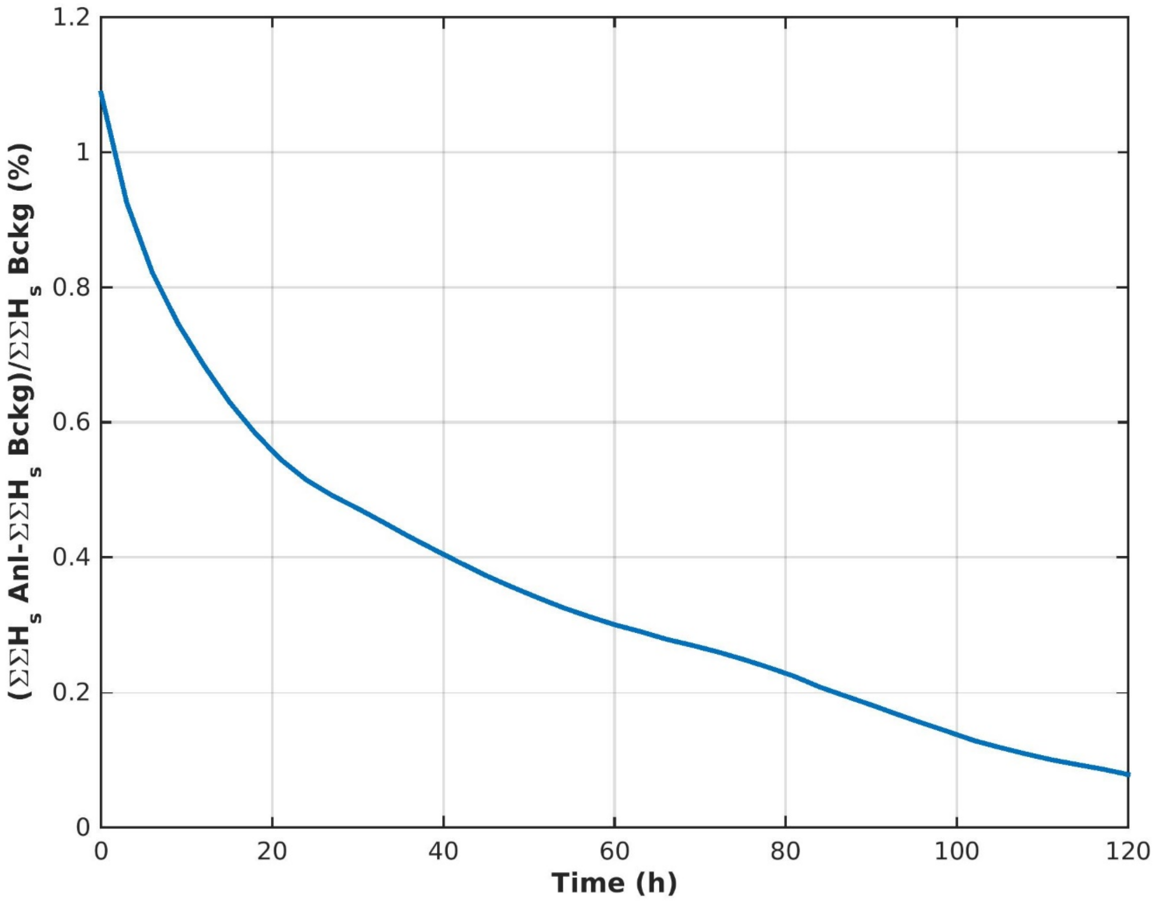


ANL

012f

024f

Impact of Wave DA



Summary

- A modular wave data assimilation suite has been developed
- Variational (GSI) and EnKF (LETKF) based approaches
- A series of supportive programs and modules are available
- Two applications: Meso-Scale analysis (Var) and Global DA system (EnKF); both systems provide solid analysis and showed potential for improvement of wave forecast

- Mesoscale Analysis (URMA) is about to be operational for CONUS and under development for the rest of the NWS domains
- Extensive validation of the global system