Broad community development of the Unified Forecast System,

using the WAVEWATCH III® wind model as an example

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Overview

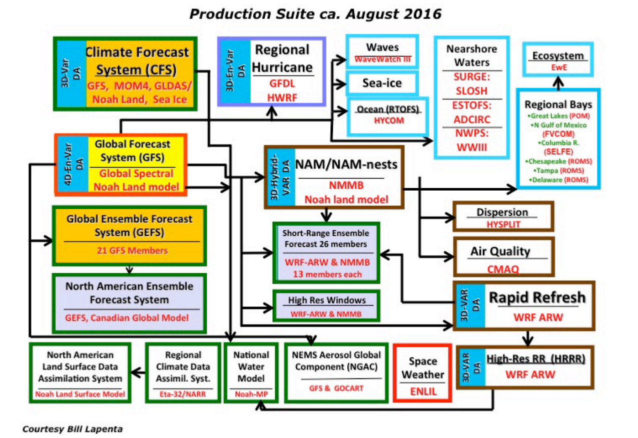
- What is the UFS
- What role plays WAVEWATCH III ® in the UFS
- WAVEWATCH III
  - The (Multidisciplinary) Basics
  - Community Approach
  - AI / Machine Learning
  - Private Sector Engagement
- Looking forward
- Q&A

What is the Unified Forecast System

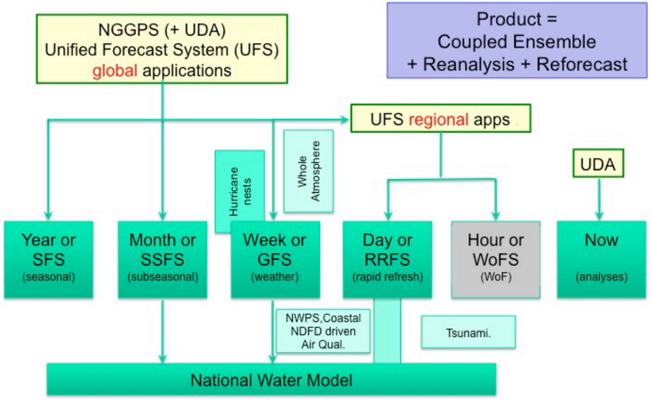
https://ufscommunity.org

NOAA Production Suite

Roadmap Fig. 1



… we will move to a product-based system that covers all present elements of the productions suite in a more systematic and efficient way



UDA: Unified Data assimilation
SFS: Seasonal Forecast System
SSFS: Subseasonal Forecast System

GFS: Weather Forecast System
RRFS: Rapid Refresh Forecast System
WoFS; Warn on Forecast System

Starting from the quilt of models and products created by the implementing solutions rather than addressing requirements ….

Roadmap Fig. 2

About the UFS

"System" in UFS =
code + governance + community

Purpose

The Unified Forecast System (UFS) is a comprehensive, ***community-developed*** Earth modeling system, designed as both a ***research tool*** and as the ***basis for NOAA's operational forecasts***.

Governance

Planning and ***evidence-based decision-making*** support improving research and operations transitions and community engagement.

Scope

UFS is configurable into multiple ***applications*** that span local to global domains and predictive time scales from less than an hour to more than a year.

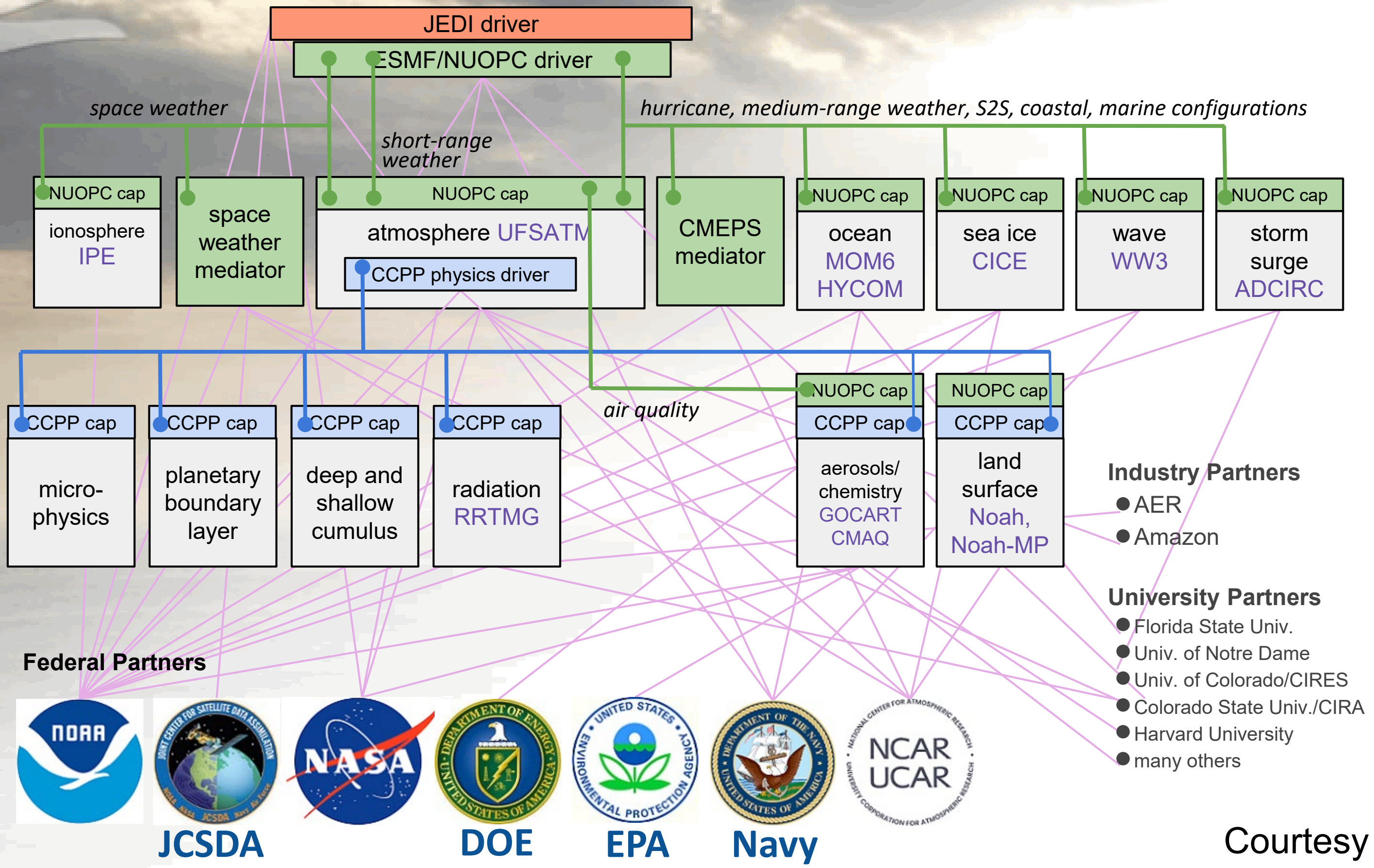
Design

UFS is a ***unified*** system because the applications within it share science components and software infrastructure.

Impact

UFS is a ***paradigm shift*** that will enable NOAA to simplify the NCEP Production Suite, to accelerate use of leading research, and to produce more accurate forecasts for the U.S. and its partners.

Components and Contributors Jan 2020



Courtesy C. DeLuca

Release and implementations

(Planned) releases / implementations

- Medium-range Weather (MRW) App 1.0.0, March 2020
  - FV3 based, Interoperable atmospheric physics and land surface supported with Common Community Physics Package (CCPP)
- GEFSv12.0, UFS based implementation September 2020
  - FV3 based, *coupled waves, aerosols*
- Medium-range Weather (MRW) App 1.1.0, October 2020
  - Updates from graduate student test responses, build systems, documentation, chgres
- GFSv16, operational implementation March 2021
  - Updated atmospheric physics, wave coupling
- Short-range Weather (SRW) App 1.0, March 2021
  - FV3 Limited Area Model before estimated 2024 implementation
- Short-range Weather (SRW) App 2.0, June 2022
- Many components, e.g., MET, CCPP, as well as first JEDI-FV3 release in Nov. 2020.

WAVEWATCH III in the UFS

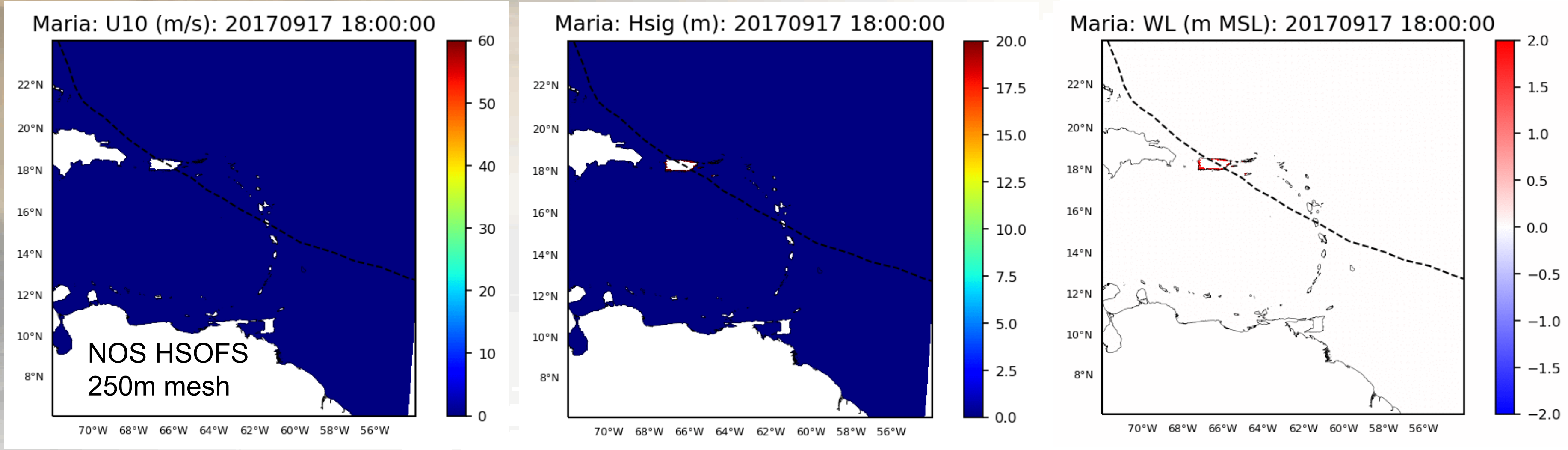
UFS-weather-model

A numerical model repository for the UFS coupled model that connects the atmospheric dycore (FV3), atmospheric physics (CCPP), a mediator (CMEPS), ocean (MOM6/HYCOM), waves (WW3), ice (CICE6)

- Serves the following applications -- Medium range weather, S2S, Short range weather, Hurricane, Air Quality
- Can run multiple configurations -- Atmospheric only mode, fully coupled, ocean only mode, regional, hurricane mode (currently in development)
- Serves NWS operations
  - Transitioned to operations for GFS v15, GFS v16, GEFS v12
  - Development model for GFS v17, HAFS v1, RRFS v1 and seasonal SFS v1

Wave – surge coupling

- ADCIRC – WAVEWATCH III coupling in UFS framework
  - Leveraging COASTAL Act funding and
  - Moving toward total coastal water capability



Hurricane Maria (2017) ATMESH-WW3-ADCIRC

WAVEWATCH III

The (Multidisciplinary) Basics

WAVEWATCH III Basics

This is ***not*** a (chaotic) initial value problem

$$\frac{D\,N(k,\theta;\boldsymbol{x},t)}{D\,t} = S_{in}(k,\theta;\boldsymbol{x},t) + S_{ds}(k,\theta;\boldsymbol{x},t) + S_{nl}(k,\theta;\boldsymbol{x},t) + \ldots.$$

Wave action variance spectrum $N(k,\theta)$ as a function of wave-number k and wave direction θ
Adapted from Bell Labs work on radar signals, Rice (1944)

Input of energy due to wind S_{in} and dissipation due to breaking S_{ds} only make waves higher or lower.
Fourth order nonlinear interactions are the lowest order process to effective make waves longer.
Described with Boltzmann integral (quantum mech.)

Linear wave propagation along great circles in deep water, numerics borrowed from dispersion modeling

In shallow water wave bottom interactions follow Snel's law, techniques borrowed from optics

WAVEWATCH III

Community Approach

Wind Wave modeling community

Community Approach

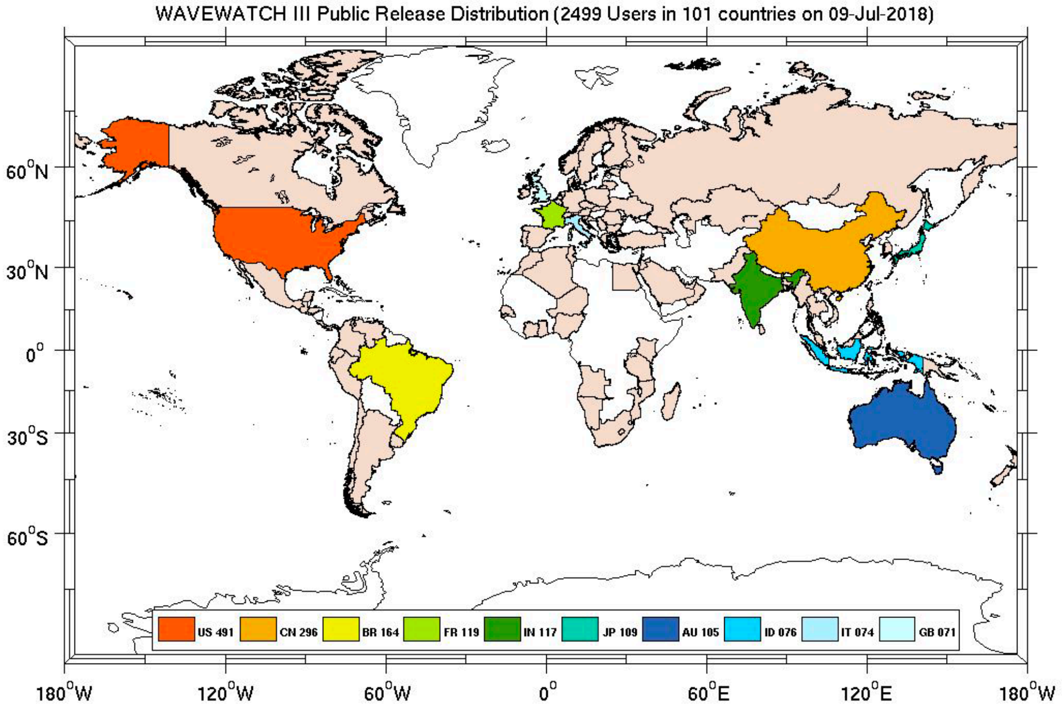
- First spectral models from the mid 1950s
- First- and Second-Generation models, assumed spectral shape
  - Divergence of approaches, many models
- Joint North Sea Waves Project (JONSWAP, 1973) established role of nonlinear interactions in evolving spectral shape
- SWAMP group book "*Ocean Wave Modeling*" (1985) established the need for explicitly modeling nonlinear interactions (no more assuming spectral shape)
- WAM: SCOR working group 83: community developing first Third-Generation (3G) wind wave model for operational use
  - WAMDIG 1988, *JPO*, **18**, 1,775-1,810

WAVEWATCH III community

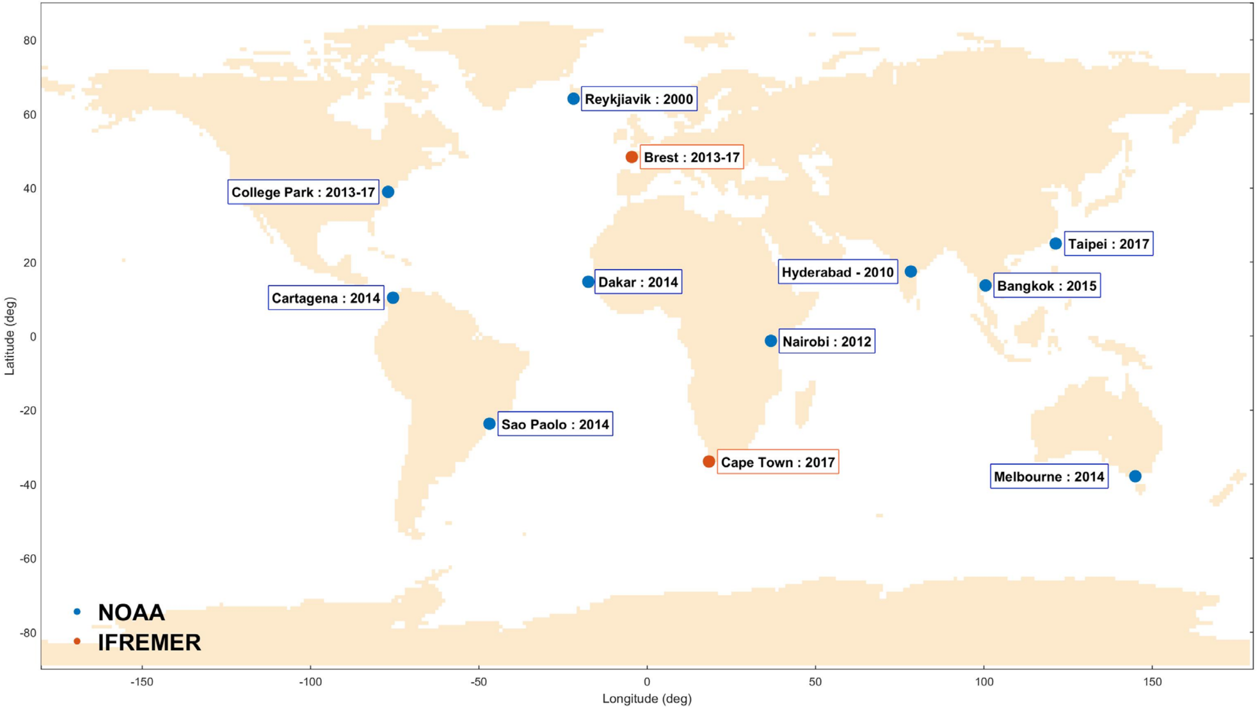
- 1999-2009 Freeware up to v2.22
- 2009: v3.14 custom open-source license
- 2008-2013 NOPP project
  - Developing Community Modeling approach
  - Modern code management (SVN repository)
  - Tolman et al., 2013, *Ocean Modelling*, **70**, 2-10
  - Proven acceleration of research to operations process
    - Early data point for buying in to UFS approach
- As part of move to UFS, WW3 code moved to GitHub (2018)
- World-wide distribution, “school sessions”

NOPP
National Oceanographic Partnership Program

July 2018 code distribution



Training through 2017



WAVEWATCH III

Artificial Intelligence / Machine Learning examples

AI/ML 1: Physics emulation

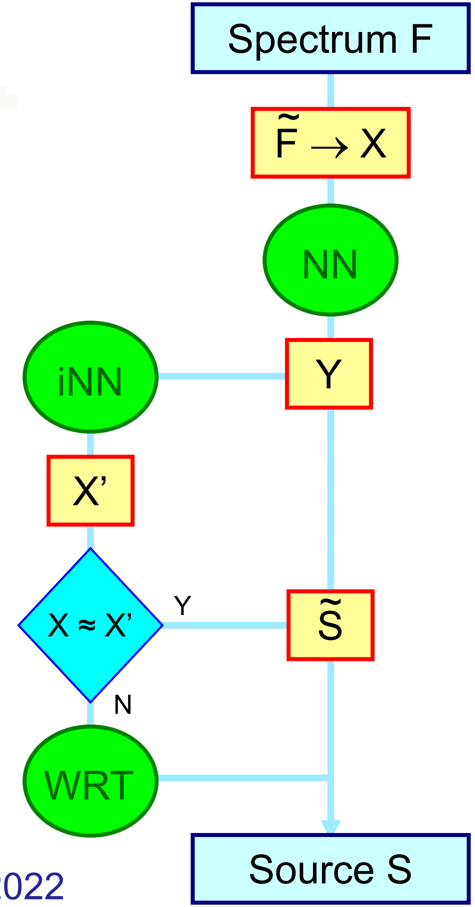
Nonlinear interactions:

- Key element to do explicitly in 3G models
- Exact solution is 6 dimensional Boltzmann integral
  - Web – Resio – Tracy (WRT) technique
  - Much too expensive for operations
- Discrete Interaction Approximation (DIA)
  - Hasselmann et al. 1985, *J. Phys. Ocean.*, **15**, 1,369-1,377
  - Makes 3G models feasible, but also introduces model errors
- One possible alternative is a Neural Network Emulator for WRT

NN source term emulator

Map spectrum F to source S

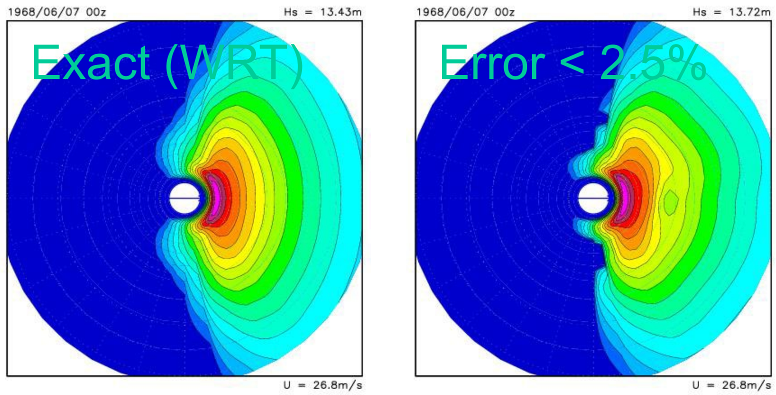
- Traditional forward NN
  - Nondimensional decomposition for Spectrum and Source
  - NN maps decomposition X to decomposition Y
  - Works well for individual mapping
  - Not stable in model integration
- Add inverse NN (iNN)
  - Allows for QC to choose NN or WRT



Hybrid NN / WRT emulator

First test of this hybrid emulator for the same time-limited growth conditions as used in the NN training

- It works, QC stabilizes model
- First attempt still expensive
  - ➤ Iterative training ?
  - ➤ Nonlinear conservative filter
- Approach abandoned
  - ➤ Lack of dominant scales
  - ➤ Too many small scales



Tolman and Krasnopolsky 2004, JCOMM Tech. Rep. 29, Paper E1
Tolman et al. 2005, *Ocean Modelling*, **8**, 253-278
Krasnopolsky et al., 2008, *Neural Networks*, **21**, 535-543

AI/ML 2: Parameter optimization

Generalized Multiple DIA (GMD)

- 2D integral for small set of interaction configurations (was 6D)
- Fitting to WRT source term only does not provide accurate model

Set of idealized test conditions

- Fit GMD ***model integration results*** to WRT results
- Compute error metrics from saved spectra.
  - Mean parameters (7) 1D spectrum (5) 2D spectrum (3)

Genetic Optimization

Directed Random Search

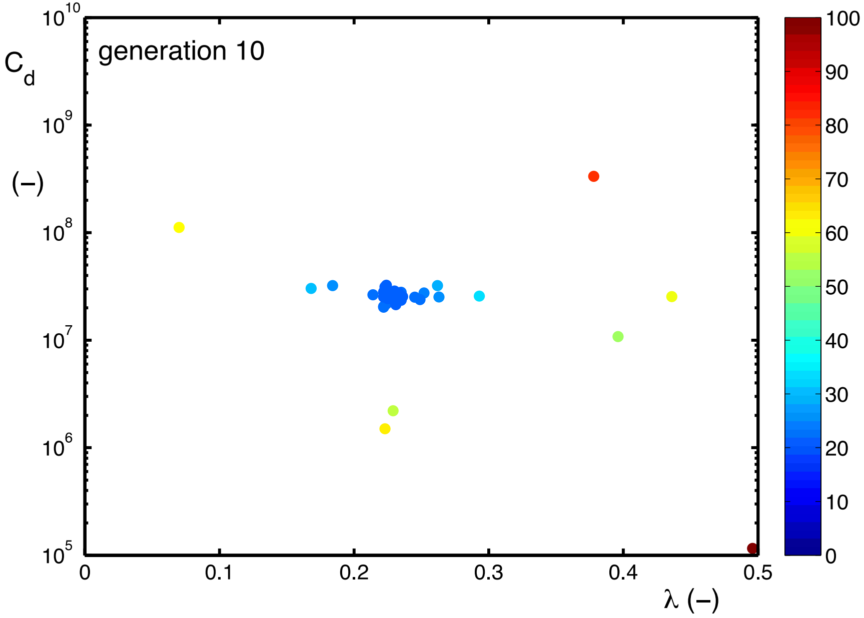
- Describe free parameters as “genome”
- Evolve a population – fit pairs + recombination and mutation

Generational evolution of search

Examples for the simplest configuration with two free parameters

- Difficult to visualize for more free parameters
- Worked effectively and efficiently for up to 20 free parameters

Error (= 1 / fitness) and members



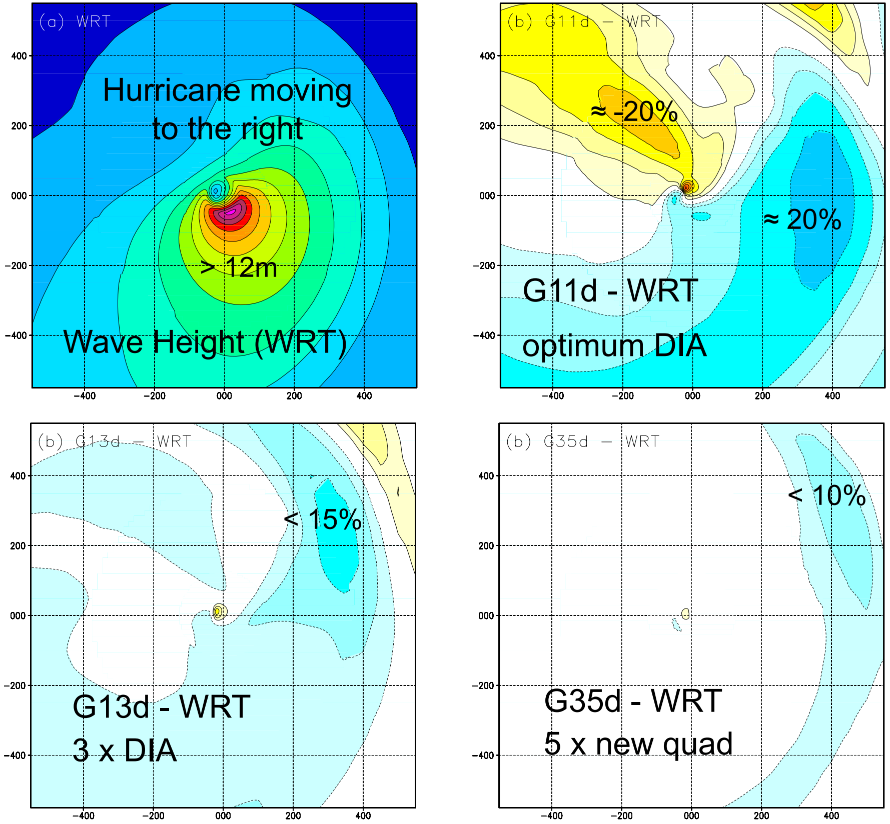
Tolman 2010, MMAB report 288, 175 pp.
Tolman 2013, *Ocean Modelling*, **70**, 11-23
Tolman and Grumbine 2013, *Ocean Modelling*, **70**, 25-37

Real world cases

- Normalized run time T_n
- Error (cost) function value in genetic optimization
  - Including spectral errors

Configur-ation	hurricane T_n (-)	hurricane Error %	Lake Michigan T_n (-)	Lake Michigan Error %
WW3	1.20	27.5	1.16	23.5
WAM	0.99	28.7	1.09	24.9
G11d	1.05	26.3	1.10	21.8
G13d	1.50	19.1	1.45	16.8
G35d	3.52	14.9	4.04	14.4
WRT	1360	---	370	---

Wave height and relative error(%)



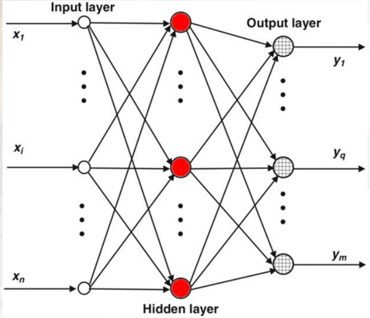
AI/ML 3: Ensemble processing

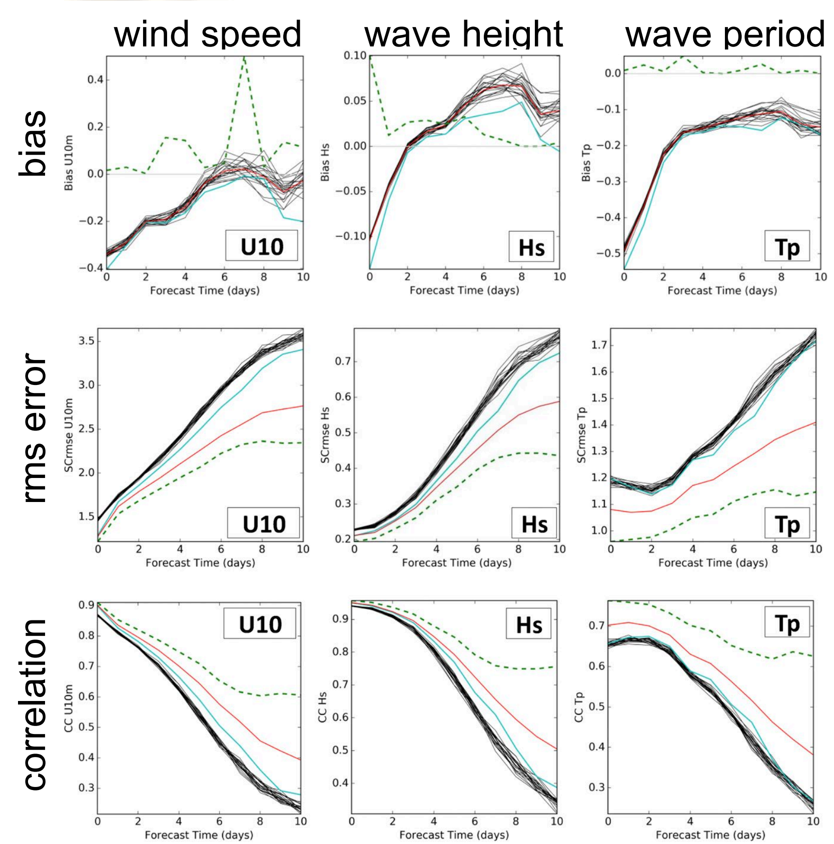
Forecasters need to communicate both the accurcy and the uncertainty of the forecasts

- Specifically important for systems with chaotic behavior
- Model uncertainty is traditionally addressed with model ensembles
  - Perturbing initialization, forcing, parameterizations etc. to obtain multiple likely solutions
  - Ensemble average generally is more accurate than deterministic model run particularly for longer forecast times
  - AI can do even better

NN for wave ensemble

- Results for Gulf of Mexico NN processing of wave ensemble
  - Ensemble Members in grey
  - NN results in green
  - Average in red





Martins Campos et al. 2019, *J. Atmospheric & Oceanic Techn.* **36(1)**, 113-127 (source of figures)
Martins Campos et al. 2020, *Ocean Modelling*, **149**, 101617

WAVEWATCH III

Private Sector Engagement

General engagement

There are an increasing number of private sector partners we are working with, and who are adopting the UFS

The focus here is just on one group, Sofar Ocean

- Pre-UFS active in wave modeling
- Focus on observations and modeling

This is just an example !

- … and a testbed for the UFS

Sofar Ocean
San Francisco, CA USA
www.sofarocean.com

With thanks to *Christie Hegermiller*, Isabel Houghton, Pieter Smit and Tim Janssen *for the following slides* and many past interactions

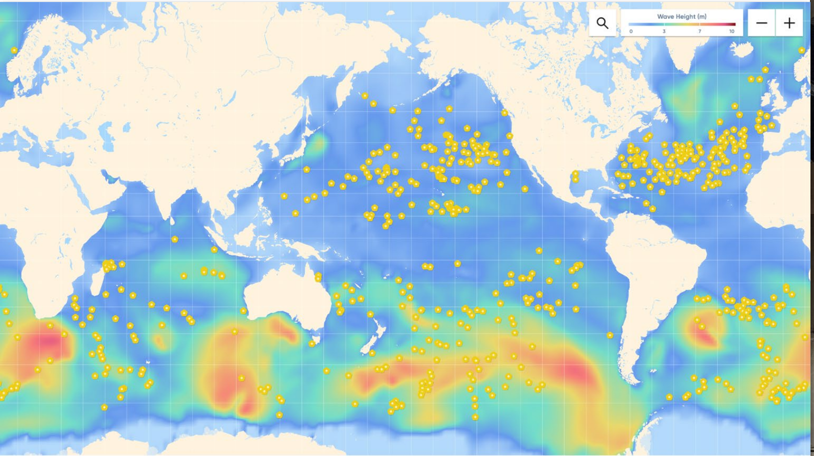
SOFAR

Global Wave Observations

Spotter is a metocean buoy powered by the sun and connected through satellite. Every **Spotter** measures and calculates:

- Sea surface temperature
- Barometric pressure
- Wind speed and direction by proxy
- Acoustic intensity
- Surface wave spectral properties

Houghton et al. (2021) *JTECH* 10.1175/JTECH-D-20-0187.1



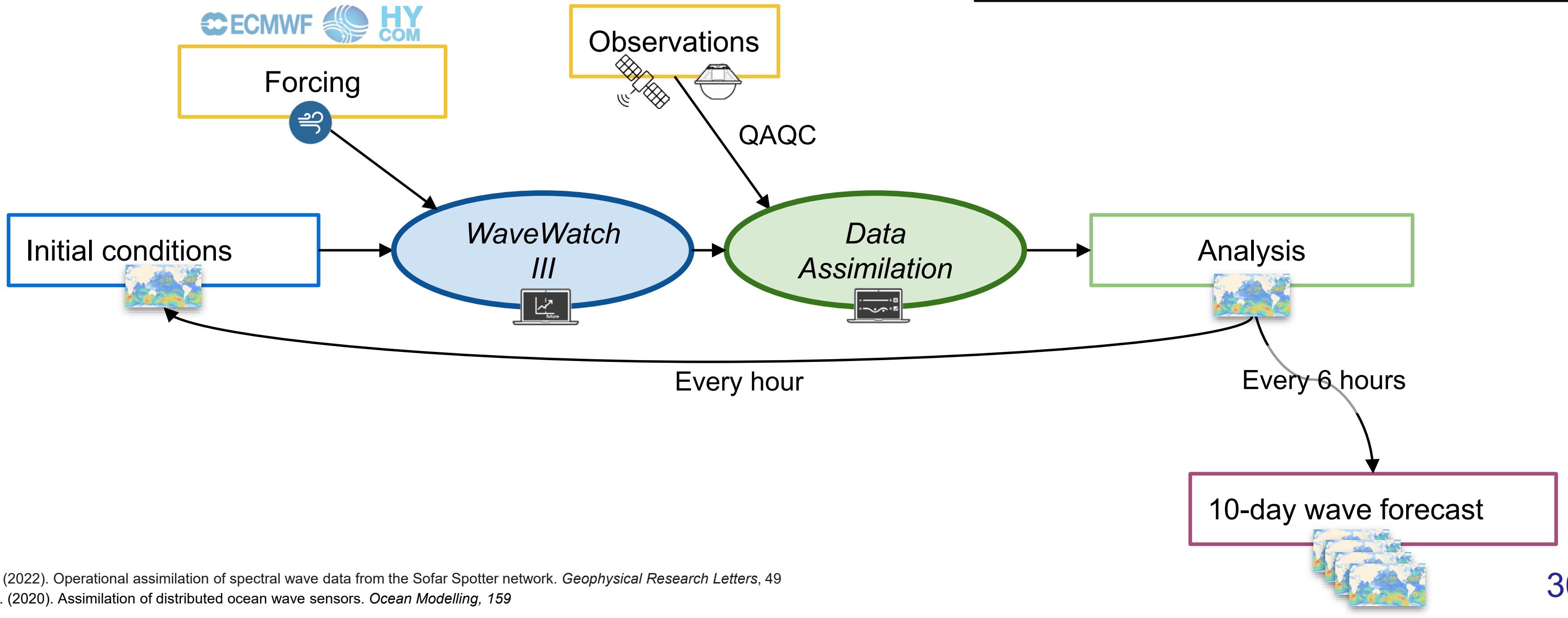

Courtesy of USNRL and UW


Courtesy of USCG Polar Star

Operational Wave Forecast System

Cloud-based, scalable compute infrastructure.

- ASTRONOMER — Monitor
- Apache Airflow — Orchestrator
- aws — Scalable compute and storage
- docker — Containerized WW3 build

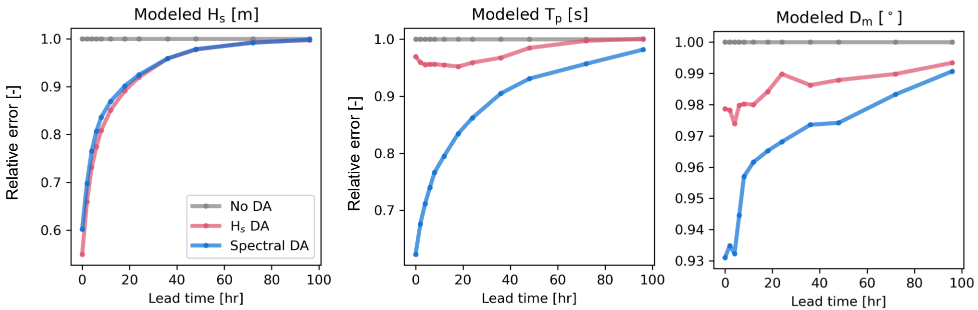


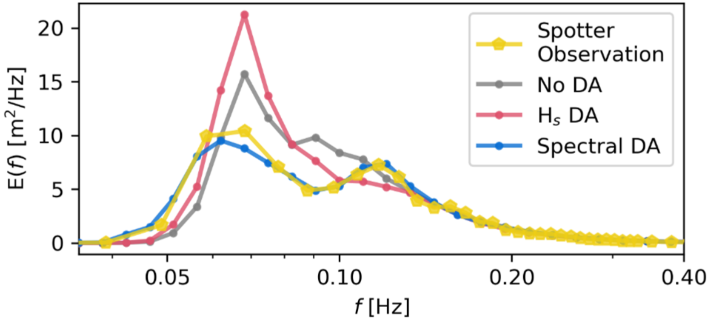
Houghton, et al. (2022). Operational assimilation of spectral wave data from the Sofar Spotter network. *Geophysical Research Letters*, 49
Smit, P. B., et al. (2020). Assimilation of distributed ocean wave sensors. *Ocean Modelling, 159*

Assimilation of wave spectra observations in WW3

- *Large scale distributed sensing networks (e.g. Spotters) substantially improve wave forecasts*
    - Large improvements in the short term (~ 24 hours)
    - Long-term relaxation towards forcing
    - Swell updates persist

- *Spectral observations are vital to reach additional impact on forecasts*
    - Improvement to frequency and direction characteristics (spectral shape) are persistent on medium timescales



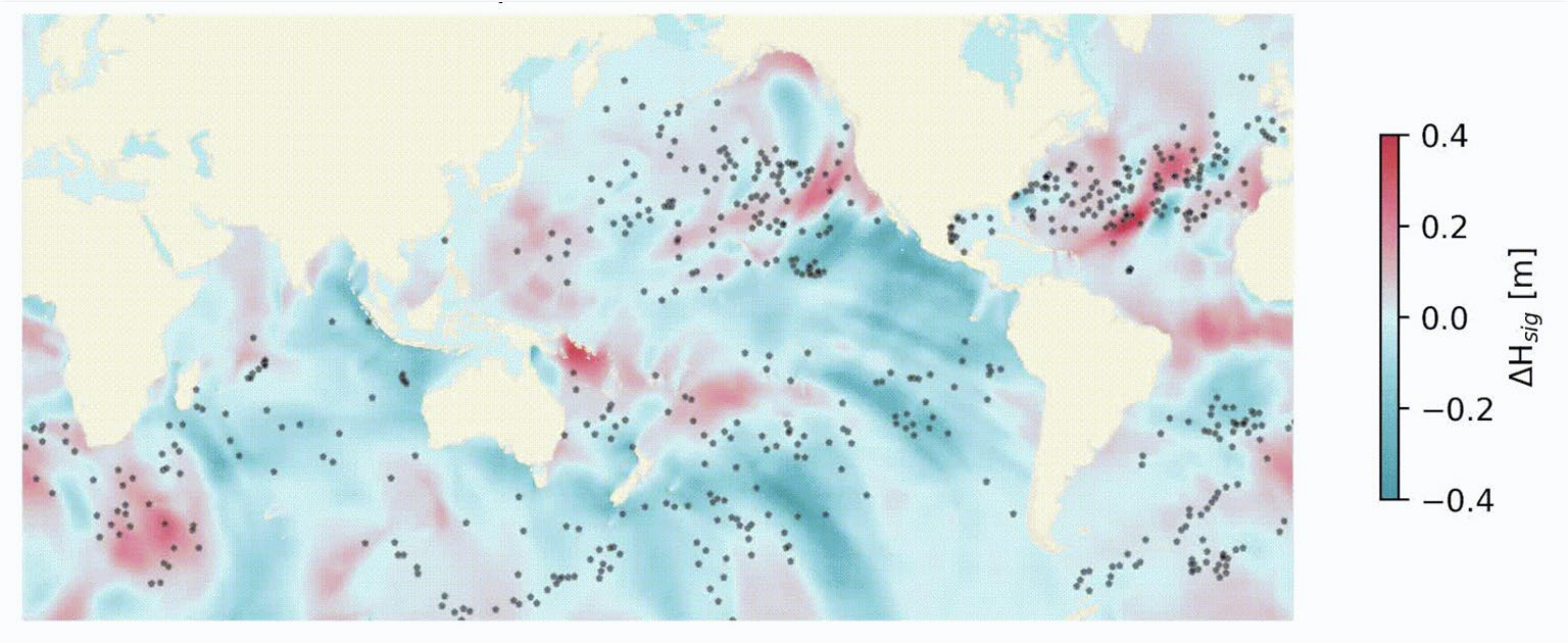


Upper: Assimilation of spectral information improves Hs, Tp, and Dm over assimilation of Hs alone.
Lower: Spectral information modifies the model spectrum to best align with observations.

Houghton, et al. (2022). Operational assimilation of spectral wave data from the Sofar Spotter network. *Geophysical Research Letters*, 49
Smit, P. B., et al. (2020). Assimilation of distributed ocean wave sensors. *Ocean Modelling, 159*

Global forecasting with assimilation of wave spectra observations in WW3

Difference in 48-hour forecast with data assimilation vs. without



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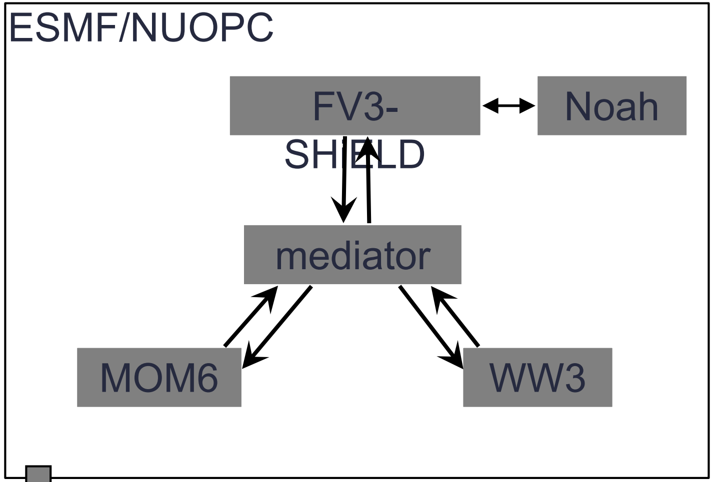
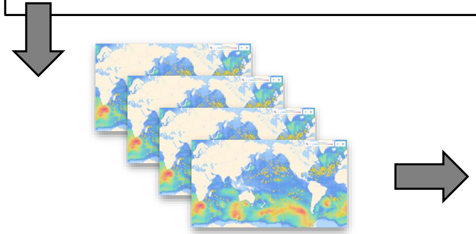
Smit, P. B., et al. (2020). Assimilation of distributed ocean wave sensors. *Ocean Modelling, 159*

SOFAR

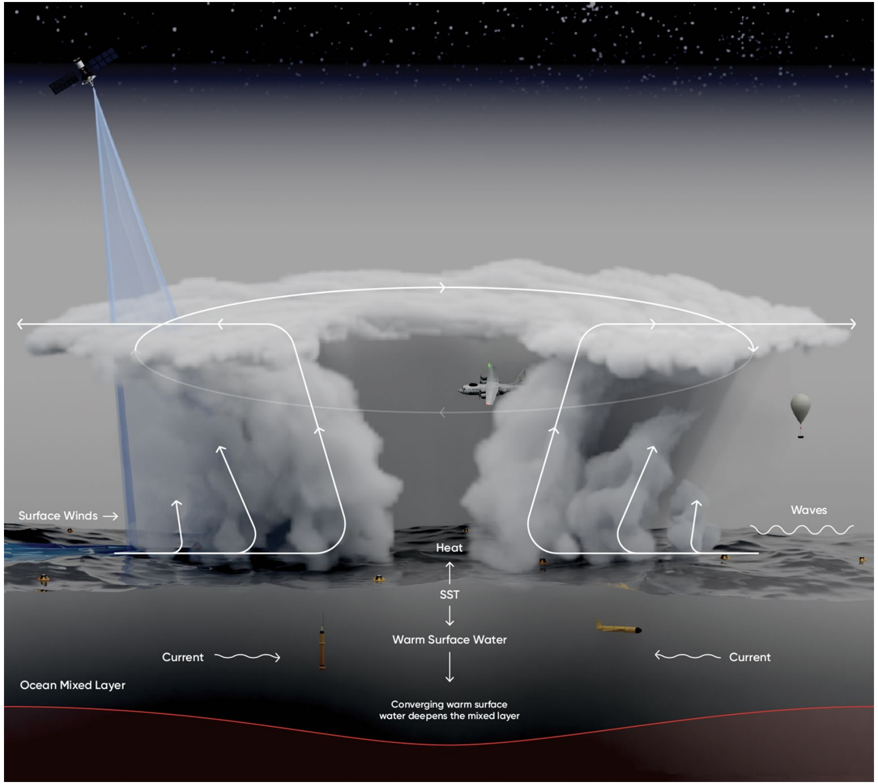
Coupled Forecasting and Data Assimilation

Developing a custom system using UFS components
to leverage Spotter observations at the air-sea interface:





Ensemble-based coupled DA



Looking forward

Present examples and more …

- Power of community modeling, including private sector
- Power of multi-disciplinary approach
- Potential of Artificial Intelligence, from examples and more
  - Model emulators
  - Model optimizations (selection of tunable parameters)
  - Postprocessing of model results (ensembles)
  - Improving Data Assimilation
  - Machine Learning from observations and model output
  - Replacing models / ensemble members ?

2020 Weather Forecast Innovations TEDX talk

Thank You!