# Coupling Strategies

Three talks in one!

*Dr. Ir. Hendrik L. Tolman*
*Senior Advisor for Advanced Modeling Systems*
*Office of Science and Technology Integration*
*National Weather Service / NOAA*

*Hendrik.Tolman@NOAA.gov*

# Content

A presentation in three parts:

- Part I: The Unified Forecast System
  - Coupling, and even waves!
- Part II: Wave response to forcing perturbations
  - Impact for how we do wave modeling and coupling
- Part III: Coupling Strategies
  - Thinking about close coupling in the UFS

Part I

# The Unified Forecast System (UFS)

*UFS – R2O*

# 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.

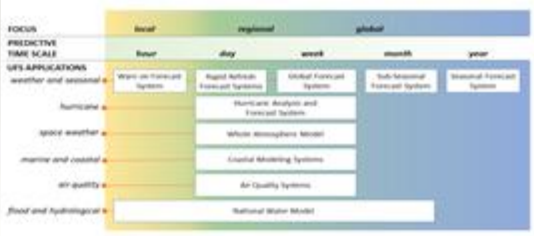
**Design** — UFS is a ***unified*** system because the applications within it share science components and software infrastructure.

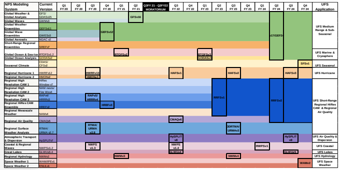
**Impact** — UFS is a ***paradigm shift*** that will enable NOAA to simplify the NCEP Production Suite, to accelerate use of leading research, and to produce more accurate forecasts for the U.S. and its partners.

# UFS in a nutshell

## Milestones:

- Buy in at AA level (UMC)
- MoA with NCAR
- Community Modeling
- Research and Ops.
- UFS R2O project
- NOAA Modeling Team
- EPIC



**1. Coupling components**
New ESMF/NUOPC mediator (CMEPS/NEMS)

**2. Interoperable atmospheric physics**
CCPP & CPF frameworks

**3. Community-friendly workflow**
CIME - CROW unification, CIME Case Control System

**4. Hierarchical model development capabilities**
Extensions of CIME data models, unit, and system testing

**5. Forecast Verification: Comparison to Observations**
Extension of METplus

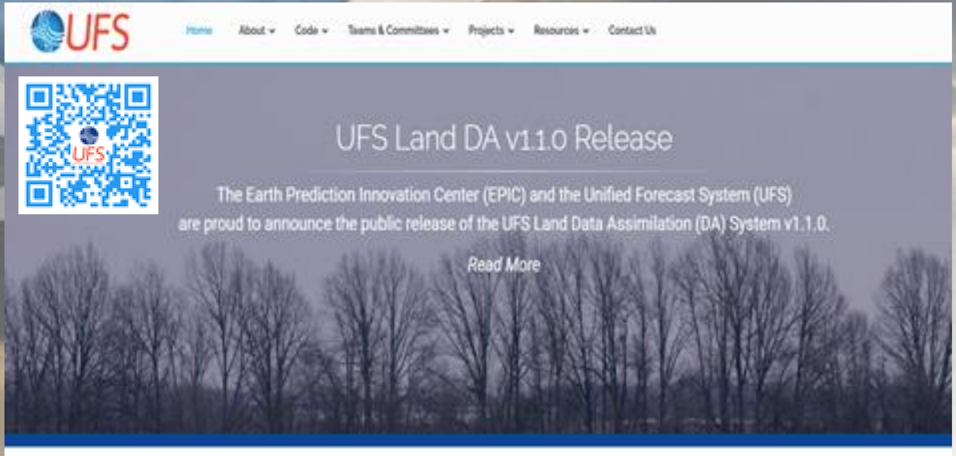
**6. Software Repository Management**
NCAR manage_externals tool

**7. User / Developer Support**
DTC and CESM Capabilities

# Founded in law …

- NDAA Dec. 2022 Section 10601, LEGEND Act. "LEARNING EXCELLENCE AND GOOD EXAMPLES FROM NEW DEVELOPERS"
  - Directed at NOAA
  - "Open Source"
  - With some exceptions
    - Obsolescent code
    - Restricted code
  - Mentioning EPIC
  - Models ***and*** Data
  - Foundational for UFS

*Purposes.--The purposes of this section are–*
*(1) to support innovation in modeling by allowing interested stakeholders to have easy and complete access to operational model codes and to other models, as the Administrator determines appropriate; and*
*(2) to use vetted innovations arising from access described in paragraph (1) to improve modeling by the Administration.*





# UFS powered by EPIC

Sign up for UFS/EPIC Mailing List


# Getting the Community Involved

## Community Workshops

**UIFCW 2024**

***Dates: July 22-26, 2024, Jackson State University (Cooperative Science Center with NOAA CCME II)***

**2nd Annual UFS Physics Workshop**

***July 9-12, 2024, NOAA NSSL***

- Will address ongoing need for improving convective parameters in the UFS

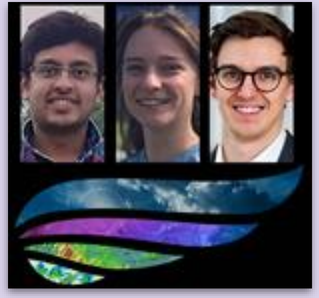
**UFS Atmospheric River Modeling Workshop**

***Oct. 8-10, 2024, UCSD***

- Collect inputs from the broader AR modeling community to improve AR modeling and evaluation in the UFS

## Student Opportunities

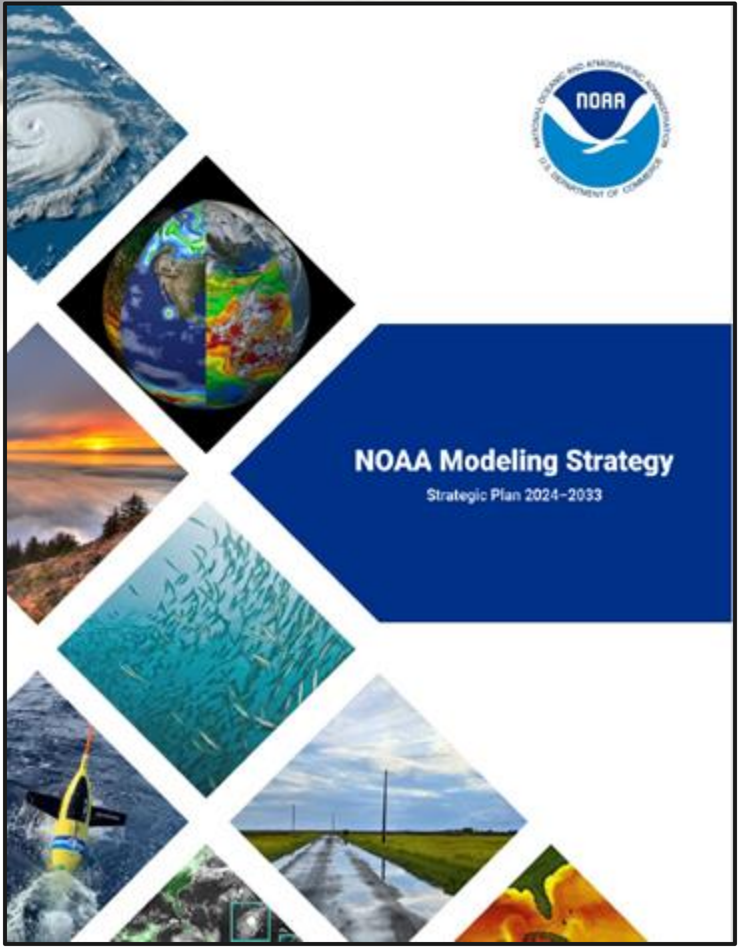
**Weather Program Office's Innovation for Next Generation Scientists**



**W.I.N.G.S.**

**PhD Dissertation Fellowship**

Officially released at AMS annual conference in Baltimore 1/30/2024



# NOAA Modeling Strategy - Goals

- Goal 1: Unify Modeling Approaches Across NOAA
- Goal 2: Integrate Modeling and Observations of the Environment
- Goal 3: Implement an Evidence-Based Governance Model, including Broad Community Involvement Where Possible
- Goal 4: Advance Software Modernization Across NOAA and Effectively Procure High Performance Computing (HPC) Assets
- Goal 5: Bolster Service Delivery Approaches and Innovative Technologies (AI!)
- Goal 6: Support workforce development

# NOAA and NSF

Traditionally NOAA and NSF have been focusing on different models / modeling systems

- NOAA – NSF leadership RoundTable last year
- UFS reaching maturity for broader community
- NSF Dear Colleague letter
  - https://www.nsf.gov/pubs/2023/nsf23095/nsf23095.jsp
  - 2023: 6 NSF projects received additional funding to work with UFS tools!

# NSF Modeling DCL

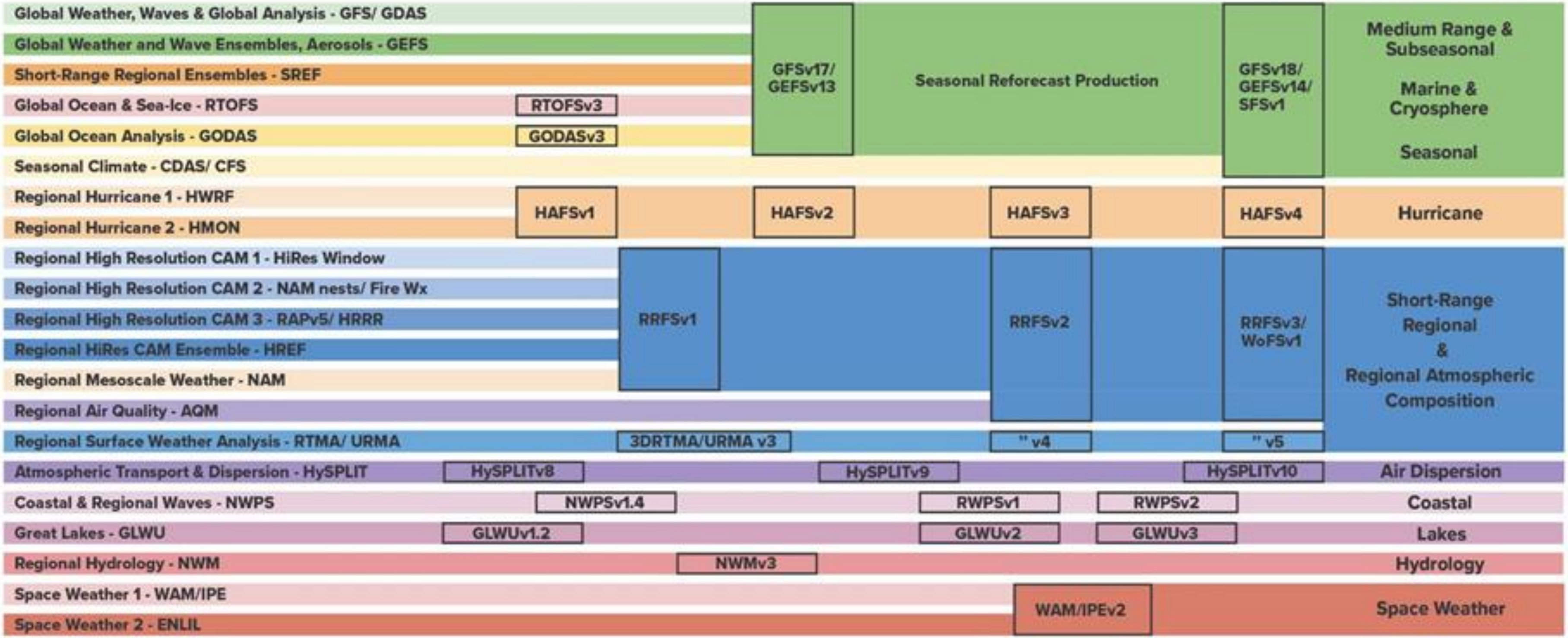
Eleven supplements were awarded, 5 for MPAS and 6 for UFS.

| MPAS | UFS |
|---|---|
| Orf (Wisconsin) – Convective storms | Fovell (Albany) – Boundary layer |
| Nolan (Miami) – Gravity waves | Minder (Albany) – Winter weather |
| Marras (NJIT) & Stephen Guimond (Hampton) -Tropical cyclones | Alvey (Miami) – Tropical cyclones |
| Zhanqing Li (Maryland) – Aerosol/Cloud Interactions | Momen (Houston) – Tropical cyclones |
| Dan Li (Boston Univ.) – Boundary layer | Zhu (Florida Intl) – Tropical cyclones |
| | Tang (Albany) – Tropical cyclones |

Nicholas Anderson, NSF, AGU 2023 UFS town hall

# UFS phased transition

~~26~~ 21 Independent Stand-alone Systems → 8 UFS Applications

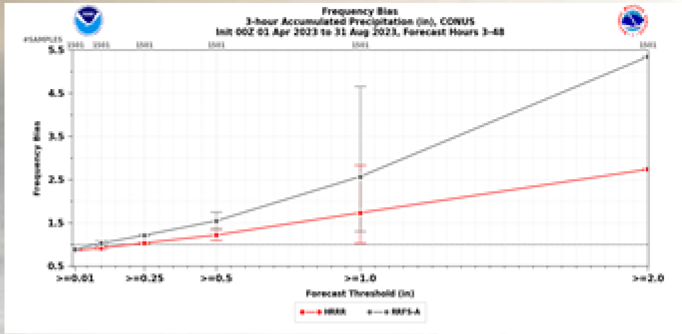


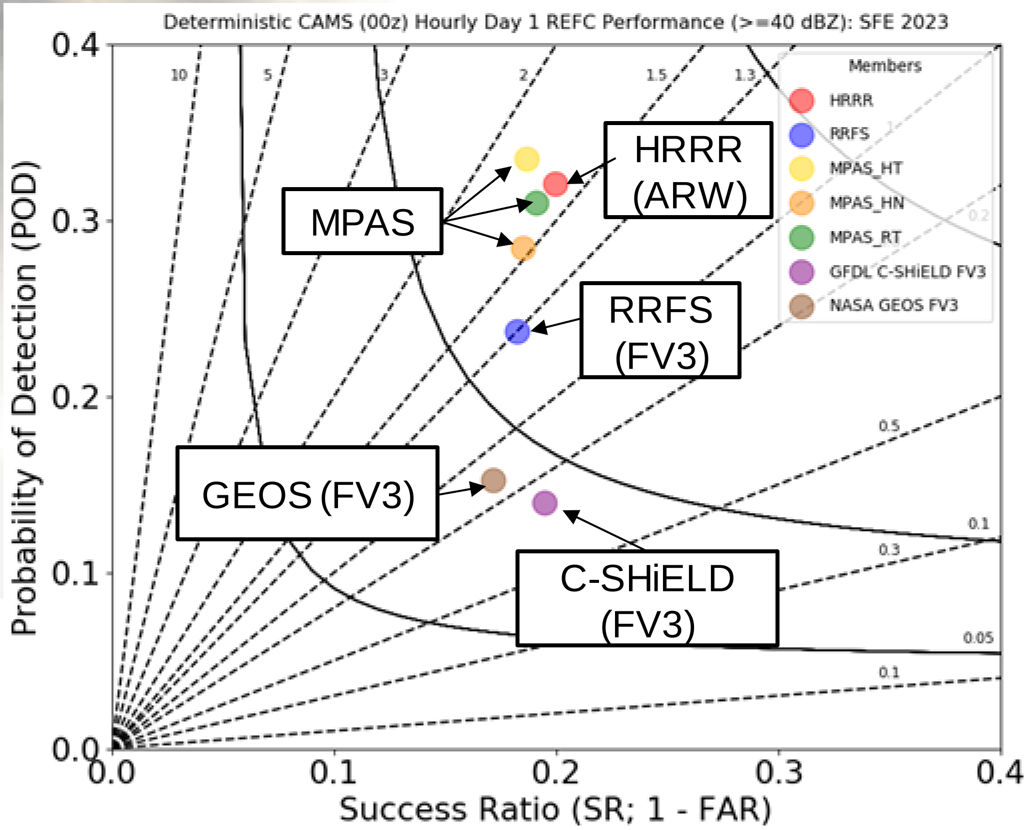
# Big Picture Progress

- **Simplifying the production suite**: reduce the complexity of the Production Suite (# of number of major applications)
  - 70% planned, 23% achieved
- **Building the community**: reducing the cost of setting up a UFS application outside of the NOAA
  - Was $15M+ for GFS, now 1 person 1 day on your computer
  - NSF starting to support UFS
- **Improving Operations**: Evidence driven, community teams
  - Much larger teams supporting development
- **NOAA planning**: 10 Year NOAA Modeling Strategy (UFS, JEDI)

# Does CAM need second dycore?

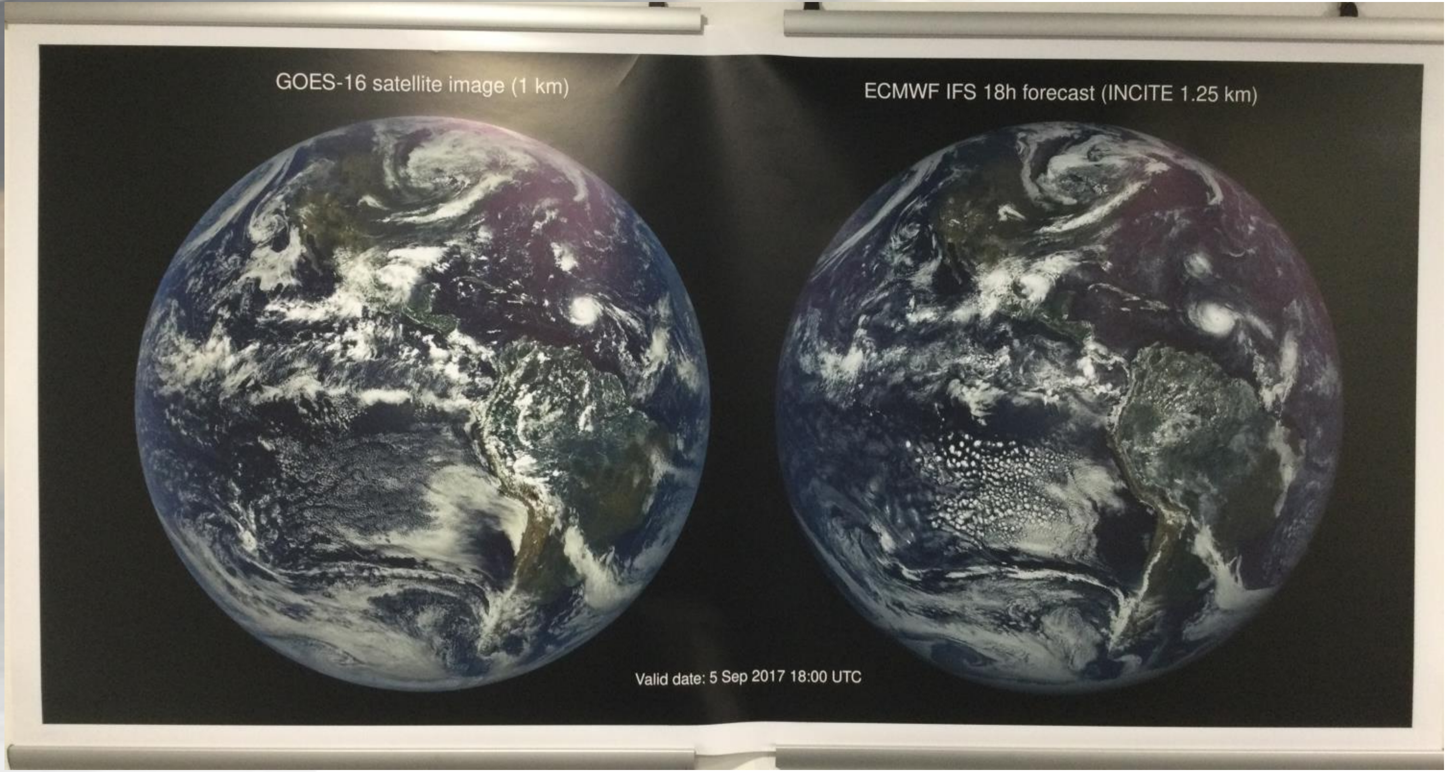
- Reducing unneeded diversity in productions suite: moving to FV3
- FV3 precip biases in severe weather
  - Do we need another dycore?
- Unified ≠ Unitary!




Courtesy Wicker et al: AMS 2024 3CMI paper 3.1

# Unique to UFS ?



Part II

# Wave response to forcing perturbations

(adapted from presentation at waves workshop at University of Notre Dame, October 2023)

# Background

## Wind is important for wind waves (dah !)

- View from meteorological perspective :
  - Accurate description of mesoscale features
- Competing viewpoints ?
  - Wave height scales quadratic with wind speed
  - Waves as low-pass filter of forcing
- Systematic assessment of impact of wind perturbations should be very insightful
  - Previous work at for selected conditions (next slide)
  - Many impacts for waves and/or coupling

# Background (history, scales)

- Gustiness, e.g.,
  - Kahma and Calkoen (1992, 1994)
  - Abdalla, Cavaleri, Bidlot, Janssen 2002 and 2003
- Resolved scales, e.g.
  - Shuyi Chen et al (2013), high-resolution hurricane work
- Propagating wind perturbations (dynamic fetch), e.g.
  - Tolman & Alves (2005), Xu et al. (2007), Chen et al (2013)
- Perturbing ensembles
  - Spread in wave ensembles is directly related to time scales of perturbation of wind field (not just amplitude) (NCEP)

# Experiments

## Systematic perturbation study with wind wave model

- WAVEWATCH III, set up as for NCEP global models
- Time limited growth starting with flat surface and $U_{10,b}$ = 20 ms$^{-1}$
- Systematically perturbed wind speed

$$U_{10}(t) = U_{10,b}\,[1 + \Delta\hat{U}\sin(2\pi\, t\, T_{\delta}^{-1} + \phi_0)\,]$$

- Gives (systematic ?) wave height perturbation

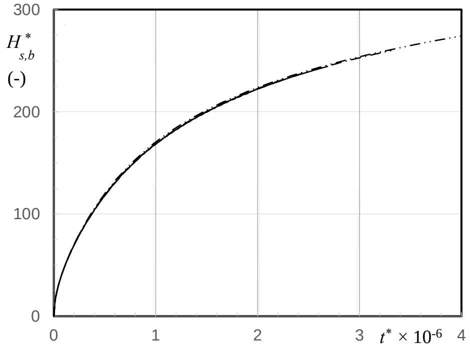
$$\Delta H_s(t) = H_s(\Delta\hat{U}, T_\delta, \phi_0; t) - H_{s,base}(t)$$

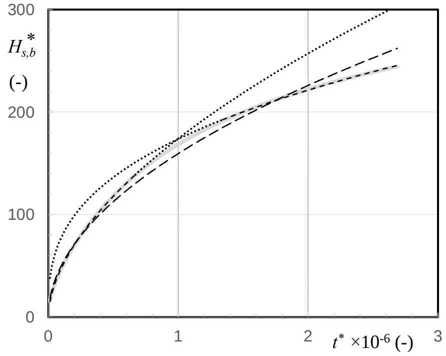
- Ideally described with $\Delta H_{s,avg}$ and std $\sigma_H$, in principle as $f(t)$

# Before actual experiments

To make sure results are reliable

- Test convergence / set time steps
- Test scaling behavior
  - Universal $u_*$ scaling for baseline run
    - Two distinct scaling ranges
  - Not for $U_{10}$ scaling
  - How do you scale with perturbed wind ?
- Sensitivity to perturbations
  - Generally good above $\Delta\hat{U} = 10\%$
  - Noise introduced due to parametric tail transition skips

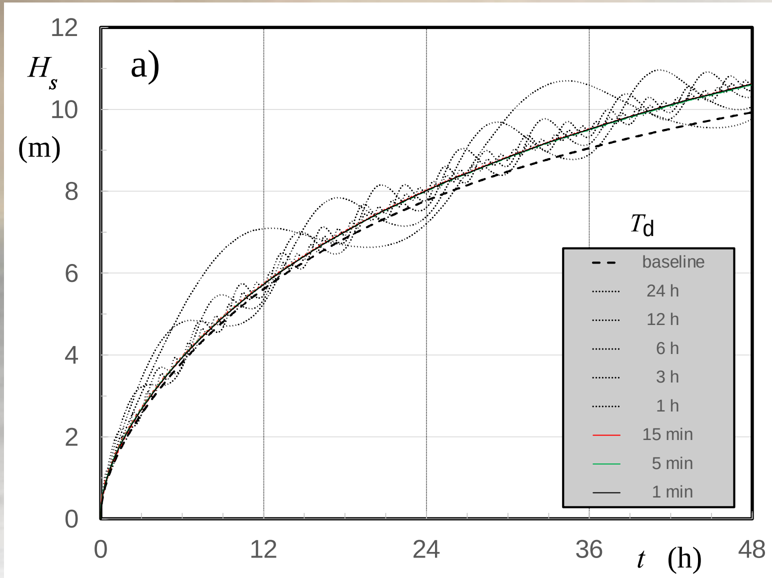


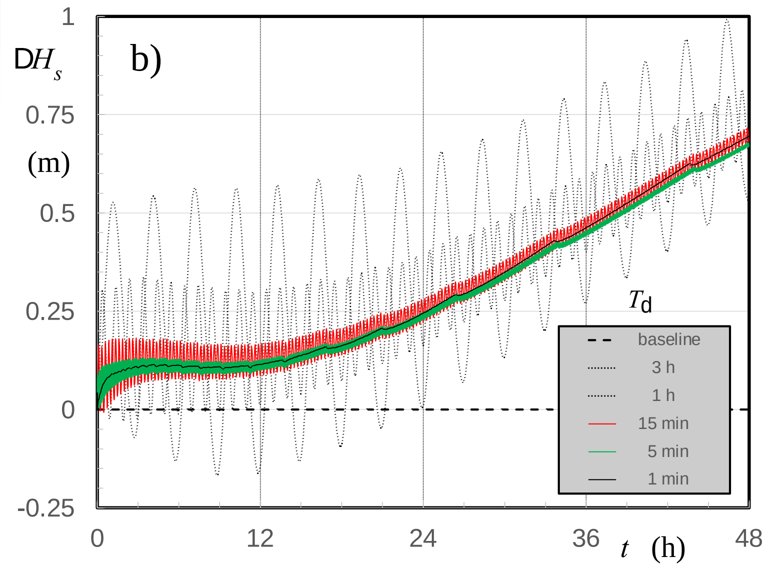



# A first look

$\Delta\widehat{U} = 30\%$ and $\phi_0 = 0$, with a large range of $T_\delta$

- Clear mean impact, clear low pass filtering even for $T_\delta$ = 24h!

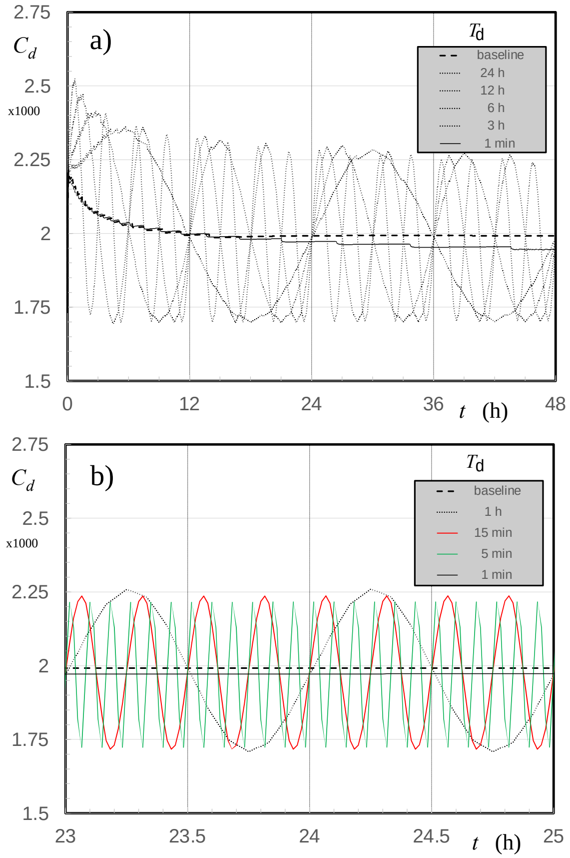


# A first look (extended)

Additional observations from the first look:

- Wave height good proxy for most mean parameters (not $\sigma_d$ or $f_p$)
- Wind direction variability has small impact
- Air-sea temperature difference has small impact
- Note that drag coefficient reacts near instantaneous, without low pass filter behavior

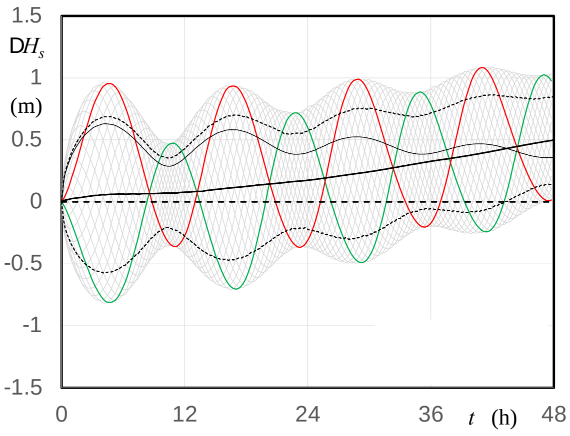


# A first look (phase averaging)

For each $(\Delta\widehat{U}, T_\delta)$, 24 $\phi_0$ are used

- The amplitude of $\Delta H_s$ is $f(\phi_0)$
- This can be removed with running box filter with width $T_\delta$
- This is directly related to cumulative effects of nonlinear initial growth
  - Physically sound
  - Not relevant in nature ?

All following results are phase $\phi_0$ averaged and filtered as needed




Example with $\Delta U_{10} = 20\%$ and $T_\delta = 12$h.

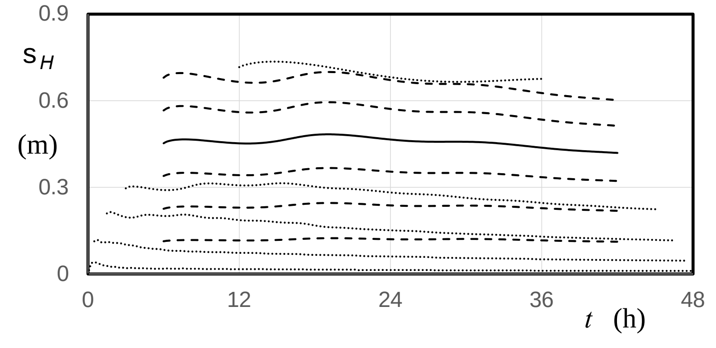
Red, green and grey lines are results with all initial phases

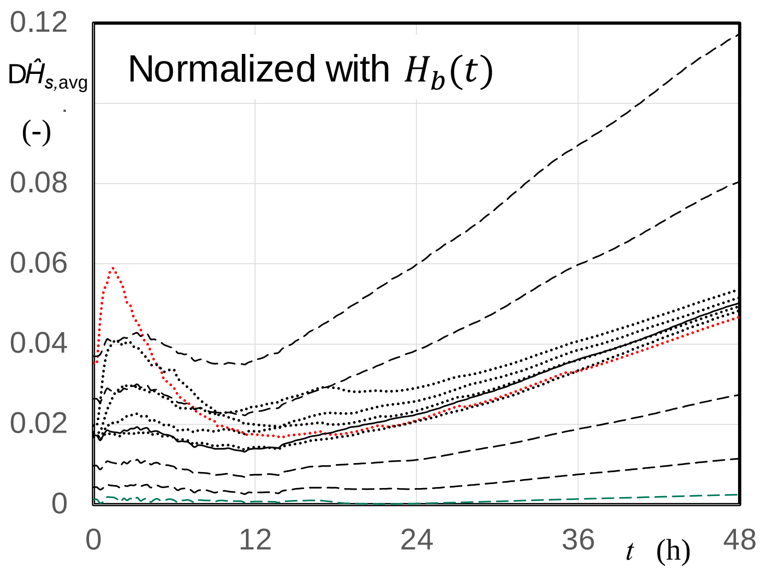
Black lines are mean parameters

# Evolution in time

## Is the impact of perturbations on average a function of *t* ?

- Variability $\sigma_H$ is nearly constant over time (0-48h)



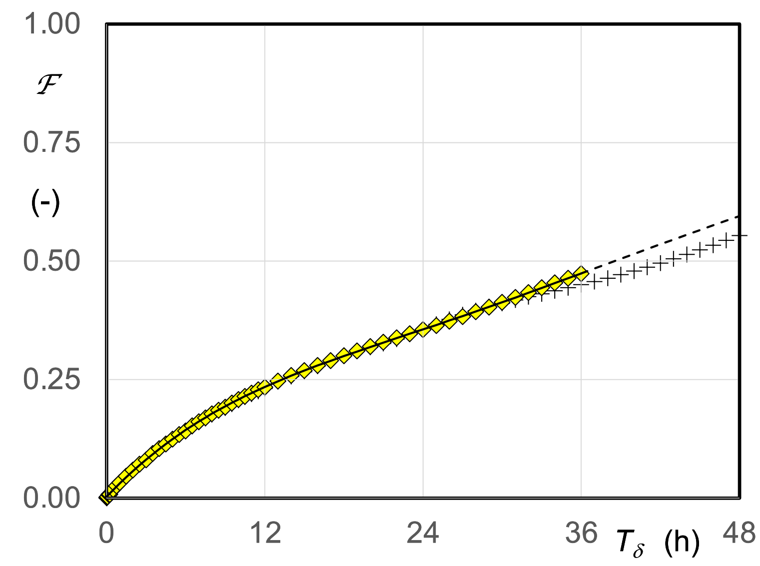

- Perturbation mean $\Delta H_{s,avg}$ is $f(t)$
  - ➤ Initial growth (3-9h) range vs.
  - ➤ mature growth (24-48h) range

# Low pass filtering

## Amplitude of wave perturbation relative to wind perturbation

- $\sigma_H$ constants in time
- Non-dimensional ($u_*$)
- Filter function $\mathcal{F}(T_\delta)$
- $\mathcal{F}(\infty) \equiv 1$
  - Form from scaling
  - Asymptote defines $\mathcal{C}$

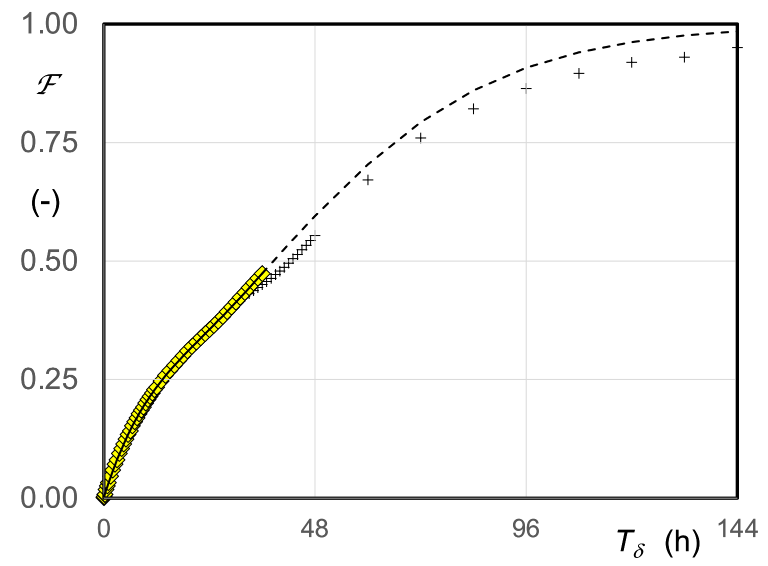
$$\frac{g\sigma_H}{u_*^2} \propto \mathcal{C}\ \mathcal{F}(T_\delta)\,\Delta\hat{U}$$



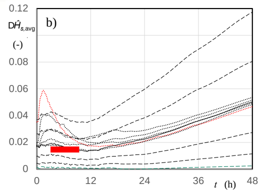
# Low pass filtering

## Low pass filtering dominates scaling behavior

- Extended exp for $T_\delta \rightarrow \infty$
- Impact for
  - Error propagation
  - Wind resolution
  - Wave ensembles
    - $T_\delta$ versus $\Delta\hat{U}$

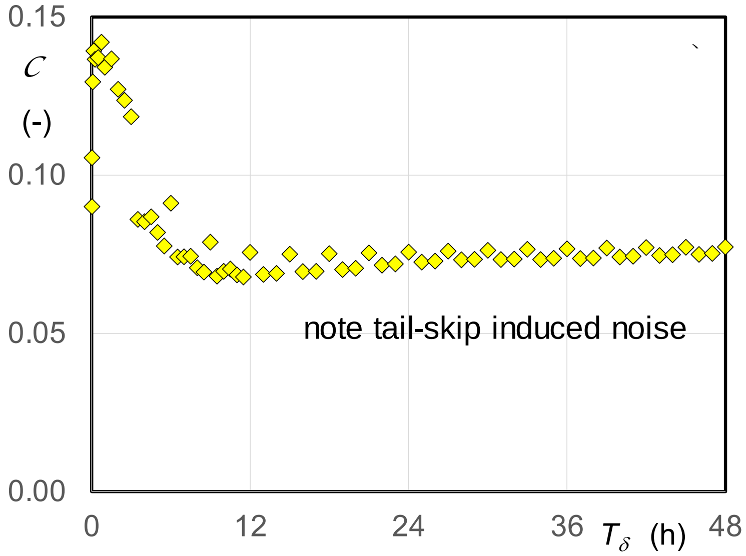


# Mean change, initial growth



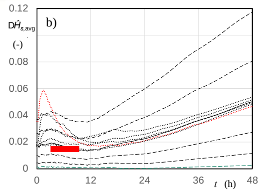

## Mean change relative to wind perturbation

- Assume $\Delta H_s$ constant for $t$ = 3-9h
- Non-dimensional ($u_*$)
- Form from scaling
- Constant $\mathcal{C}$ from experiment
- $\mathcal{C}$ asymptotes for $T_\delta$ > 24h
- $\mathcal{C}$ enhancement for $T_\delta$ < 12h



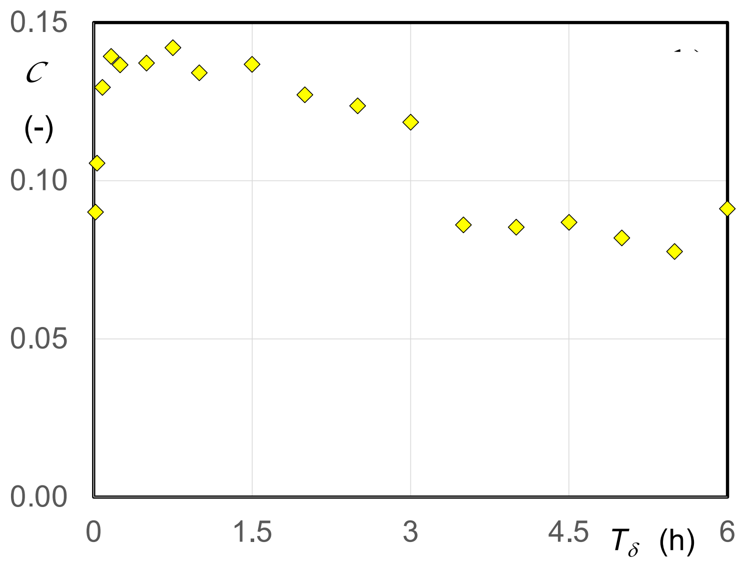

$$\frac{g \Delta H_{s,init}}{u_*^2} \propto \mathcal{C}\, \Delta \widehat{U}^2$$

# Mean change, initial growth

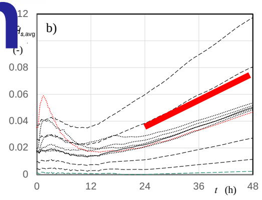



## Constant behavior with enhancement area

- Results for $T_\delta \downarrow 0$ like asymptote
  - ➤ Consistent with expectation
- Enhanced impact range
  - ➤ Nonlinear feedback ?
- Impact for
  - ➤ Gustiness
  - ➤ Scale-aware physics
  - ➤ Wind resolution

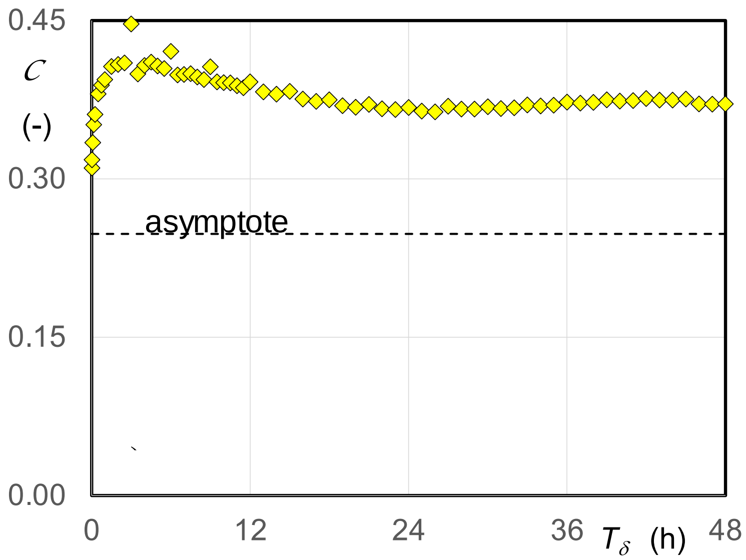


# Mean change, mature growth



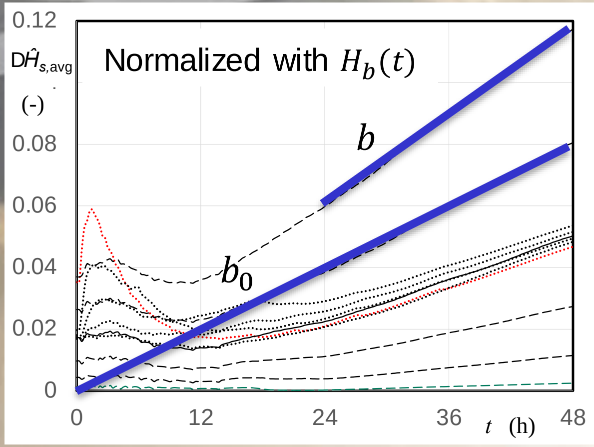

## Mean change relative to wind perturbation

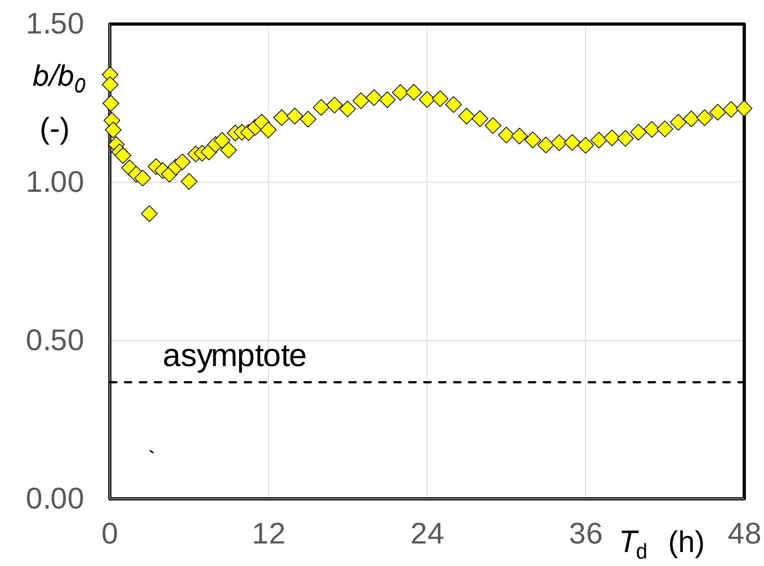
- Increases for $t$ = 24-48h
- Same formulation as $\Delta H_{s,init}$
- Tail-fit noise less evident
- $\mathcal{C}$ asymptote for $T_\delta \gg$ 48h
- $\mathcal{C}$ enhancement for most $T_\delta$
- Bigger impact than for $\Delta H_{s,init}$




$$\frac{g\Delta H_{s,mat}}{u_*^2} \propto \mathcal{C}\,\Delta\widehat{U}^2$$

# $\Delta H_s\,(t)$, mature growth



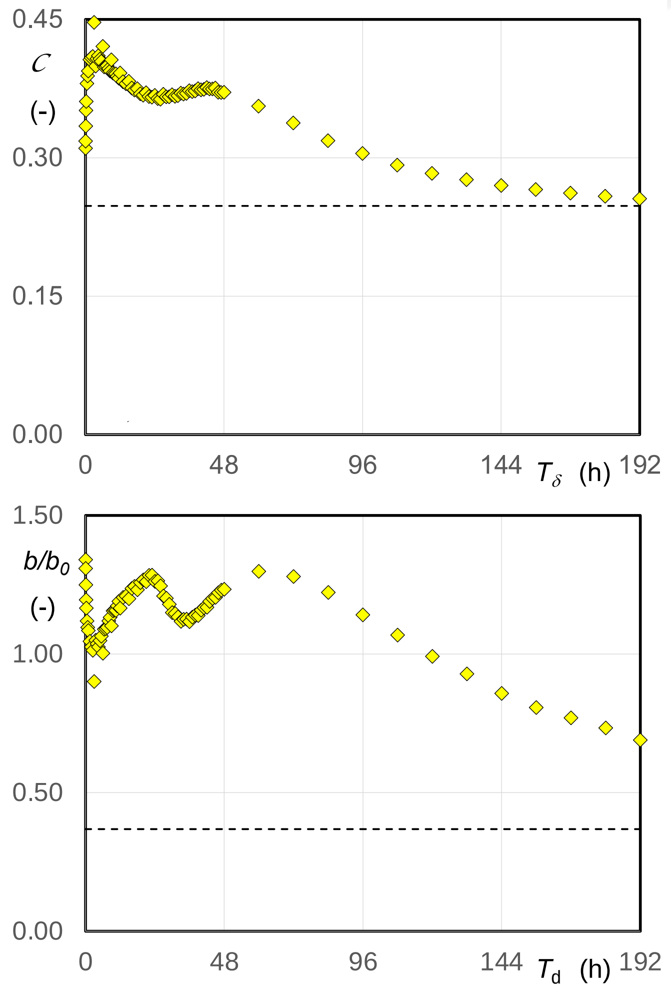

## Linear growth with time

- Normalized slope $b/b_0$
- Fit for $t$ = 24-48h
  - $\Delta H_s = a + b\,t$ , $\Delta H_s = b_0\,t$

# Mature growth

Enhancement throughout (vs. asymptote)

- Impact for
  - Gustiness
  - Wind resolution
  - Scale aware physics



# Sooooo ....

Interesting results for

- Low pass filter behavior
  - Impacts ensemble building
  - Impacts DA
  - Impacts for coupling time scales
- Enhanced mean impacts
  - Including previously unseen secondary feedback
  - Do we need scale-aware physics?
    - Can approaches with “effective wind” work?

# But ….

## Limitations:

- A specific WW3 configuration
- In highly idealized conditions

## Possible next steps:

- Nondimensional growth time and time scales assessments from operational models
- Similar assessments in fetch-limited conditions
- Similar assessment in moving storm conditions
- Other physics packages ?

Part III

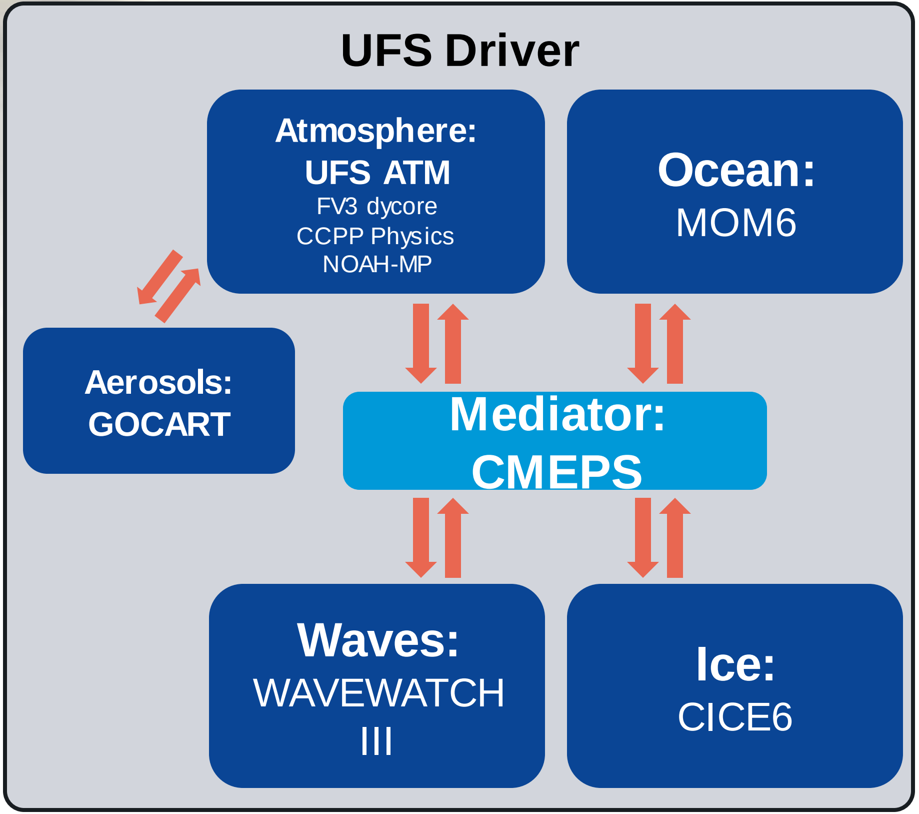
# Coupling Strategies

(From a UFS perspective)

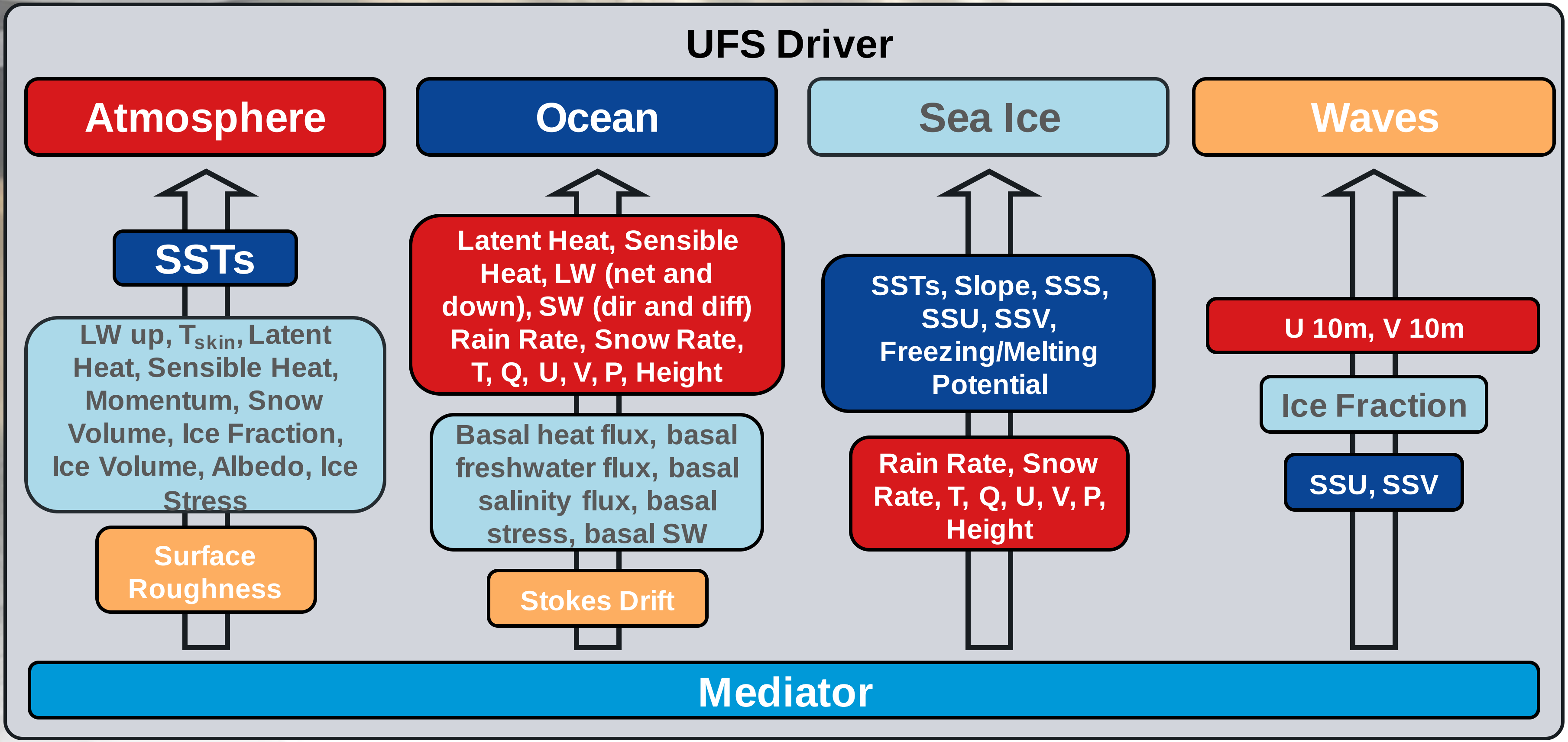
# UFS coupling approach

## Base design principles

- Do coupling with minimal impact on component models.
- Coupling with “wrappers” around community models
  - ESMF / NUOPC / CMEPS
  - Language / Dictionary / Book
- Learn coupling now, redesign techniques later
- Coupling to simplify Production Suite



# Coupling in GEFS/UFS



# Second generation UFS coupling

I intend to develop a position paper this year. We tentatively intend to move from “loose” (API based) coupling to close (integrated code) coupling.

Why move away from loose coupling?

- Inefficiencies in load balancing within components
- Inefficiencies in load balancing between components
- Coupling can dictate component model time stepping

Example of potential/need for close coupling:

- MOM6-ice coupling (driven by ice thermodynamic time scales)

# Basic of (closer) coupling I

## Why do we have component models?

- Convenience: smaller problems, need to fit in resources
- Has become an established way of doing business

## Why do we do loose coupling?

- Recognizing the need for interactions between component models based on physics
- Easy next step beyond stand-alone models
- Pitfall: “just exchange data”, ignore numerics involved

# Basic of (closer) coupling II

Systematic approach to loose coupling

- Treat as a numerical problem, with basics we use inside the components, e.g.
  - Stability (CFL) and accuracy assessments
  - Assess aliasing and Gibbs effect
  - Treat as another “fractional step” (Yanenko 1971)?
- Loose coupling enforces outcome of this as a global component model time step!

# Basic of (closer) coupling III

Close coupling enables diversified time stepping

- Barotropic/baroclinic splitting in time integration in ocean models
- Four time steps + dynamic source term integration in WW3

Effective closer coupling requires

- Running parts of the models rather than a “full increment”, or
- being able to call part of one component in another, or
- use schedulers integrated in the model (e.g. Uintah, U. of Utah),

x Close coupling requires code modernization

- functional object-oriented code

# Code modernization !!!

Closer coupling is a (software) engineering problem and requires code modernization. This is also driven by

- "Old" codes in research and operations
  - We are now moving to GPUs
  - The last structural hardware change we had to deal with was vector → parallel processing (ca. 1999)
- Community modeling move
  - Needs high quality documented codes in general
  - Needs performance portability
    - Domain specific languages (UM leads the way)

Modern Modular Wave Modeling!

# Thank You!