Optimizing Observations to Explore Predictive Skill: An Ocean Perspective

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with input from Carol Anne Clayson, Bruce Cornuelle, Meghan Cronin, Chelle Gentemann, Donata Giglio, Momme Hell, Tony Lee, Matt Mazloff, Bia Villas Bôas and many others

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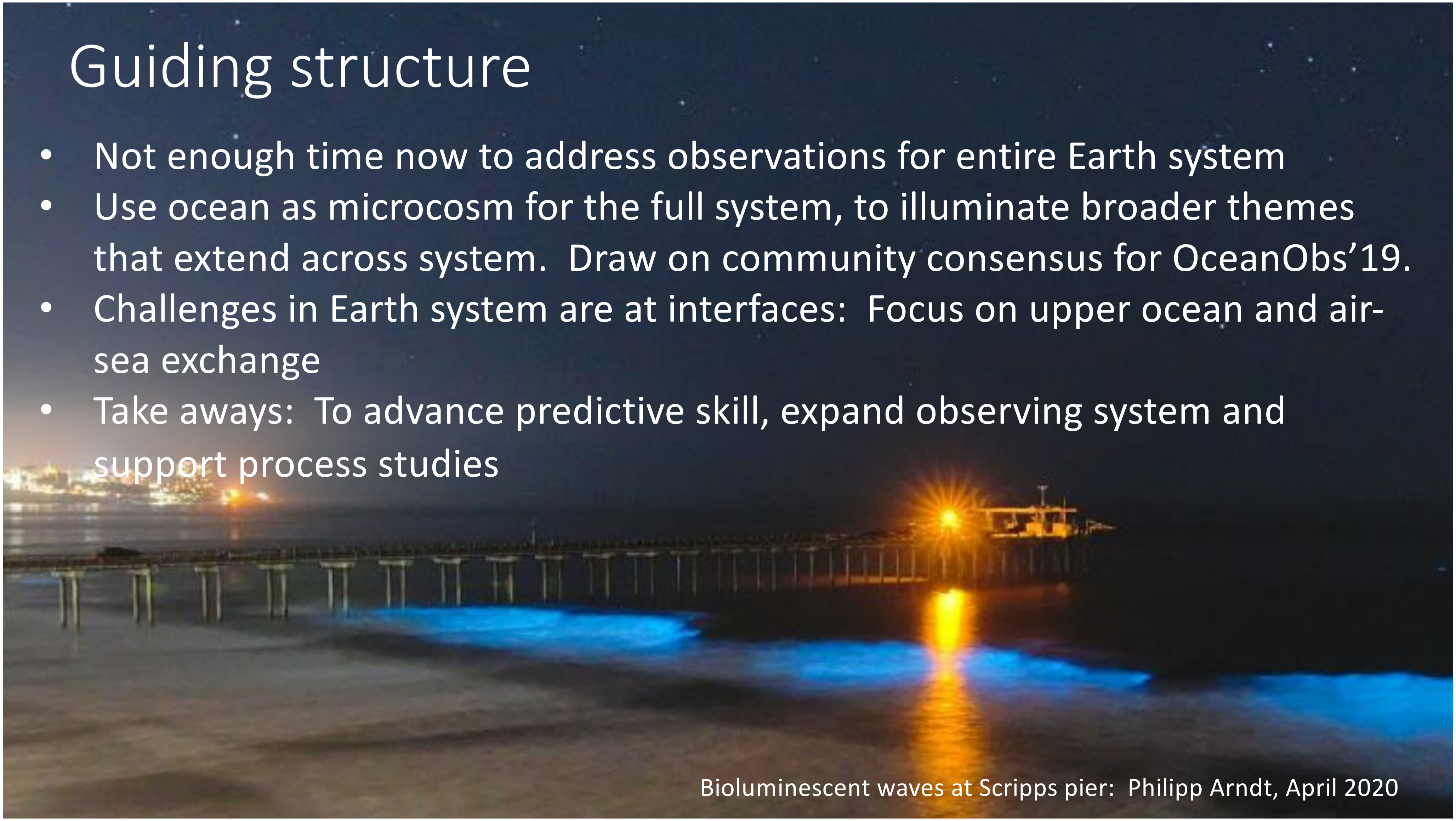
Guiding structure

- Not enough time now to address observations for entire Earth system
- Use ocean as microcosm for the full system, to illuminate broader themes that extend across system. Draw on community consensus for OceanObs'19.
- Challenges in Earth system are at interfaces: Focus on upper ocean and air-sea exchange
- Take aways: To advance predictive skill, expand observing system and support process studies



Bioluminescent waves at Scripps pier: Philipp Arndt, April 2020

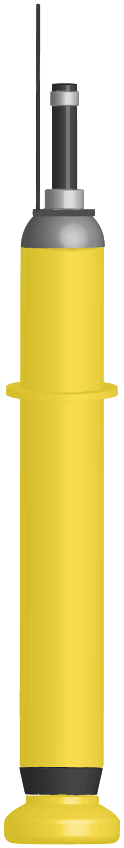
The energy to warm the atmosphere by 1°C is equivalent to energy to warm the top 2.5 m of the ocean by 1°C

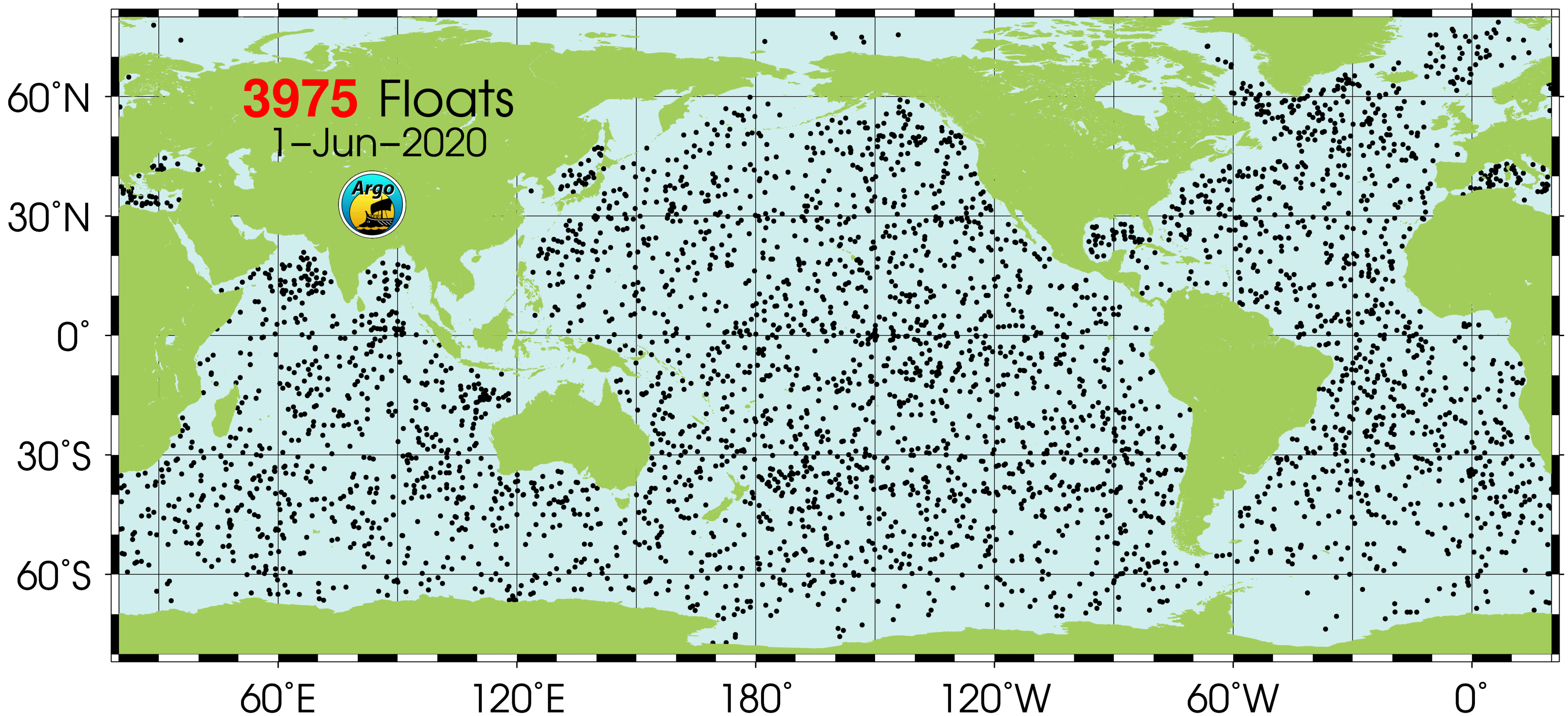
The average ocean depth is 4 km → 400 times more mass than the atmosphere and 1600 times more heat storage per unit area

The ocean covers about 70% of the Earth → 1°C change in atmospheric temperature is equivalent to <0.01°C change in mean ocean temperature.

How much of the ocean communicates with the atmosphere? How big are the fluxes?

ARGO FLOATS: TEMPERATURE & SALINITY TO 2000 M, EVERY 10 DAYS





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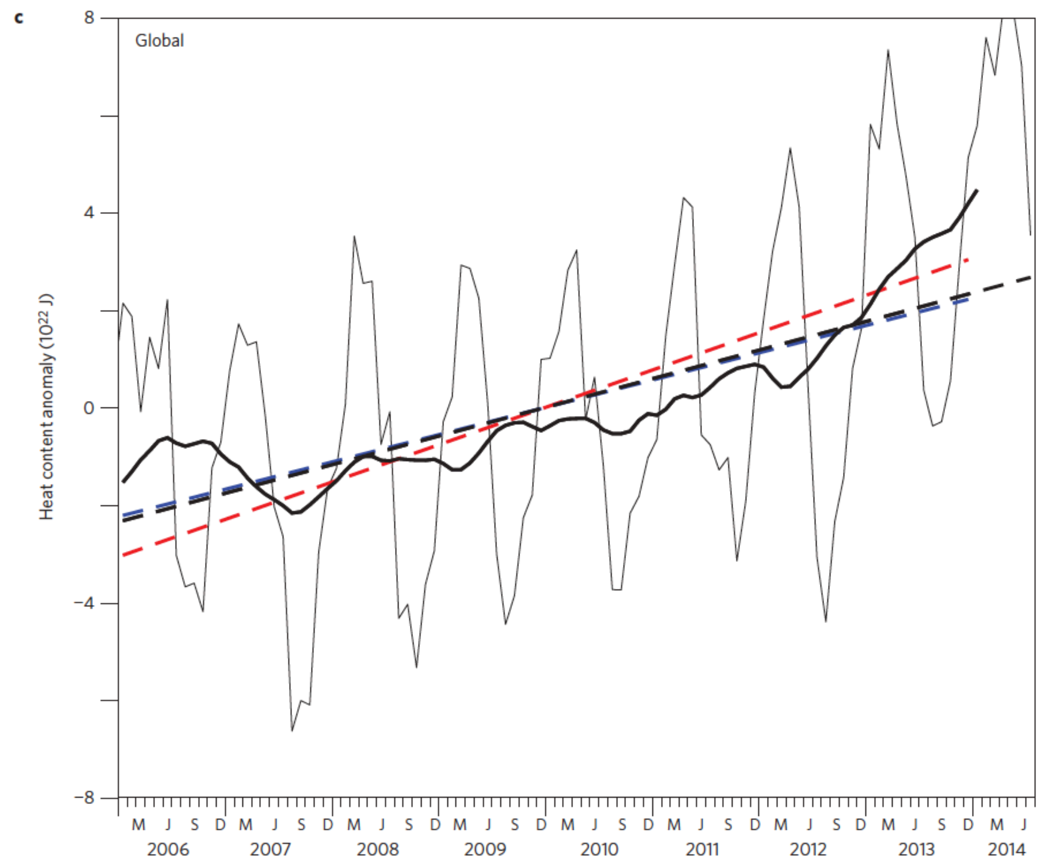
http://www.argo.ucsd.edu/

OCEAN HEAT CONTENT CHANGES MEASURED BY ARGO FLOATS

Argo resolves **annual cycle** in warming and cooling of the ocean

Long-term ocean heat gain equivalent to **0.5-0.7 W/m²** net heat flux to ocean.

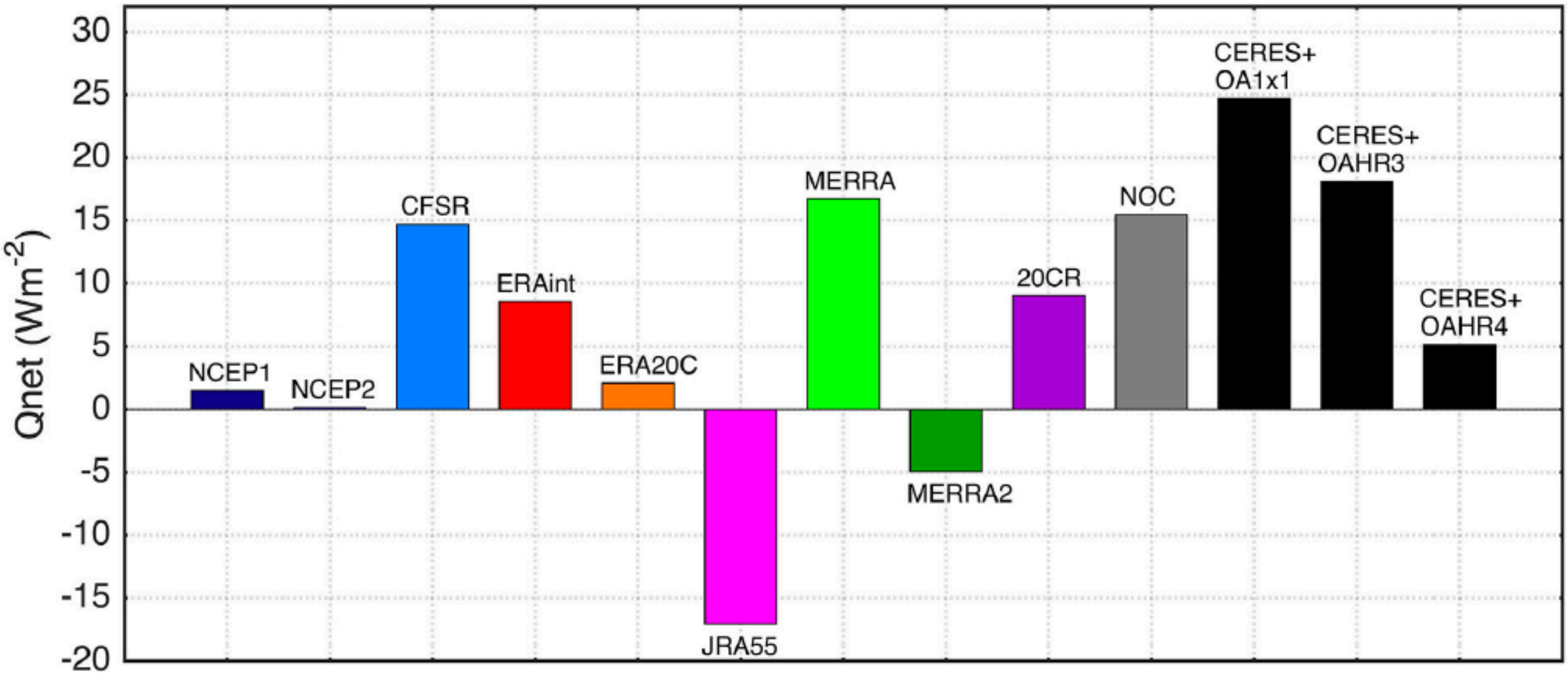
(Biogeochemical and Deep Argo now extending capabilities.)



Roemmich et al, Nature Climate Change, 2015

GLOBAL MEAN AIR-SEA HEAT FLUX: NO AGREEMENT AMONG PRODUCTS

Flux products not accurate enough to see 0.5 W m^2 net uptake



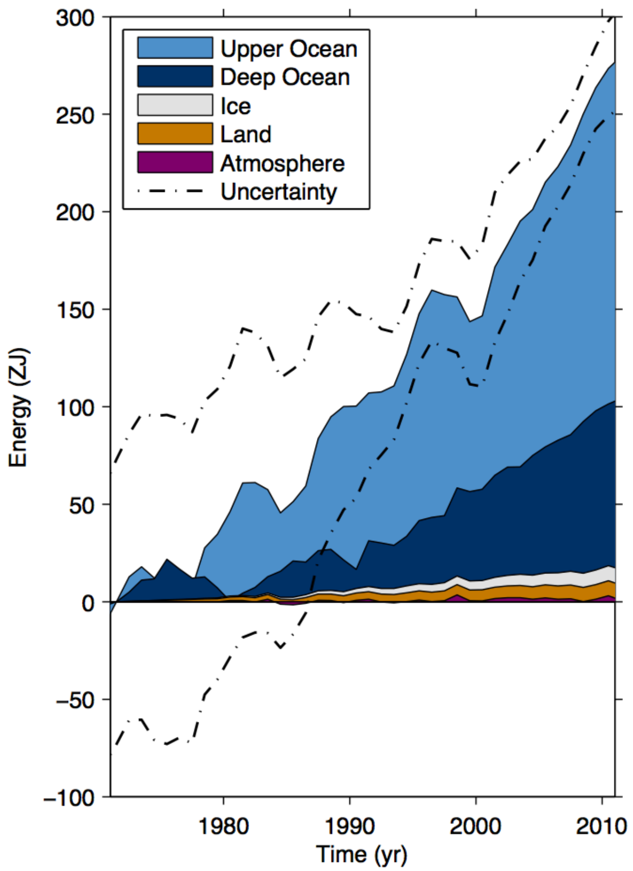
Cronin et al, *Frontiers in Marine Science*, 2019

DECADAL SCALE HEAT STORAGE IN THE EARTH SYSTEM

On decadal scale, Argo + historic data show that most of the Earth's heat storage in the upper ocean + deep ocean.

Observations to support decadal predictability: Keep doing Argo + Deep Argo over full water column.

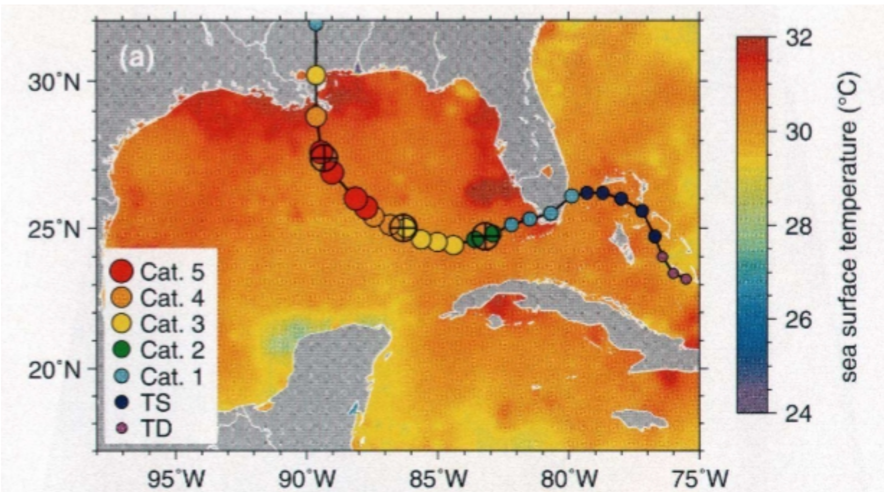
Observations for 10-day to 3-year time-scales: Require a more nuanced and local understanding of ocean exchanges with the atmosphere (in context of analysis/reanalysis/assimilation requirements)



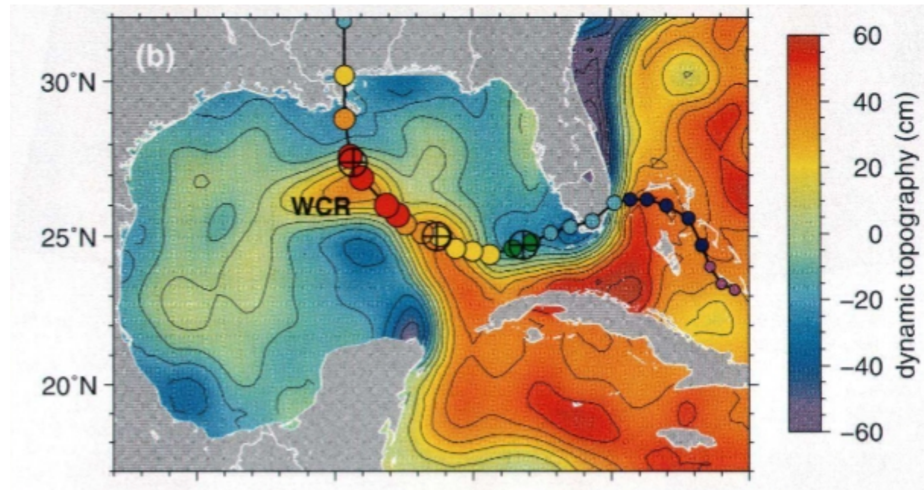
IPCC AR5, Ch. 3: http://www.ipcc.ch/report/ar5/wg1/

Upper ocean heat influences hurricanes (not just SST)

Hurricane Katrina - Intensification correlated with ocean heat content



Sea Surface Temperature

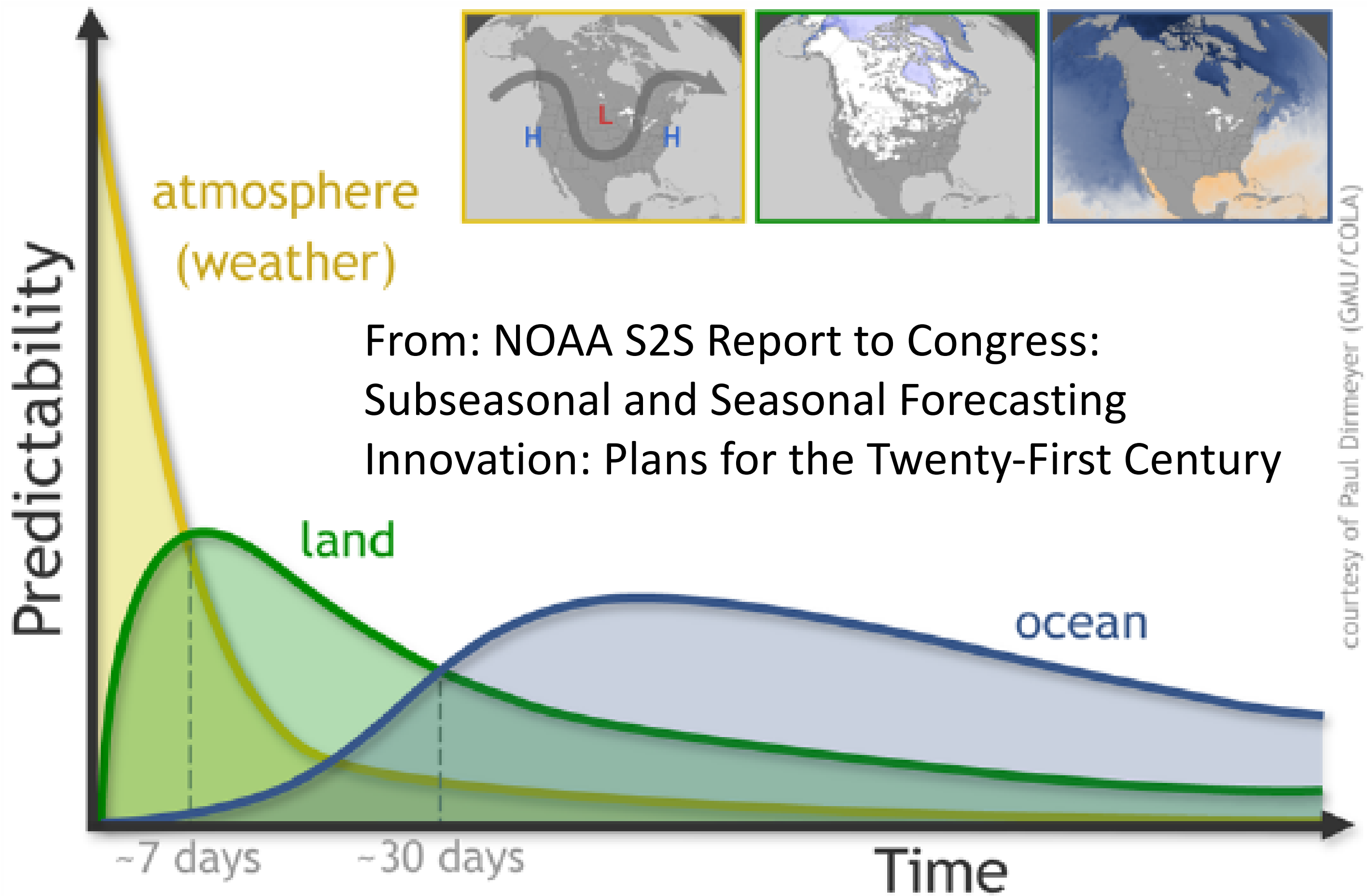


Ocean Heat Content

The upper ocean matters for El Niño/La Niña, monsoons, as well as hurricanes.

Scharoo et al, *Eos*, 2005

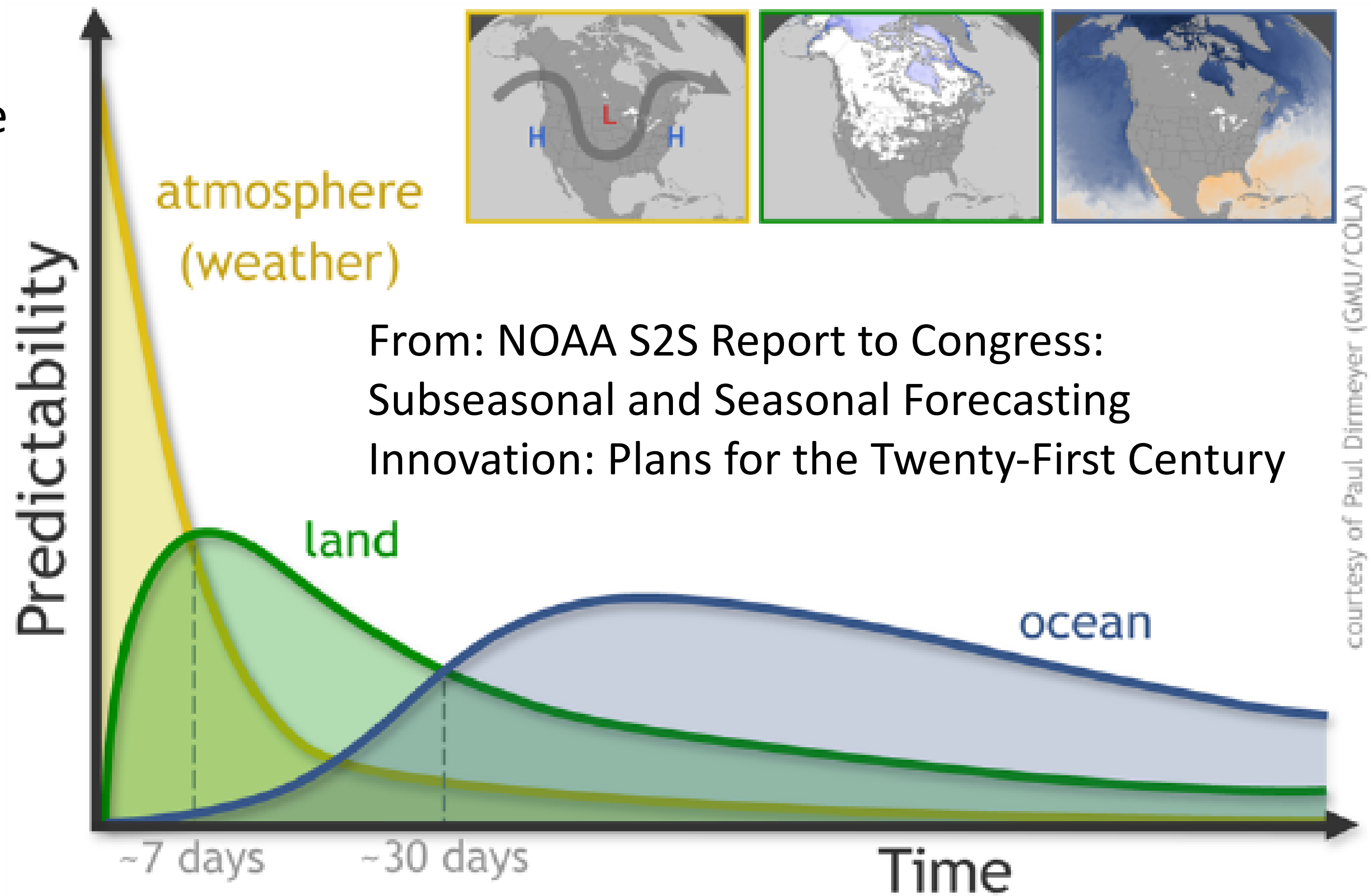
NASA and NOAA sketch of sources of S2I predictability



From: NOAA S2S Report to Congress: Subseasonal and Seasonal Forecasting Innovation: Plans for the Twenty-First Century

NASA and NOAA sketch of sources of S2I predictability

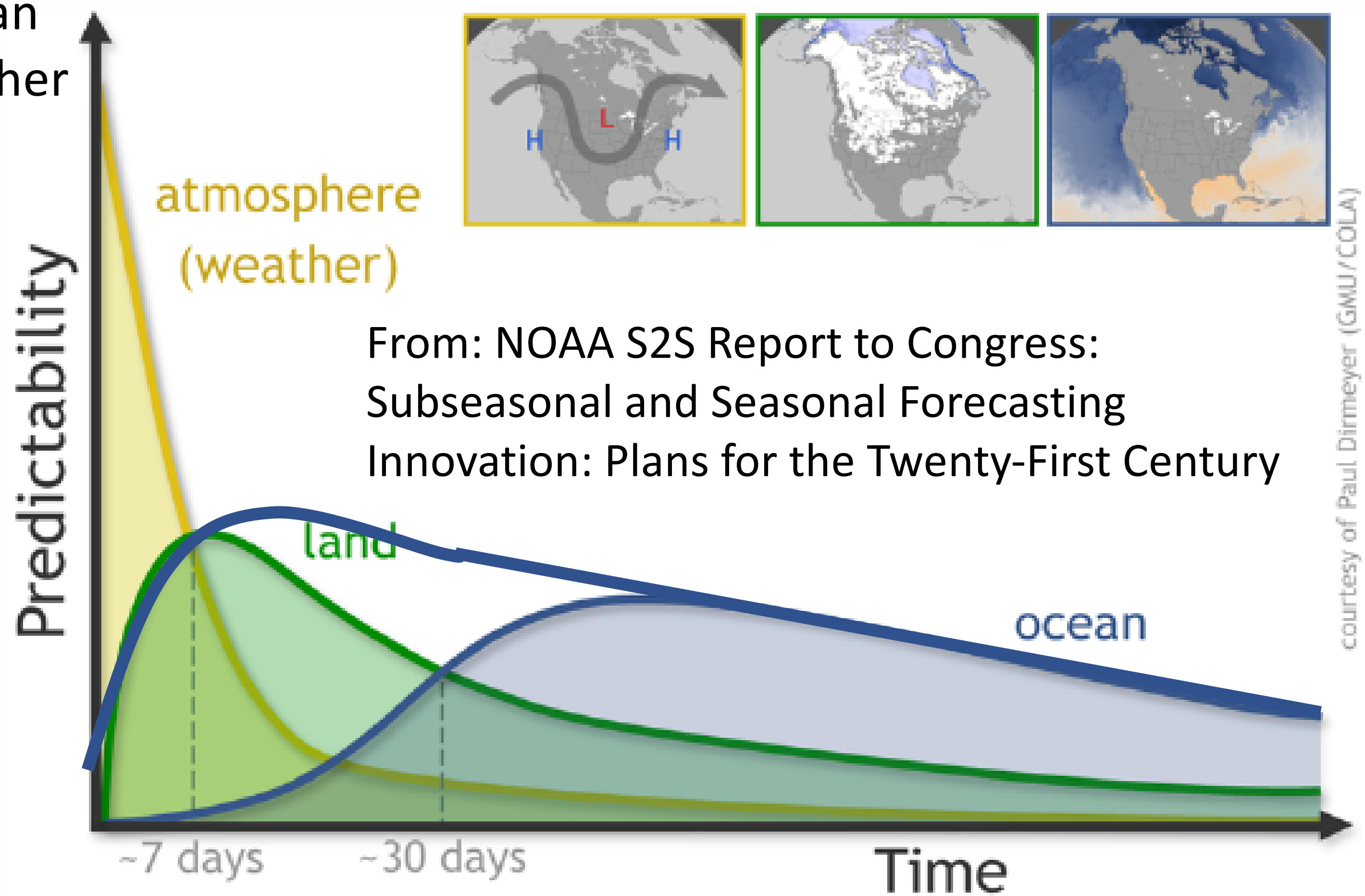
Drawn by a
Soil moisture
Person!!



From: NOAA S2S Report to Congress:
Subseasonal and Seasonal Forecasting
Innovation: Plans for the Twenty-First Century

Revised sketch for S2I predictability for the West

Defaced by an Oceanographer



From: NOAA S2S Report to Congress: Subseasonal and Seasonal Forecasting Innovation: Plans for the Twenty-First Century

ROLE OF THE UPPER OCEAN: MIXED LAYER AS VESTIBULE

Gateway between atmosphere and ocean interior. Need:

- Surface fluxes (heat, freshwater, momentum, gas)
- Fluxes through base of mixed layer
- Physical processes responsible for turbulent mixing in mixed layer, flux out of base of mixed layer, and surface fluxes.
  - When can we use statistical approximations?
  - When do we need to be exact?

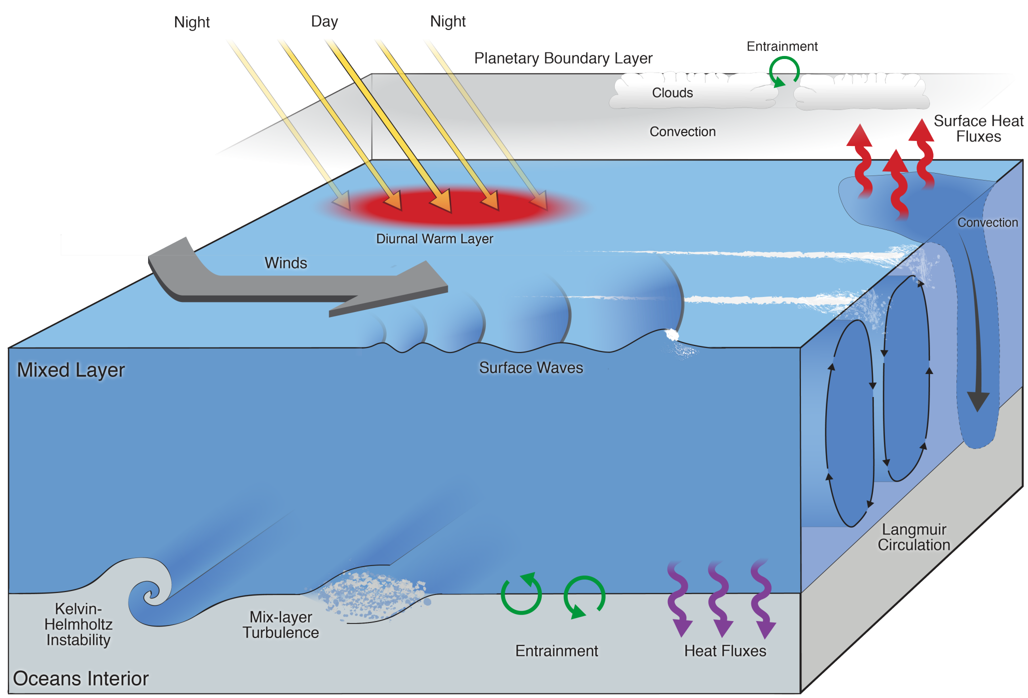


Figure by Momme Hell

ROLE OF THE UPPER OCEAN: MIXED LAYER AS VESTIBULE

Gateway between atmosphere and ocean interior. Need:

- Surface fluxes (heat, freshwater, momentum, gas) [1]
- Fluxes through base of mixed layer [2]
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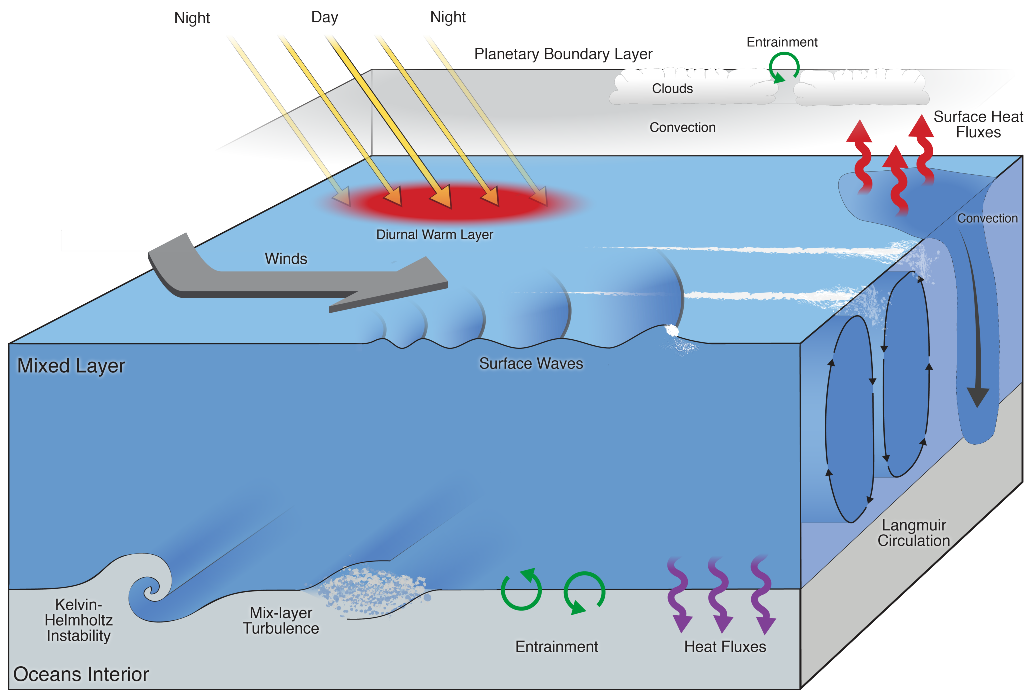
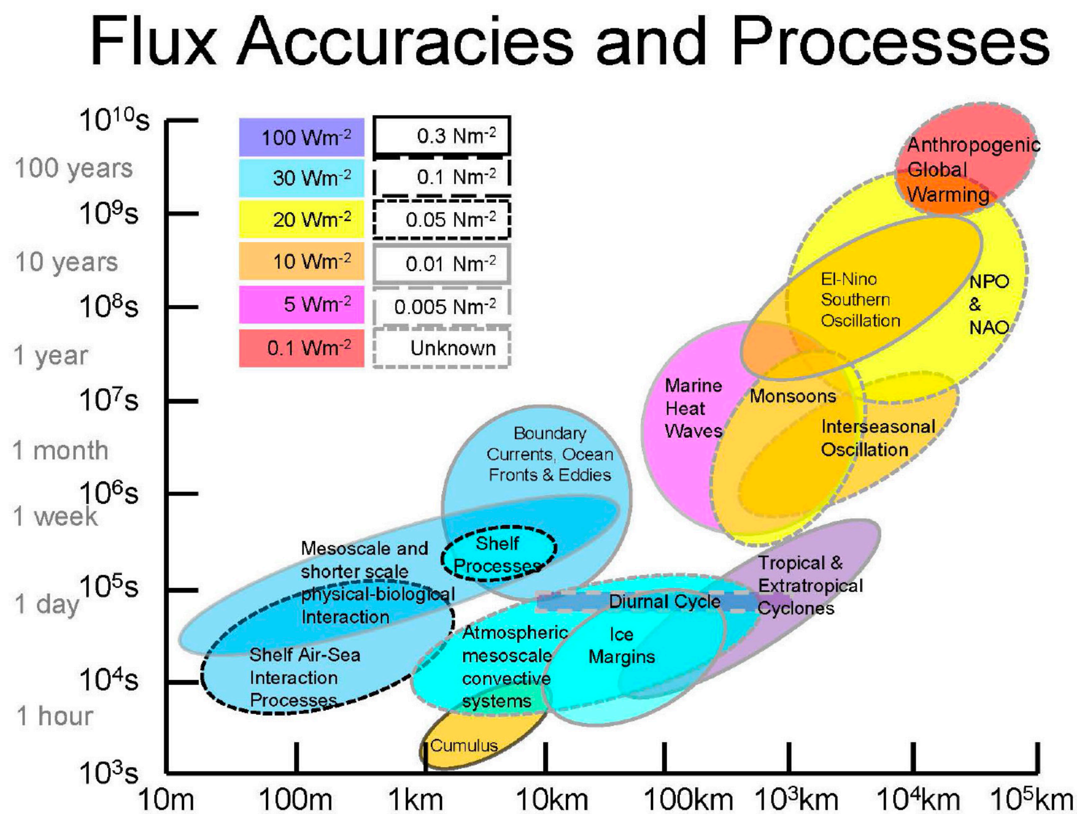


Figure by Momme Hell

SURFACE FLUX REQUIREMENTS DEPEND ON APPLICATIONS

OceanObs'19 Community Consensus on air-sea flux requirements for heat and momentum fluxes



Cronin et al, *Frontiers in Marine Science*, 2019

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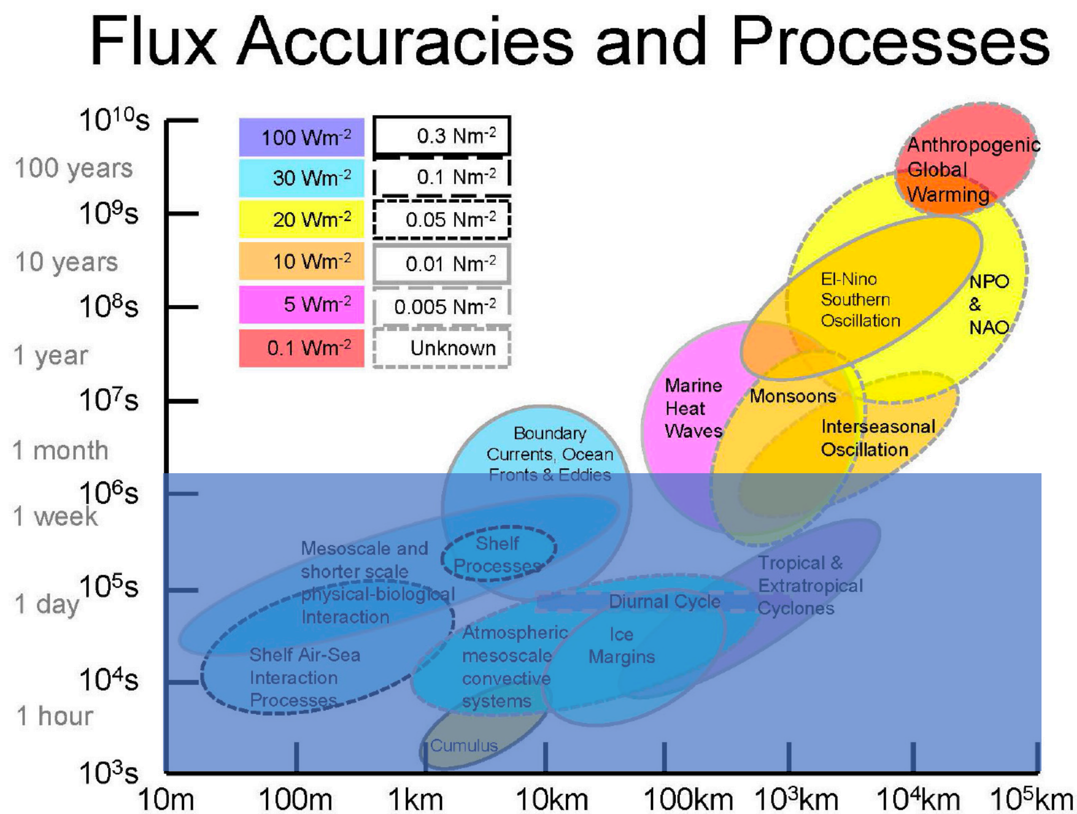
For 10-day to 3-year time scales, maybe we can exclude high-frequency and small-scale processes.



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SURFACE FLUX REQUIREMENTS DEPEND ON APPLICATIONS

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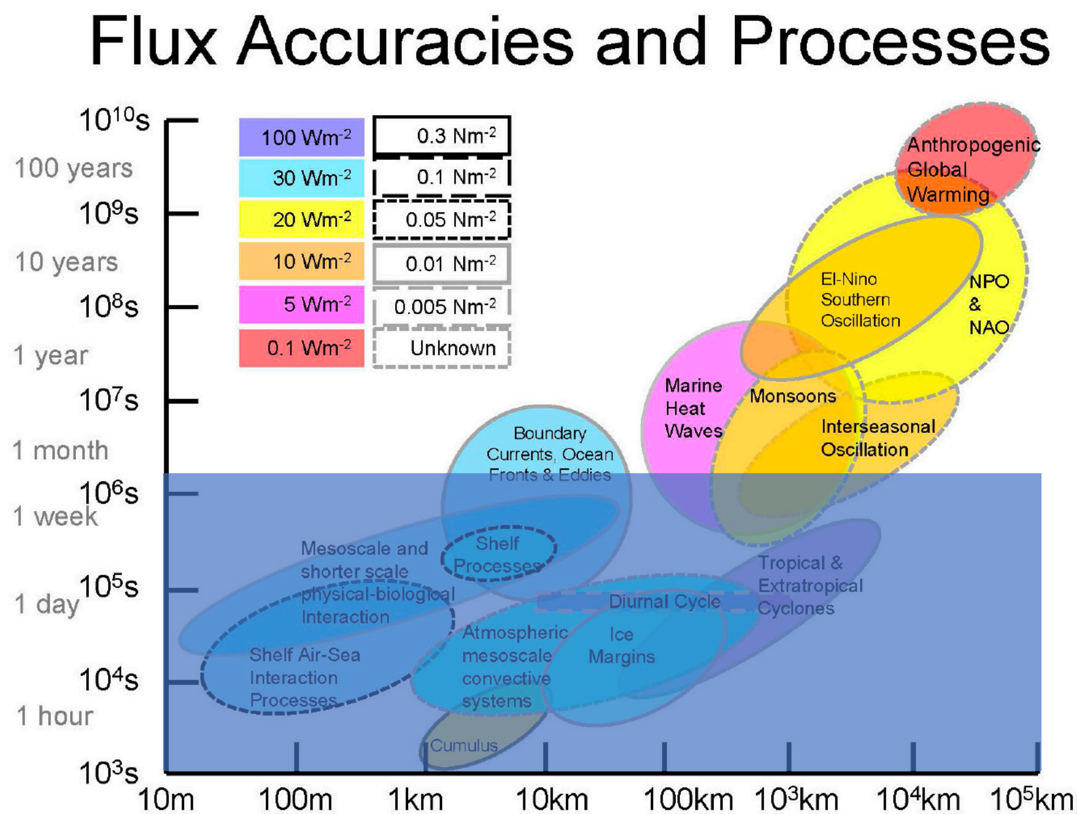
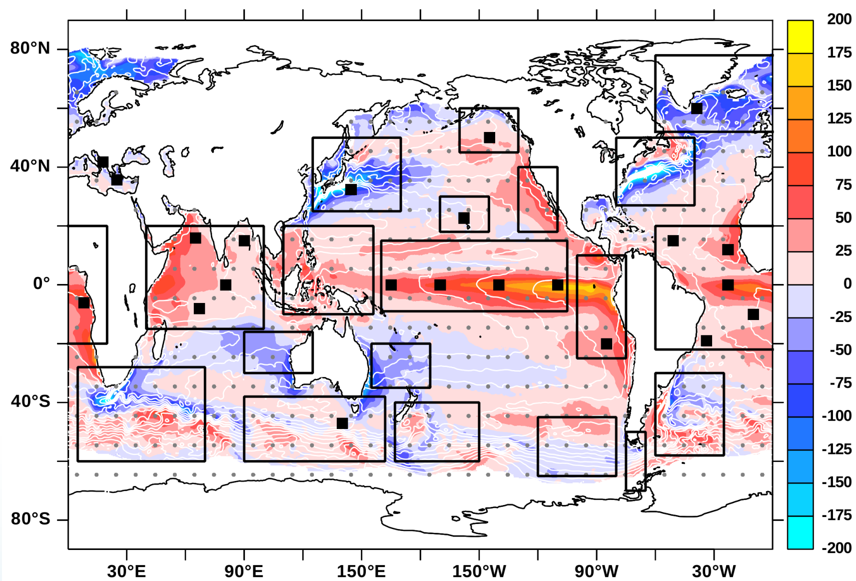
For 10-day to 3-year time scales, maybe we can exclude high-frequency and small-scale processes.

No, high-frequency, small-scale processes matter



Cronin et al, *Frontiers in Marine Science*, 2019

OceanObs’19 Recommendation: Create an Integrated Surface Ocean Observing System



Mean Net Surface Heat Flux (Wm^{-2})

Cronin et al. (2019) **“Air-sea fluxes with a focus on heat and momentum”**

Satellite Platforms

■ OceanSITES surface platforms that measure Net Surface Heat Flux

▯ Key regions needing new OceanSITES flux platforms

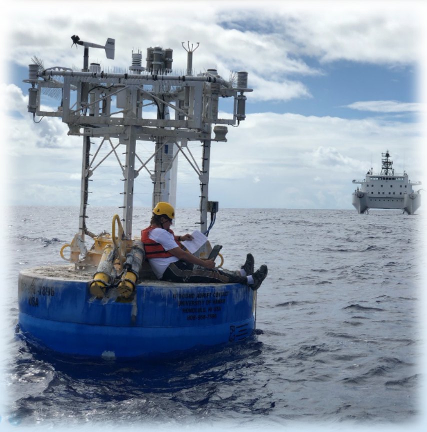
▪ 10°x10° gridpoints. With 1000 platforms, each gridbox could have 2-3 platforms. (Mazloff et al 2018 suggest 4°x4° sampling)

Fixed Platforms (Examples)

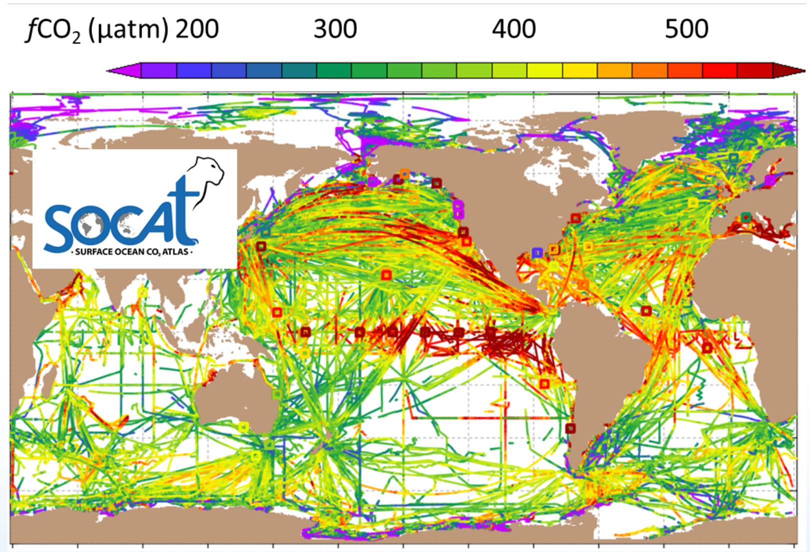
Mobile and Drifting Platforms (Examples)

OceanObs'19 Recommendation: Create an Integrated Surface Ocean Observing System

Established Platforms:



Surface ocean CO_2 flux: all seawater pCO_2 measurements collected since 1957

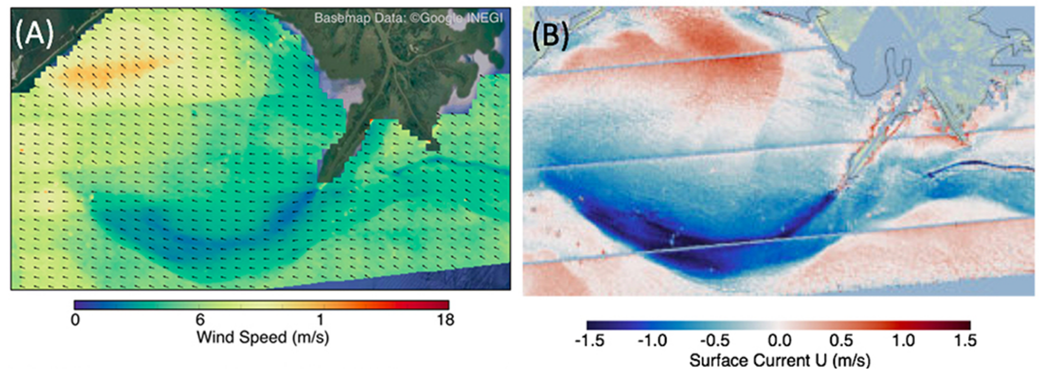


Wanninkhof et al. (2019) **"A Surface Ocean CO_2 Reference Network, SOCONET and Associated Marine Boundary Layer CO_2 Measurements"**

New Technologies:

SATELLITE-BASED OBSERVATIONS TO COMPLEMENT IN SITU OBSERVATIONS

Momentum exchange: WACM (Winds and Currents Mission); SKIM (ESA proposal: waves and currents), CFOSAT (Chinese-French Ocean satellite: winds and waves)



Heat flux: FluxSat (coincident SST, T_{air}, q_{air}, wind speed)

Sensible heat flux

$$Q_{sen} = \rho_a C_p C_H U (T_{sea} - T_{air})$$

Air density; Air specific heat capacity; Turbulent exchange coefficient; Wind speed; Sea-air temperature difference

Latent heat flux

$$Q_{lat} = \rho_a L_v C_E U (q_{sea} - q_{air})$$

Air density; Latent heat of vaporization; Turbulent exchange coefficient; Wind speed; Sea-air humidity difference

Freshwater flux: Precipitation missions

Villas Bôas et al, 2019; Gentemann et al, 2020

A VISION FOR THE FUTURE: IN SITU AND SATELLITE FLUX MEASUREMENTS

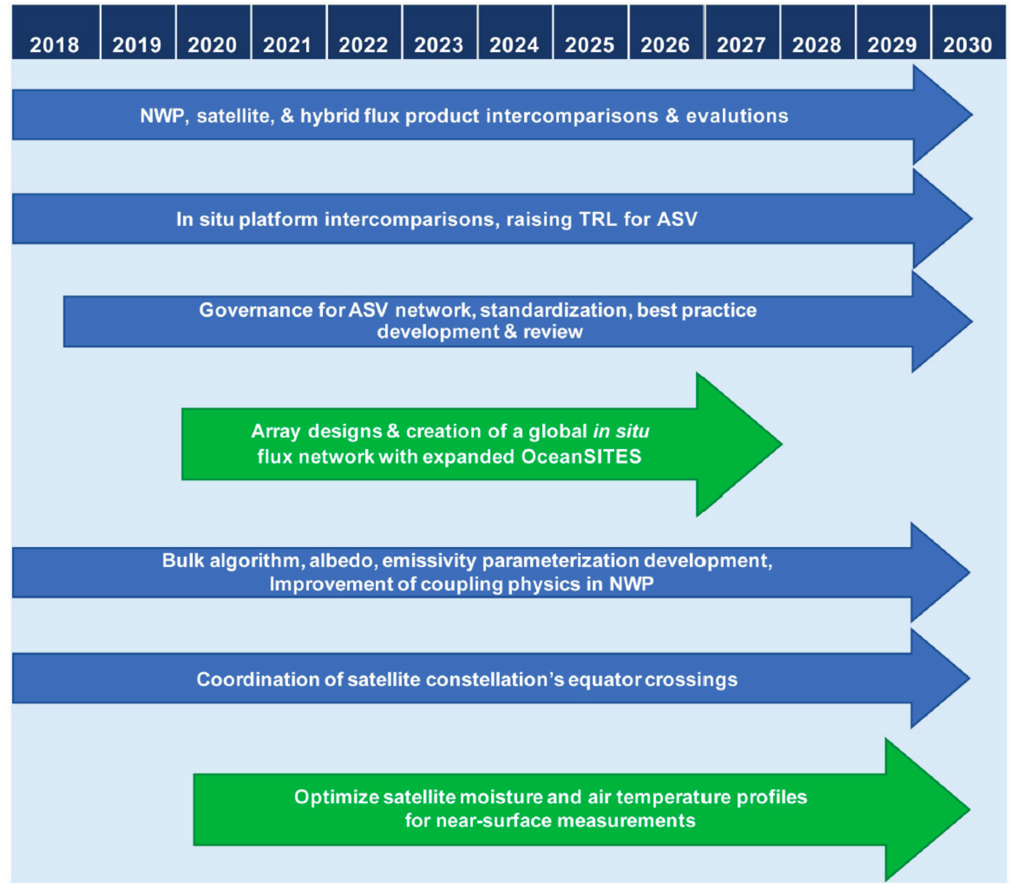
Goal for 2030:

Gridded (3-hourly at 25 km)
Air-Sea Fluxes with breakthrough
1-day random uncertainties of:

15 W m^{-2} (5%) & 0.01 N m^{-2} (5%)

And Biases less than:

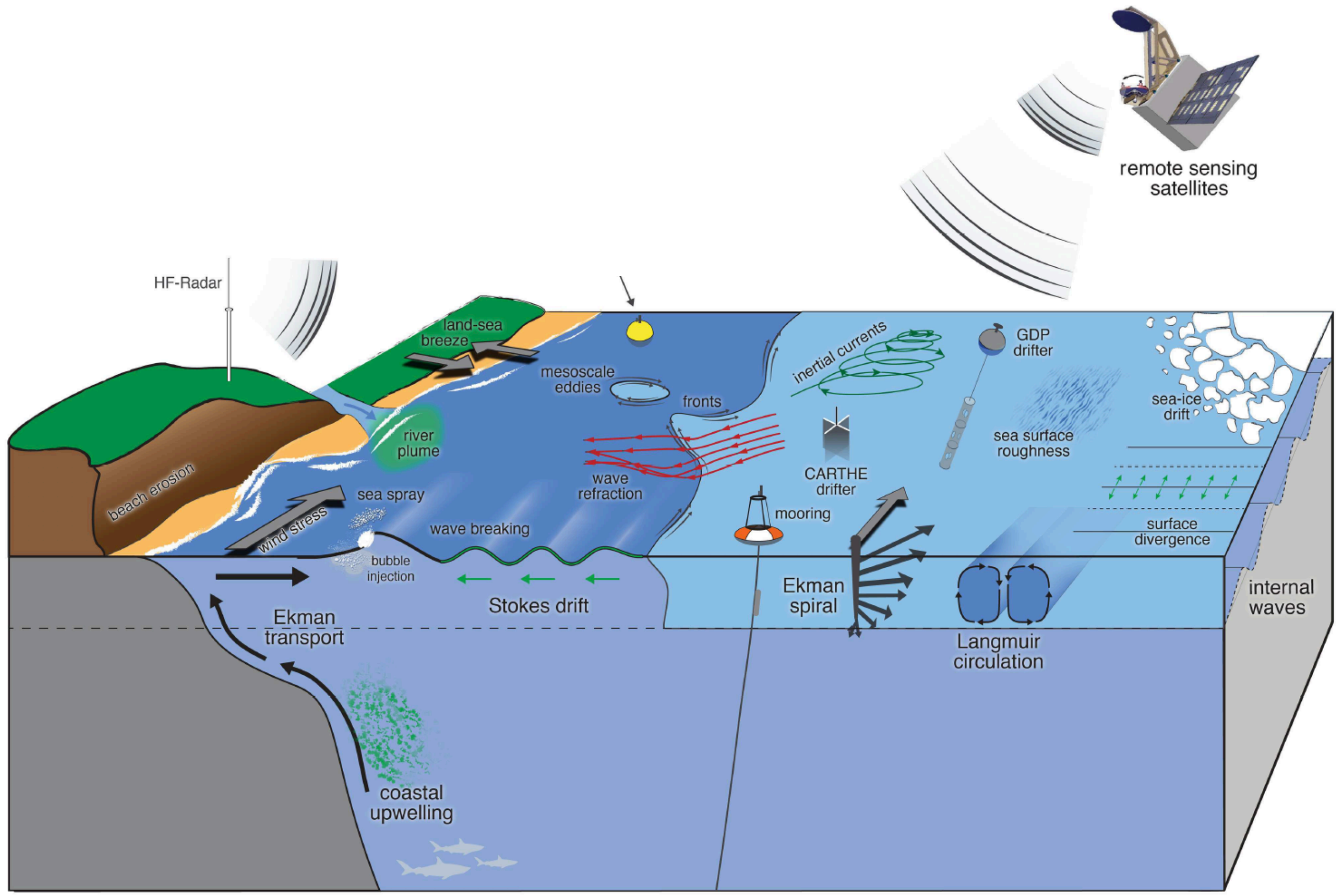
5 W m^{-2} & 0.005 N m^{-2}



HOW DO WE REPRESENT THE IMPACT OF UPPER-OCEAN PROCESSES?

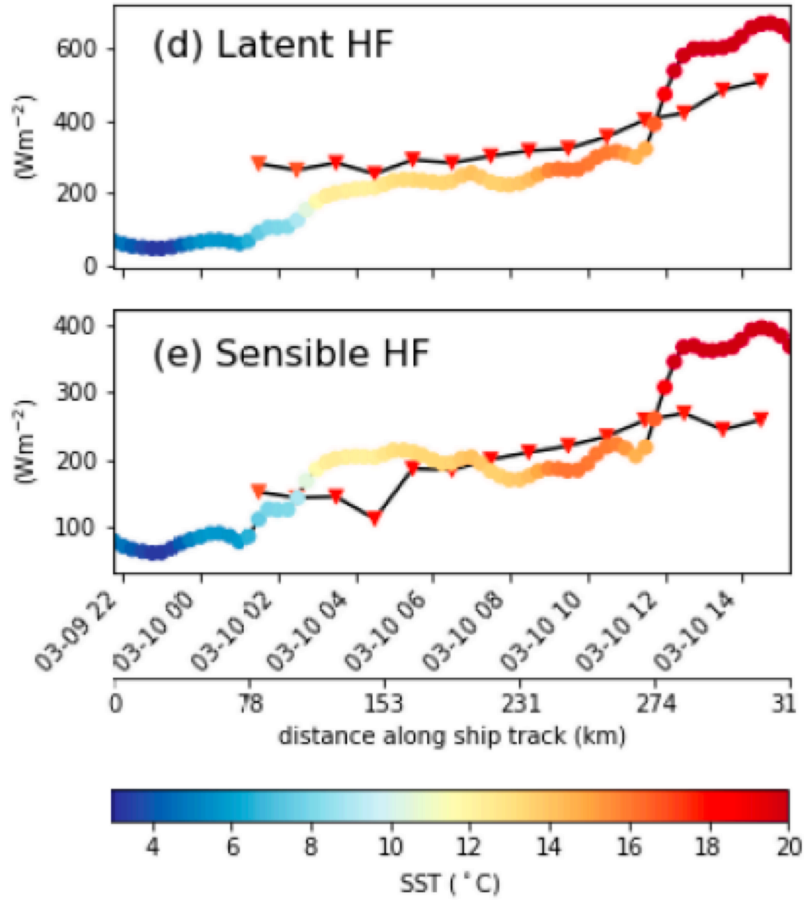
Upper ocean supports a multitude of processes:

- Surface waves---wave breaking, aerosol formation, bubbles
- Turbulent mixing and mixed-layer deepening
- Internal waves
- Wind-current and wind-SST interactions



Villas Bôas et al, *Frontiers in Marine Science*, 2019

FLUXES ACROSS THE GULF STREAM: SHARP GRADIENTS

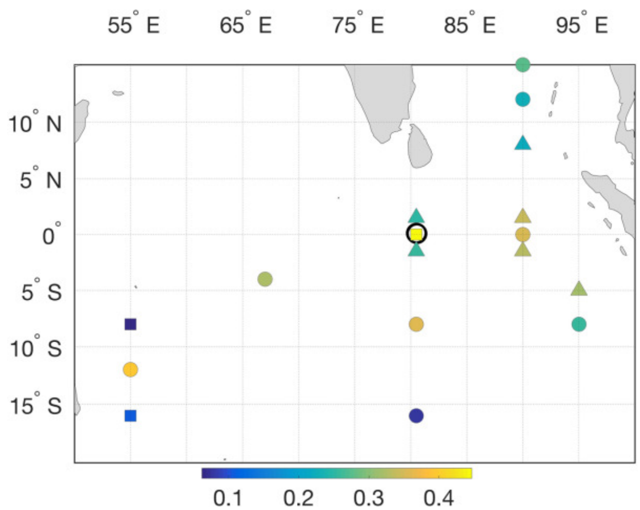


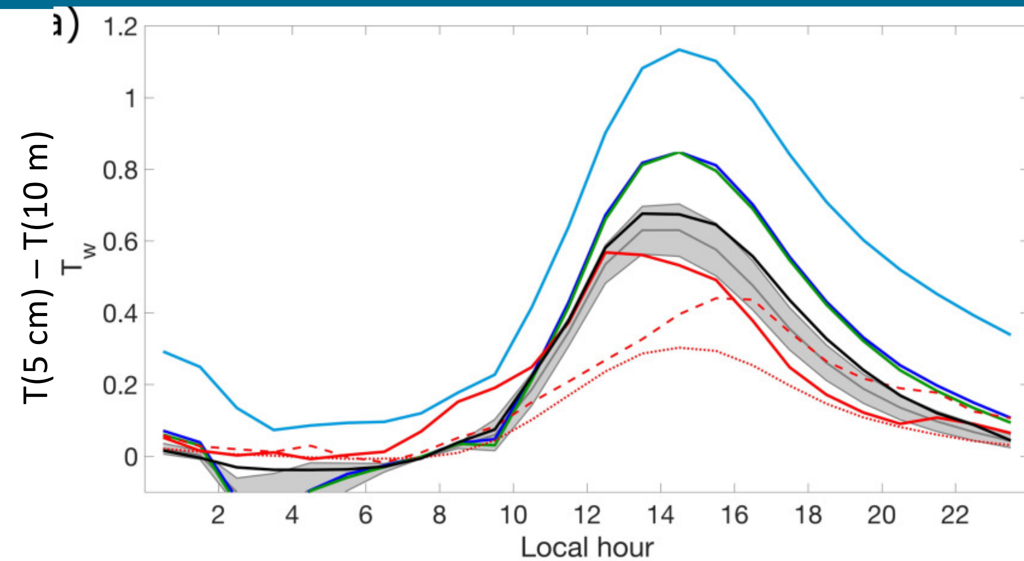
Air-sea exchanges vary at the scale of ocean eddies and fronts.

Sharp gradients in latent and sensible heat flux measured from ship are not detected in satellite-derived SeaFlux product (black line)

Gentemann et al, *Remote Sensing*, 2020

GUSTY WINDS NEEDED TO EXPLAIN UPPER OCEAN TEMPERATURE





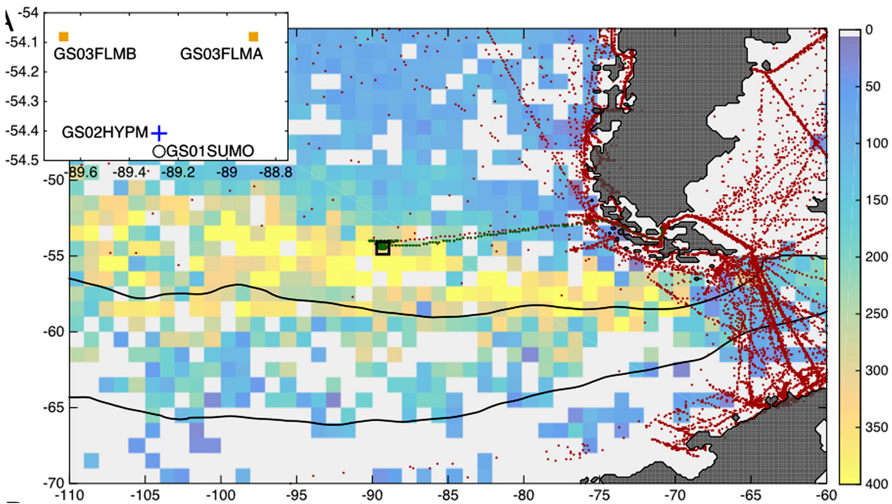
RAMA array in Indian Ocean. Focus on October 2011 MJO event at yellow circle.

Generalized Ocean Turbulence Model.

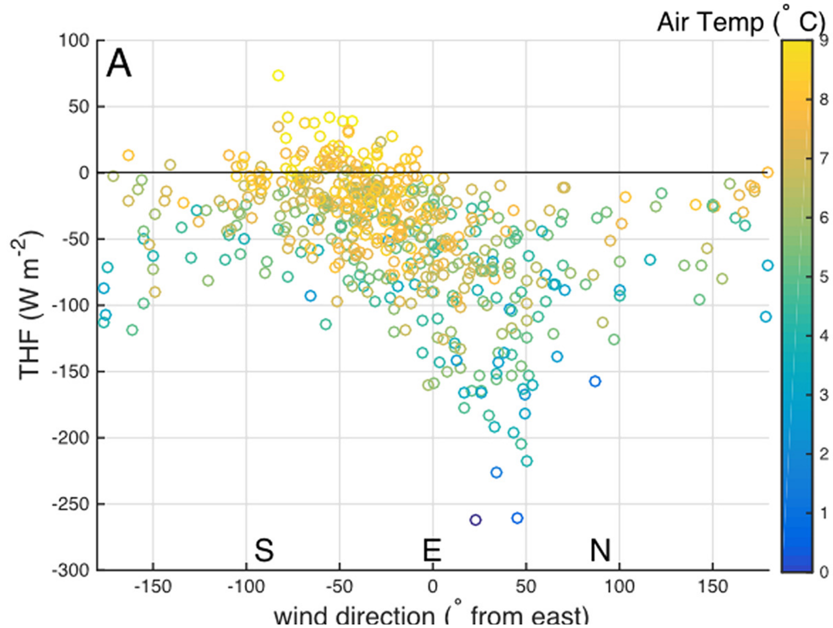
Observations best matched with model forced with **true winds** or **stochastic gusty winds** while **constant winds** or **diurnal cycle** imply too little mixing.

Giglio et al, *JGR-Oceans*, 2017

MIXED LAYERS DEEPEN IN RESPONSE TO EPISODIC EVENTS



Southern Ocean (OOI) Mooring at a location of deep winter mixed layers.



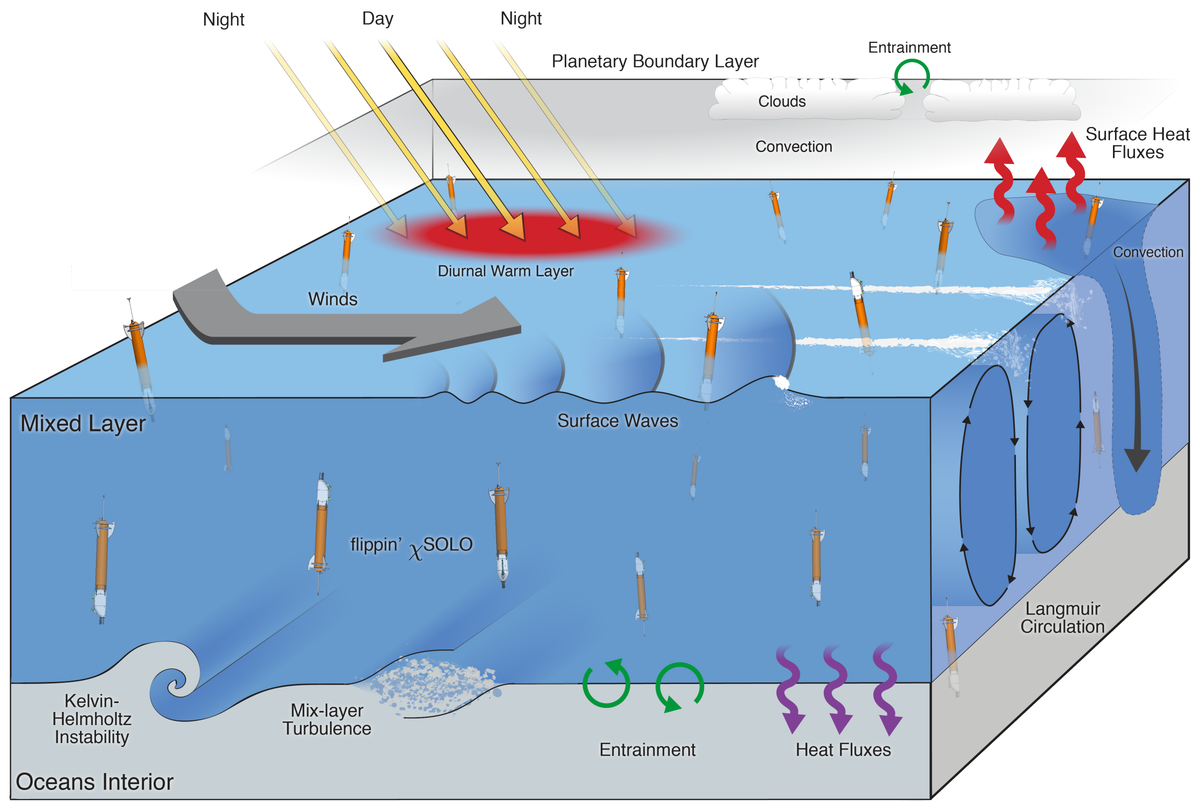
Strong cooling heat fluxes coincide with winds from the south; single events deepen the mixed layer.

Ogle et al, *GRL*, 2018

ENVISIONING PROCESSES STUDIES FOR MIXED-LAYER TURBULENCE

Hypothesis: small-scale, high-frequency, episodic processes govern turbulent mixing and mixed-layer depth.

- Measure vs parameterize?
- What instruments?
- What statistical and modeling tools? (Machine learning? Super parameterization? Surrogate models?)



Flippin' χSOLO: Turbulence-measuring Argo-float variant

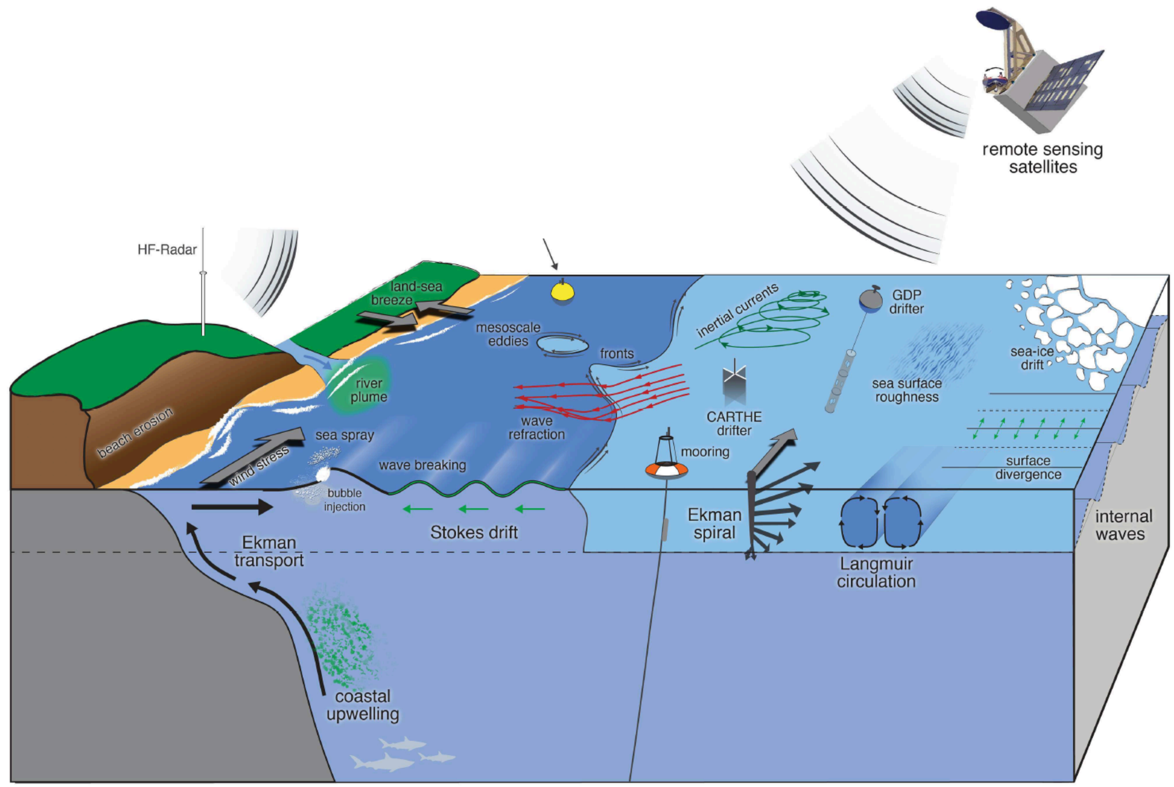
Figure by Momme Hell

SUMMARY: A VISION FOR OPTIMIZING OBSERVATIONS

Observing system: in situ plus satellite observations provide boundary conditions and model verification. Configure to resolve key variability.

Process studies: probing episodic turbulent processes (things we don't yet know how to parameterize)

FAIR: findable, accessible, interoperable, reusable



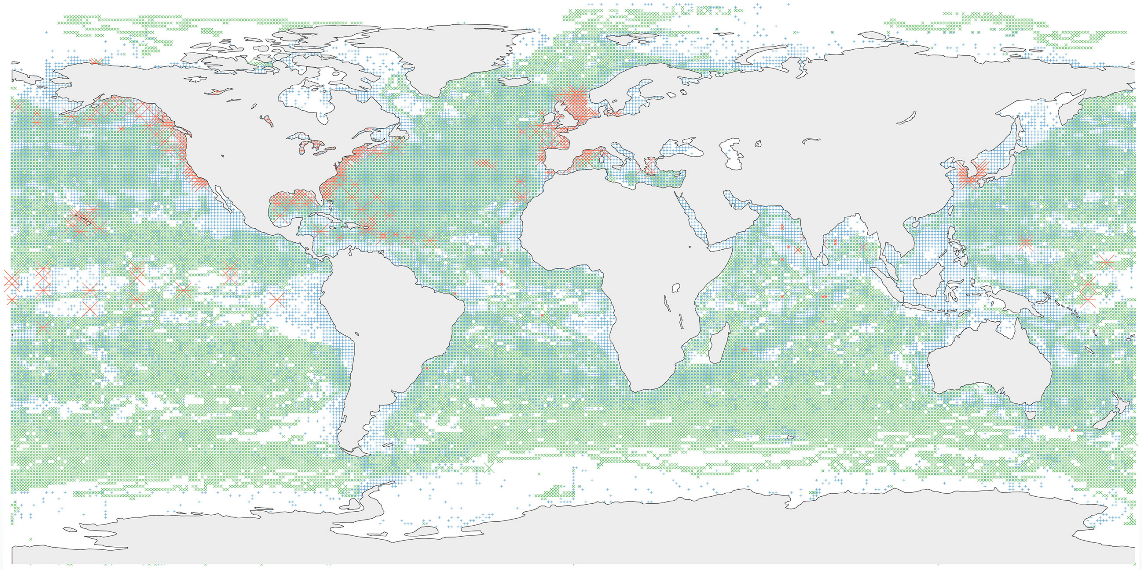
Villas Bôas et al, *Frontiers in Marine Science*, 2019

EXTRAS

More than two dozen OceanObs19 Community Strategy Papers address surface ocean:

- Cronin et al. (2019) “Air-Sea Fluxes with focus on Heat and Momentum” https://www.frontiersin.org/articles/10.3389/fmars.2019.00430/full
- Centurioni, et al. (2019) “Multidisciplinary Global In-Situ Observations of Essential Climate and Ocean Variables at the Air-Sea Interface in Support of Climate Variability and Change Studies and to Improve Weather Forecasting, Pollution, Hazard and Maritime Safety Assessments” https://www.frontiersin.org/articles/10.3389/fmars.2019.00419/full
- Wanninkhof et al. (2019) “A surface ocean CO_2 reference network, SOCONET and associated marine boundary layer CO_2 measurements” https://www.frontiersin.org/articles/10.3389/fmars.2019.00400/full
- Ardhuin, et al. (2019) “Observing sea states” https://doi.org/10.3389/fmars.2019.00124
- Ardhuin, et al. (2019) “SKIM, a candidate satellite mission exploring global ocean currents and waves” https://doi.org/10.3389/fmars.2019.00209
- Bourassa, et al. (2019) “Remotely Sensed Winds and Wind Stresses for Marine Forecasting and Ocean Modeling” https://doi.org/10.3389/fmars.2019.00443
- Domingues, et al. (2019) “Ocean Observations in Support of Studies and Forecasts of Tropical and Extratropical Cyclones”. Front. Mar. Sci. 6:446. doi: 10.3389/fmars.2019.00446
- Foltz et al. (2019) “The Tropical Atlantic Observing System” doi: 10.3389/fmars.2019.00206
- Gommenginger, et al. (2019) “SEASTAR: a mission to study ocean submesoscale dynamics and small-scale atmosphere-ocean processes in coastal, shelf and polar seas” https://doi.org/10.3389/fmars.2019.00457
- Groom, et al. (2019) “Satellite Ocean Colour: Current Status and Future Perspective”. Front. Mar. Sci. 6:485. doi: 10.3389/fmars.2019.00485
- Kent et al. (2019) “Observing requirements for long-term climate records at the ocean surface” https://doi.org/10.3389/fmars.2019.00441
- Lombard, F., E. Boss, A. M. Waite, and others. (2019). Globally Consistent Quantitative Observations of Planktonic Ecosystems. Frontiers in Marine Science 6: 196. doi:10/gfzvfd
- Maximenko, et al. (2019) Toward the Integrated Marine Debris Observing System. Front. Mar. Sci. 6:447. https://doi.org/10.3389/fmars.2019.00447
- Meinig, et al. (2019) Public–Private Partnerships to Advance Regional Ocean-Observing Capabilities: A Saildrone and NOAA-PMEL Case Study and Future Considerations to Expand to Global Scale Observing. Front. Mar. Sci. 6:448. doi: 10.3389/fmars.2019.00448
- Muelbert, et al. (2019) ILTER – The International Long-Term Ecological Research Network as a Platform for Global Coastal and Ocean Observation. Front. Mar. Sci. 6:527. doi: 10.3389/fmars.2019.00527
- Newman, L. and co-authors. (2019). Delivering sustained, coordinated and integrated observations of the Southern Ocean for global impact. *Frontiers Mar. Sci.,* doi: 10.3389/fmars.2019.00433.
- O’Carroll, et al. (2019) “Observational Needs of Sea Surface Temperature” https://doi.org/10.3389/fmars.2019.00420
- Pinardi, et al. (2019) The Joint IOC (of UNESCO) and WMO Collaborative Effort for Met-Ocean Services. Front. Mar. Sci. 6:410. doi: 10.3389/fmars.2019.00410
- Powers M, Begg Z, Smith G and Miles E (2019) Lessons From the Pacific Ocean Portal: Building Pacific Island Capacity to Interpret, Apply, and Communicate Ocean Information. Front. Mar. Sci. 6:476. doi: 10.3389/fmars.2019.00476
- Smith, et al. (2019) “Ship-Based Contributions to Global Ocean, Weather, and Climate Observing Systems” https://doi.org/10.3389/fmars.2019.00434
- Smith et al. (2019) Tropical Pacific Observing System
- Steinhoff, et al. (2019) “Constraining the oceanic uptake and fluxes of greenhouse gases by building an ocean network of certified stations: the ICOS Oceans Network” https://doi.org/10.3389/fmars.2019.00544
- Subramanian, et al. (2019) Ocean Observations to Improve Our Understanding, Modeling, and Forecasting of Subseasonal-to-Seasonal Variability. Front. Mar. Sci. 6:427. doi: 10.3389/fmars.2019.00427
- Swart et al. (2019) “Constraining Southern Ocean air-sea-ice fluxes through enhanced observations” https://doi.org/10.3389/fmars.2019.00421
- Villas Boas, A. B. et al. (2019) “Integrated observations and modeling of winds, currents, and waves: requirements and challenges for the next decade” https://doi.org/10.3389/fmars.2019.00425

OceanObs'19 Recommendation: Create an Integrated Surface Ocean Observing System



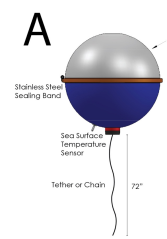
Surface marine observations transmitted on the GTS in 2018

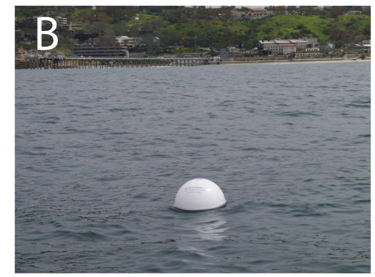
Ships (+) Drifting buoys (x) Moored buoys (x)

Symbol size indicates number of days in 2018 when the 1°x1° cell was observed from · : 30 days or less, to X: 335 days or more

Centurioni et al. (2019) **"Global in situ Observations of Essential Climate and Ocean Variables at the Air-Sea Interface"**

New technology for measuring directional waves





… and meteorological variables