A NASA Earth Venture Mission - EVM3 - Proposed Mission

EVMs are science driven, competitively selected, low cost satellite missions

BUTTERFLY

a satellite mission to reveal the oceans' impact on our weather and climate.

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Project Scientist: Dr. Tony Lee
Deputy Project Scientist: Dr. Shannon Brown

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Collaborators: Jeff Whitaker, Daryl Kleist, Jackie May, Philip Browne, Chris Harris, Misako Kachi, Hiroyuki Tomita, Abderrahim Bentamy

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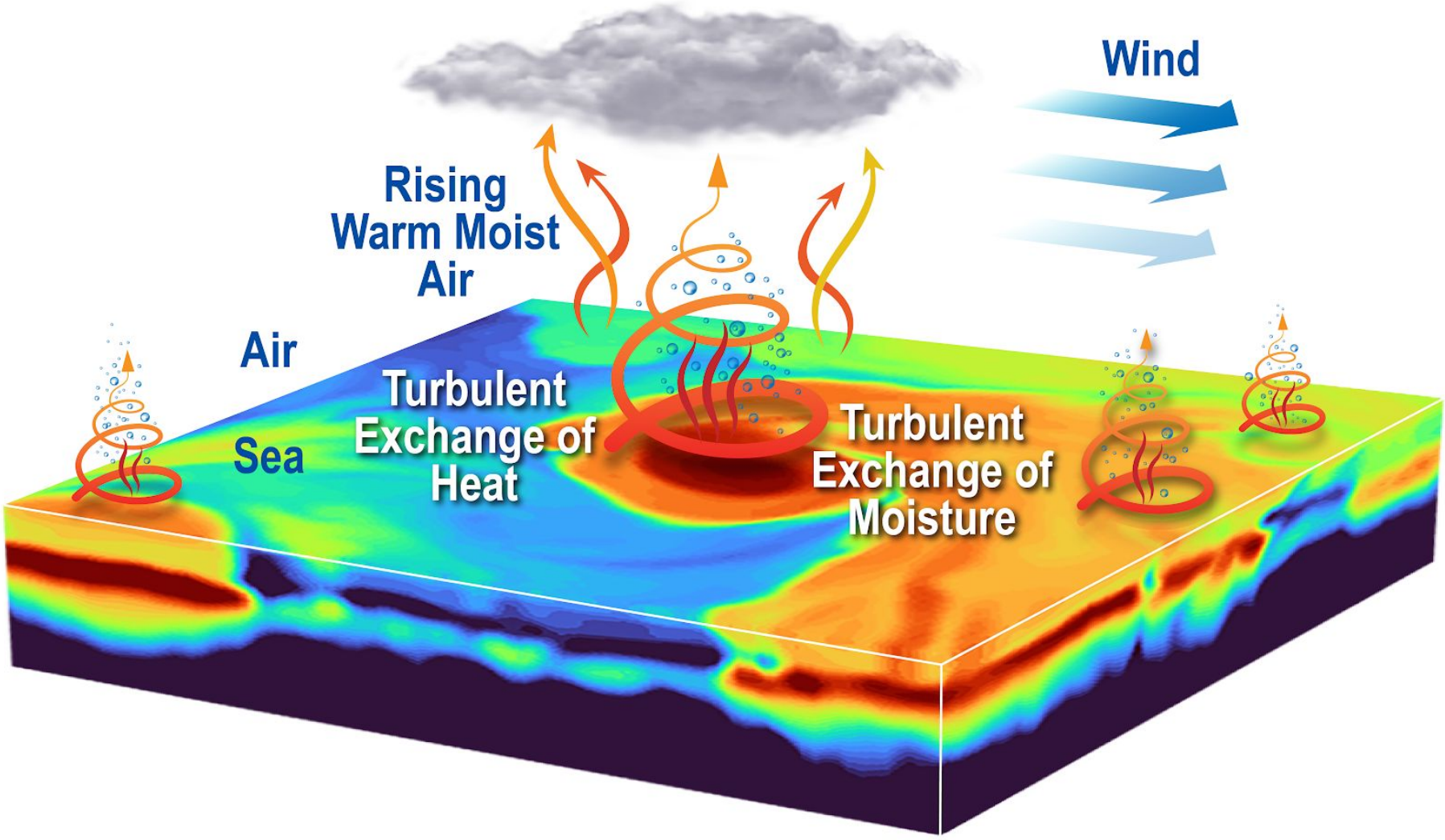
At the ocean surface, the exchange of heat and moisture fuel atmospheric weather and climate *and ocean variability*.



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Increased resolution reveals new and different coupling between the ocean and atmosphere. At scales <1000 km, the SST-wind speed correlation reverses sign, indicating that the ocean is forcing the atmosphere.

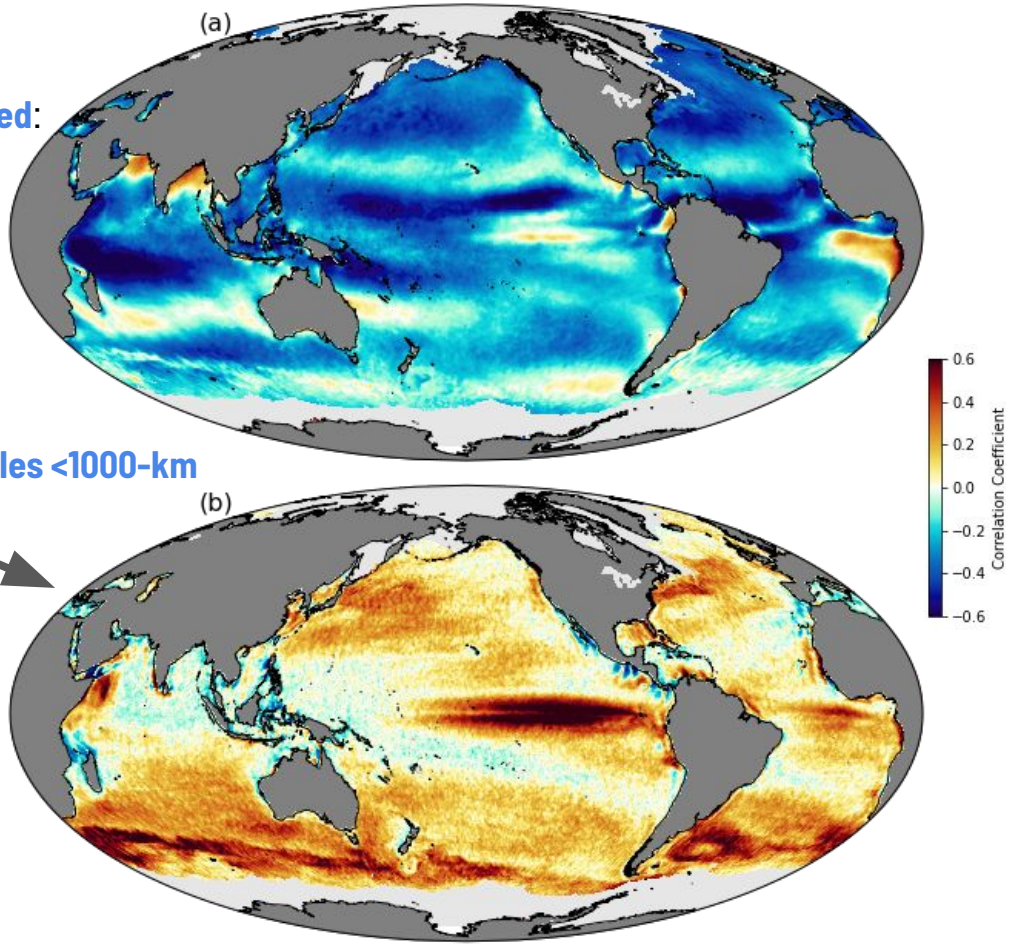
Wind & SST data show:

At large scales the **atmosphere** drives the ocean.

At small scales the **ocean** drives the atmosphere.

How it started:

How's it going? At scales <1000-km



Gentemann et al. (2020)

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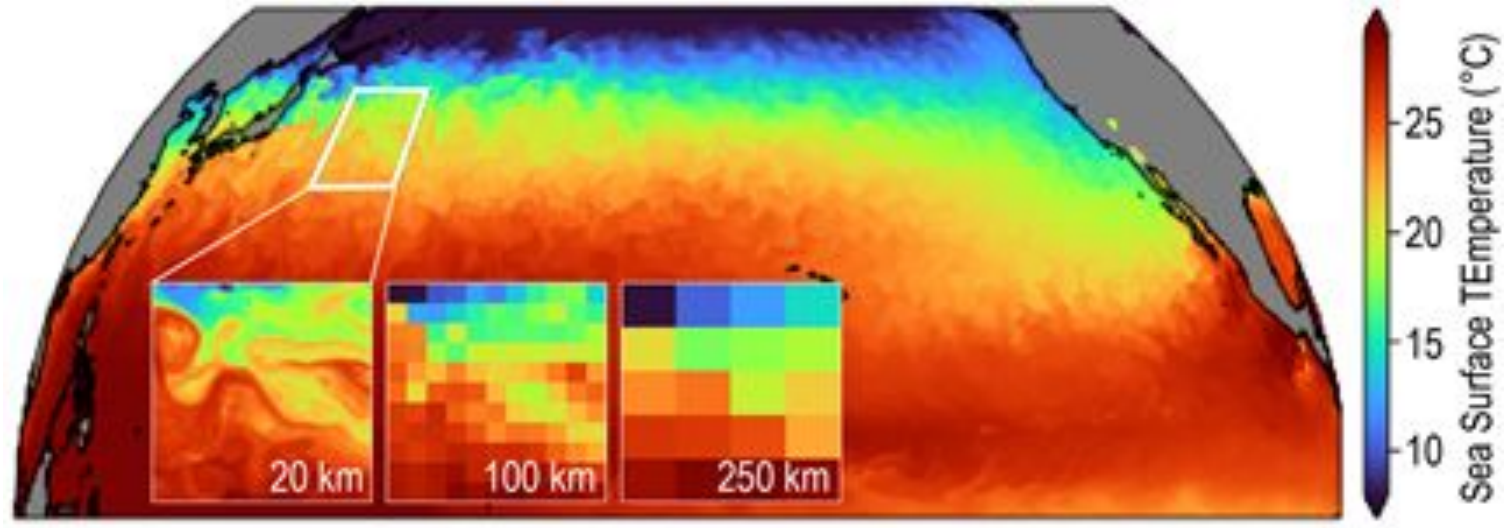
Fronts and eddies fill the global ocean and affect air-sea fluxes but the existing air-sea flux data are calculated by cobbling together different datasets with low accuracy/resolution



Model studies shows that ~25-km fluxes and their subsequent effect on the lower atmosphere influence the upper atmosphere (tropospheric) circulations through different mechanisms than the linear response suggested by lower-resolution models. This discrepancy is due to the low-resolution model's inability to represent the non-linear interactions between the atmosphere and ocean.

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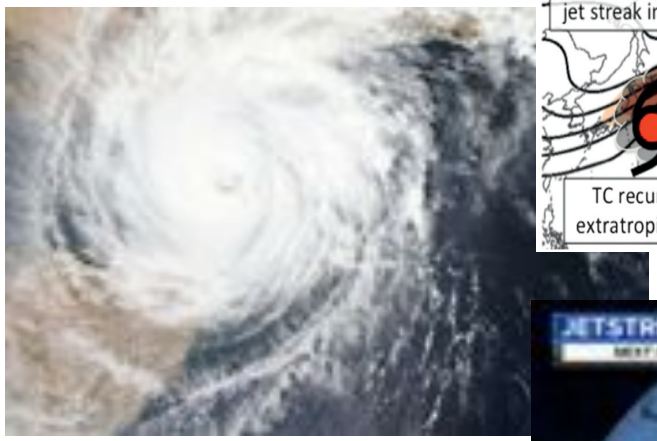
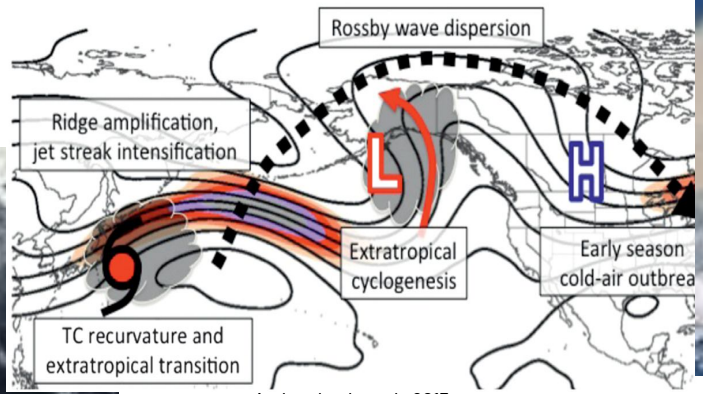
Models show us that....

storms in the Eastern Pacific respond to 25 km air sea fluxes

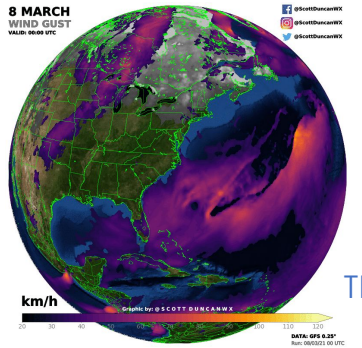


This can shift regional weather patterns



Archambault et al., 2013

Affecting weather across the U.S.



This also happens in the Gulf Stream / Europe

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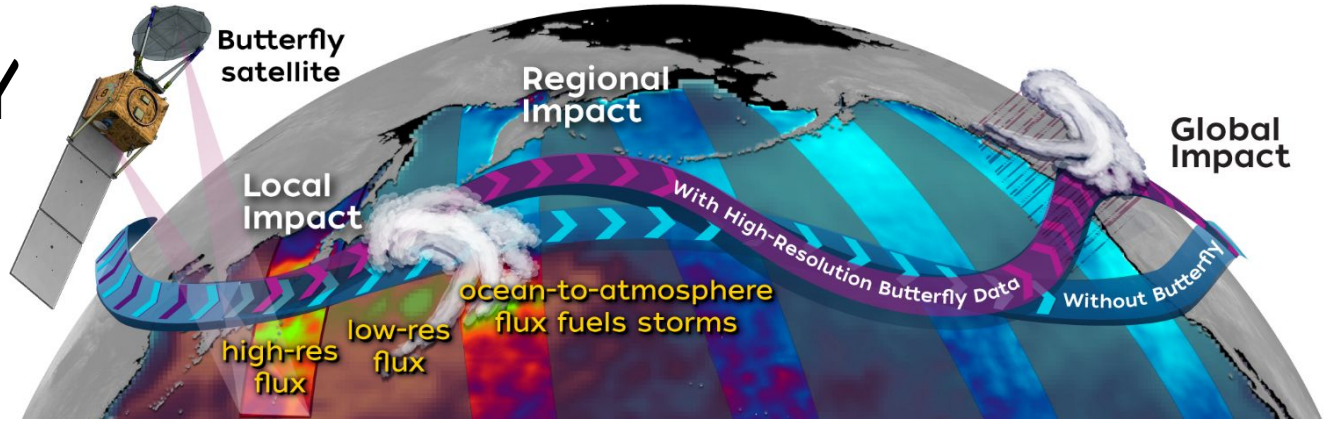
BUTTERFLY

BUTTERFLY

revealing the oceans' impact on weather & climate



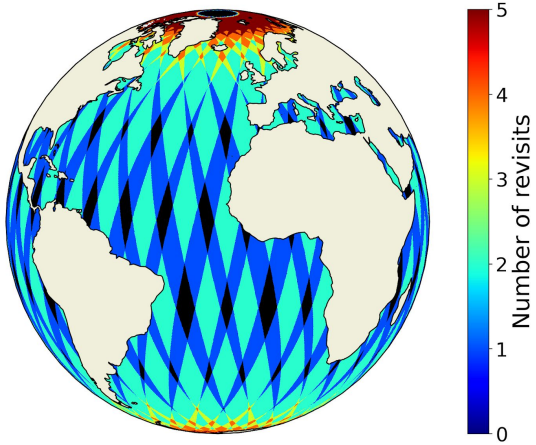
WHAT

Butterfly is the first satellite mission to **simultaneously** measure sea surface temperature, wind, & near-surface air temperature & humidity in order to estimate air–sea turbulent heat and moisture fluxes at a spatial resolution and accuracy sufficient to resolve the impact of small-scale ocean features on large-scale weather and climate.

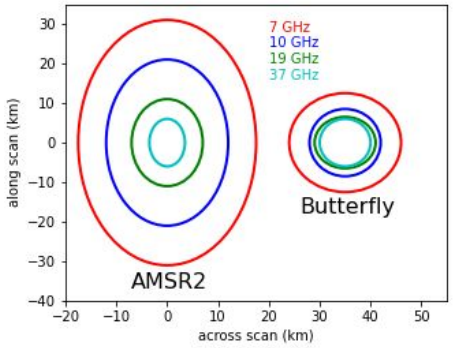
WHY

The ocean supplies the atmosphere with heat and moisture, dominating the global water and energy cycles while fueling weather and climate variability. Butterfly measures this air–sea exchange at spatial scales never before observed to unlock how the small-scale ocean "drives" the large-scale atmosphere, transforming predictability from mere days to weeks.

2-DAY COVERAGE



Mission	Details
Launch Date	4/2026
Length (minimum)	18-months
Orbit	>80° inclination
Swath Width	640 km
Resampled Footprint	20 km



HOW

Butterfly's passive microwave instrument measures from 7-175 GHz and is specially designed to measure air-sea turbulent heat and moisture flux at <25-km resolution.

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How?

Butterfly's single instrument combines:

Passive microwave 7-175 GHz

7, 11, 19, 24, 37 GHz: sea surface temperature & wind speed

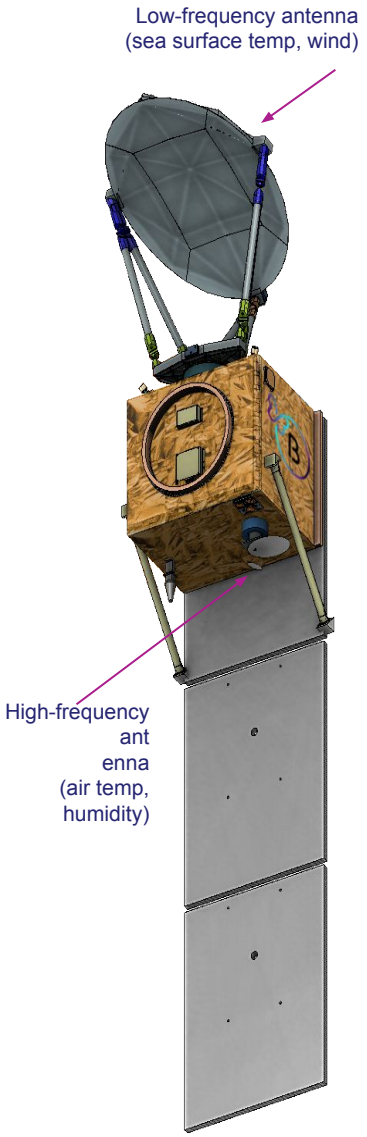
109-117, 150-175 GHz: near-surface air temperature & humidity

Two spinning reflectors

Achieves 20 km spatial resolution

Digital backend

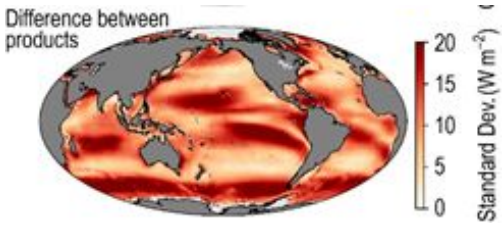
Improves accuracy and provides RFI-robust data

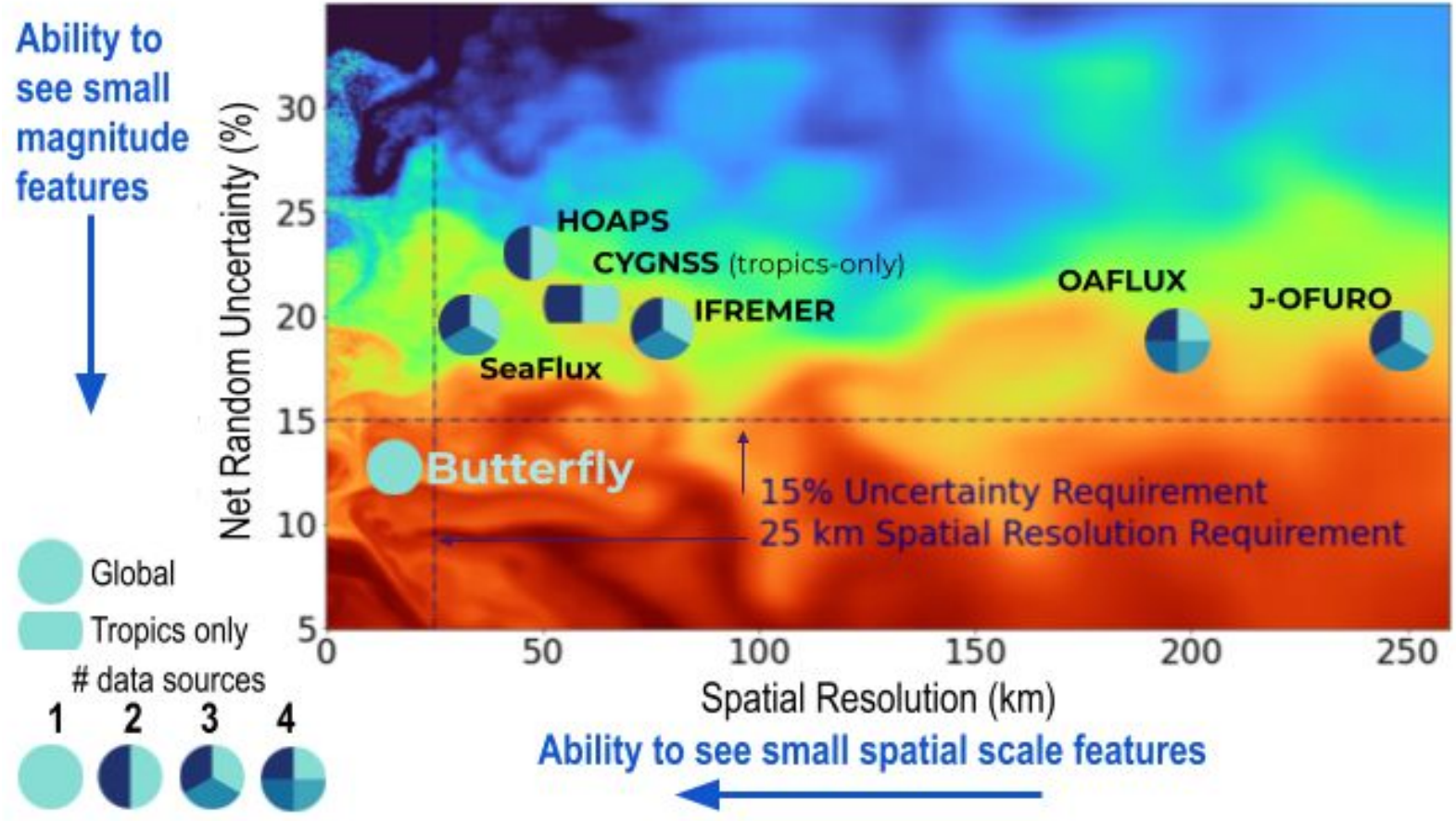


No existing satellite is designed to measure the air-sea turbulent heat fluxes.

Existing flux products:

- Use data from satellites not designed to measure Tair/Qair
- Interpolate multiple data sources in space and time
- Gridded at 25 km, but use data with lower resolutions





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Why now?

Our observations have fallen behind modeling and science needs

Weather and seasonal forecasting. Butterfly's 2026 launch will align with expected resolution advances in coupled models (e.g. NOAA's UFS)

Climate Change. Butterfly will provide air–sea flux estimates to test and improve climate models and their projections (e.g. CMIP7)

Ocean Sustainability Science. 2021–2030 is the UN Decade of Ocean Science for Sustainable Development

Decadal Survey science priorities. Butterfly data will advance 7 out of 13 'Most Important' or 'Very Important' Weather and Climate Panel Science and Application Questions.

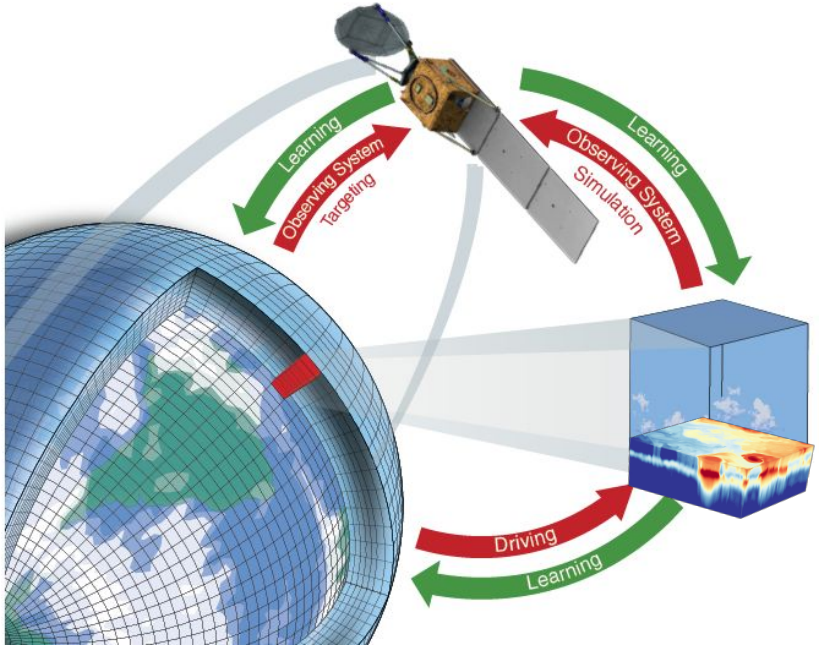

Image credit: https://climate-dynamics.org/earth-system-modeling-2-0/

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EVM3 = not selected

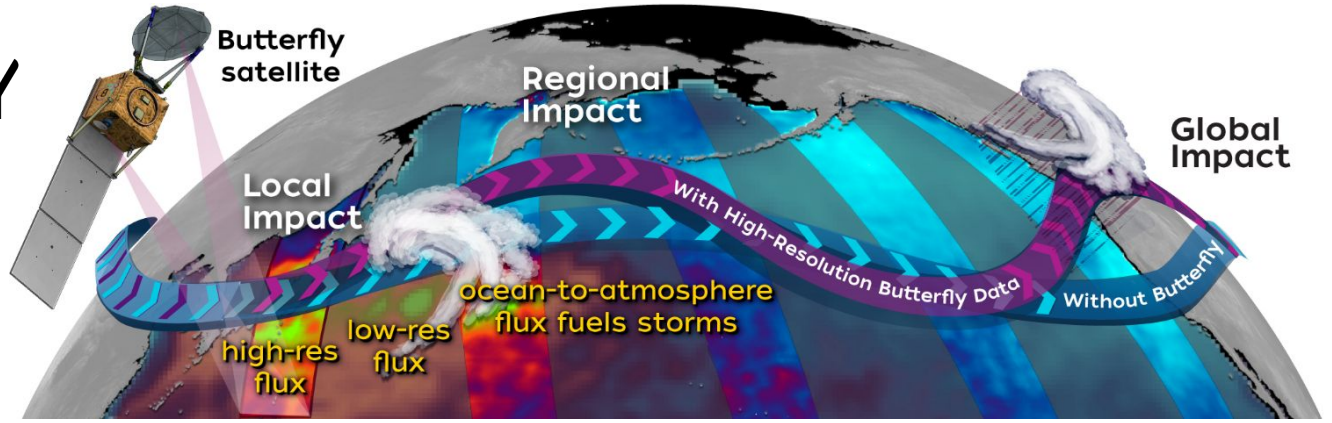
Debrief: 12/3
Why Butterfly wasn't selected:

- Was there a major weakness in our science or implementation?
- Programmatic reasons?

Next steps:
Evaluate options, most likely EVM4
Build community support and science

BUTTERFLY

revealing the oceans' impact on weather & climate



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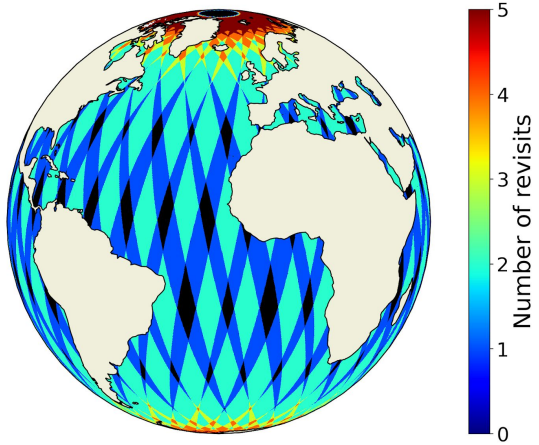

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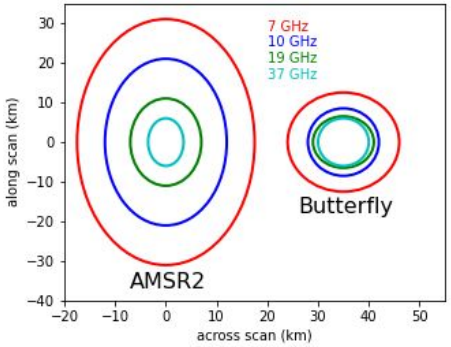

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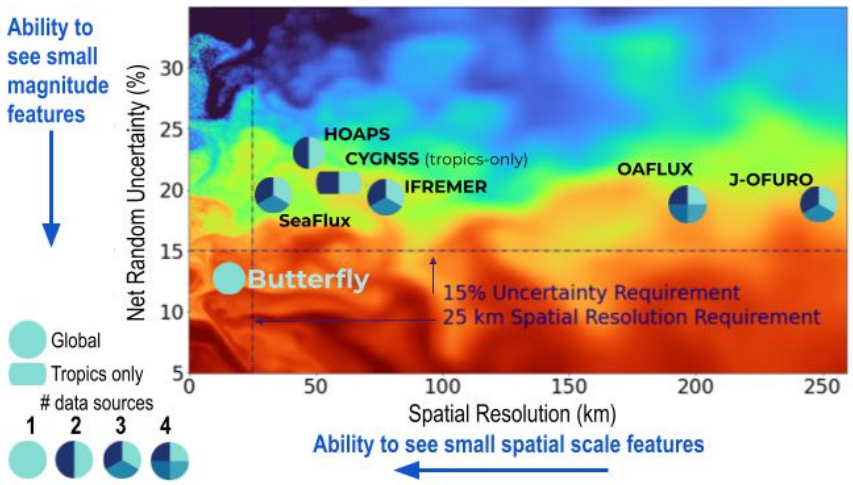
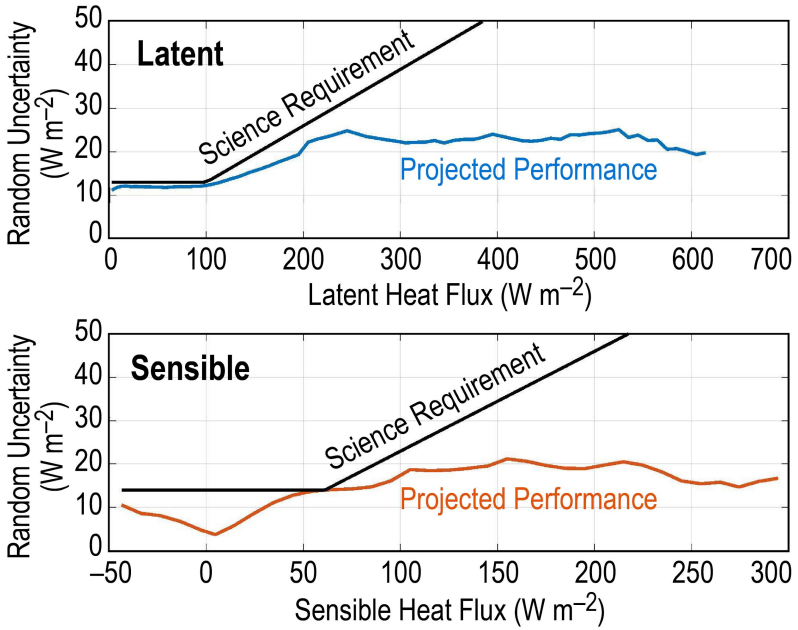
Extra slides

~40% reduction of errors

Instantaneous observational random errors for each input variable and the flux errors for current missions and Butterfly based on error propagation.





The errors of current flux products due to temporal/spatial mismatch of input variables have not been included. Butterfly is not affected by such mismatch because of its simultaneous measurements of input variables.

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The global water and energy cycles affect the Earth's weather and climate

The ocean absorbs >90% of the energy trapped by global warming

86% of global evaporation occurs over the ocean, constituting the single largest flux in Earth's water cycle. It also has the largest uncertainty.

Climate models have 100% error in global mean latent heat fluxes.

Can we close the global for air-sea heat and moisture budgets on regional to global scales with better data?

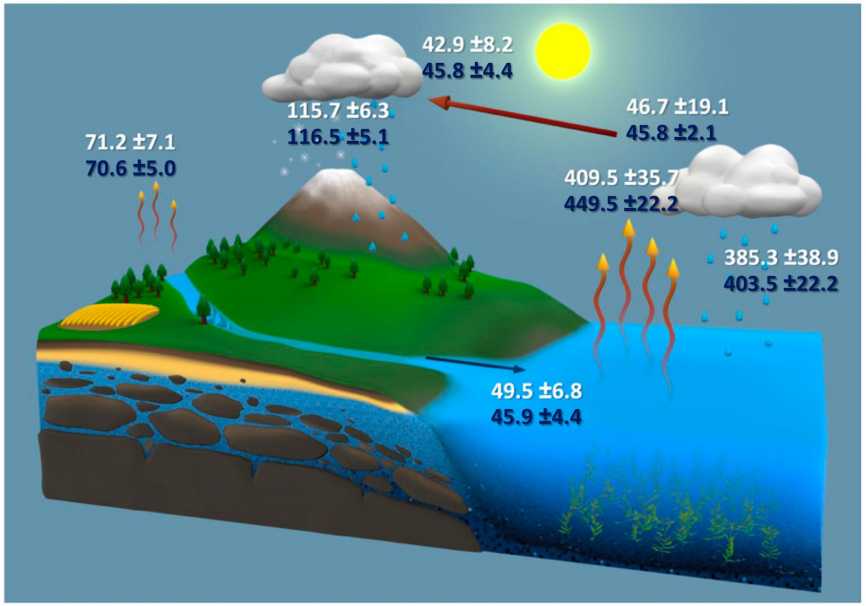
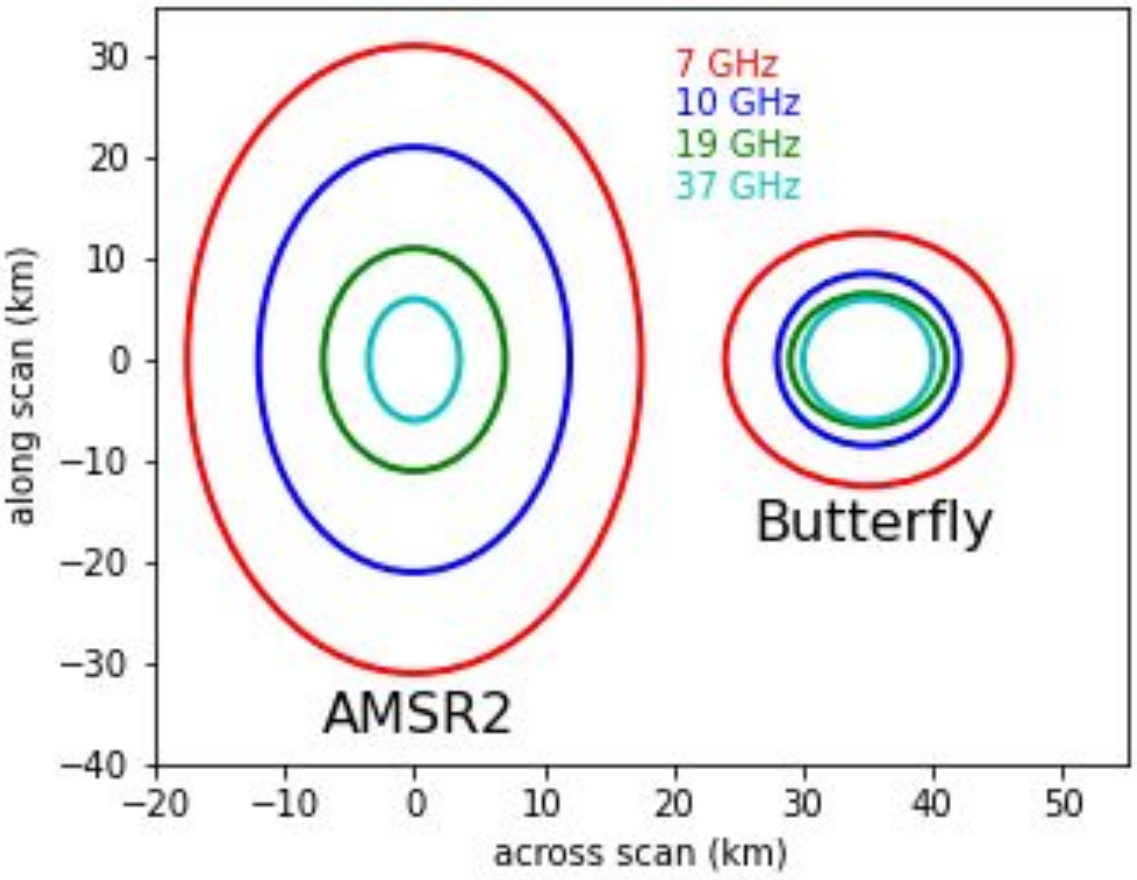


FIG. 2. Mean annual fluxes ($10^3\,km^3\,yr^{-1}$) of the global water cycle, and associated uncertainties, during the first decade of the millennium. White numbers are based on observational products and data integrating models. Blue numbers are estimates that have been optimized by forcing water and energy budget closure, taking into account uncertainty in the original estimates.

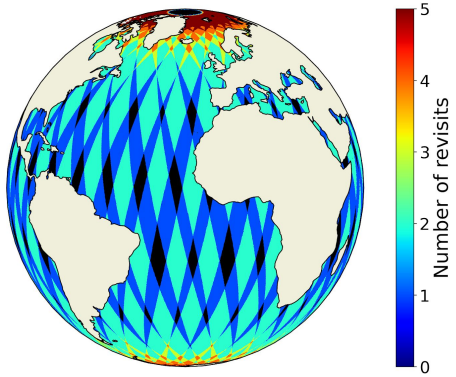
Image Credit: Rodell et al. 2015

20 km data, 640 km swath width, and 91% global coverage in 2 days



Channel (GHz)	Footprint (km)
7	25x22
11	17x14
19	13x12
24	12x11
37	12x10
110-116	17x14
150-170	12x10
Resampled	20

2-DAY COVERAGE



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Estimate the air-sea turbulent heat fluxes:

Turbulent heat flux = Sensible heat flux + Latent heat flux

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

- ρ_a: Air density
- C_p: Air specific heat capacity
- C_H: Turbulent exchange coefficient
- U: Wind speed
- $(T_{sea} - T_{air})$: Air-sea temperature difference

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

- ρ_a: Air Density
- L_v: Latent heat of vaporization
- C_E: Turbulent exchange coefficient
- U: Wind speed
- $(q_{sea} - q_{air})$: Air-sea humidity difference

Data Sources: Butterfly Model Coefficients

The turbulent heat fluxes include sensible and latent heat fluxes. The latent heat flux is directly related to moisture flux through evaporation.

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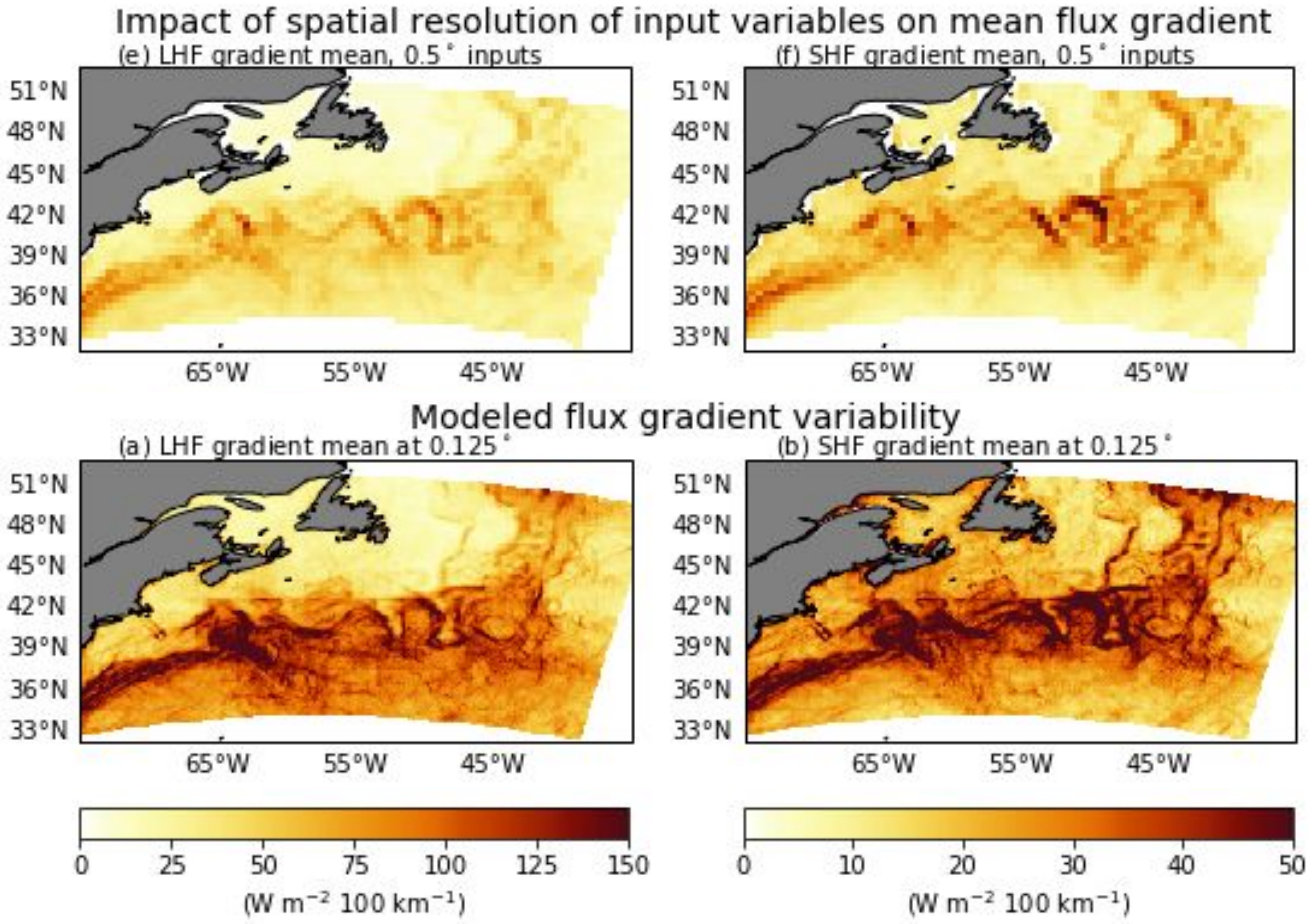
A new view of fluxes



A WRF-based assessment

Now

Butterfly

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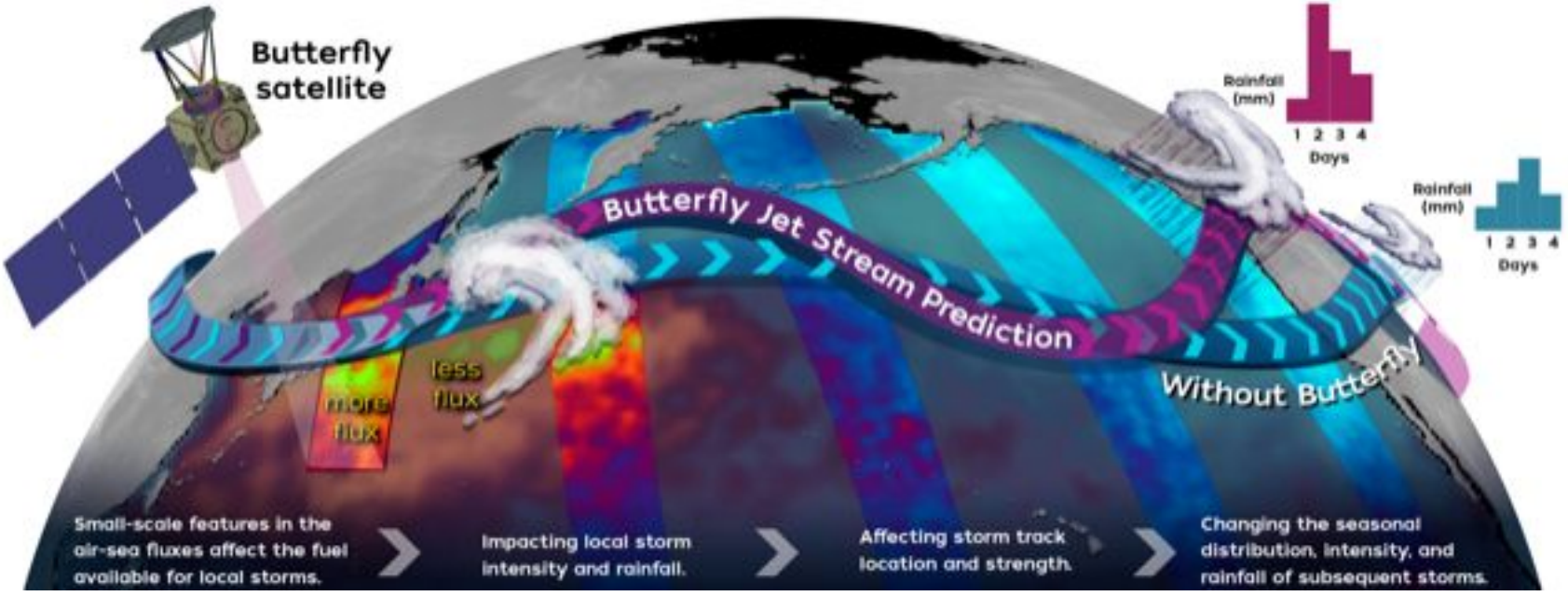
Butterfly Science

Local to Regional

Addressing Decadal Survey Question W-3 *"How do spatial variations in surface characteristics modify transfer between domains and thereby influence weather and air quality?"*

Science Objective 1: Determine the degree to which 25-km resolution turbulent heat and moisture fluxes influence midlatitude storm evolution and long-term weather.



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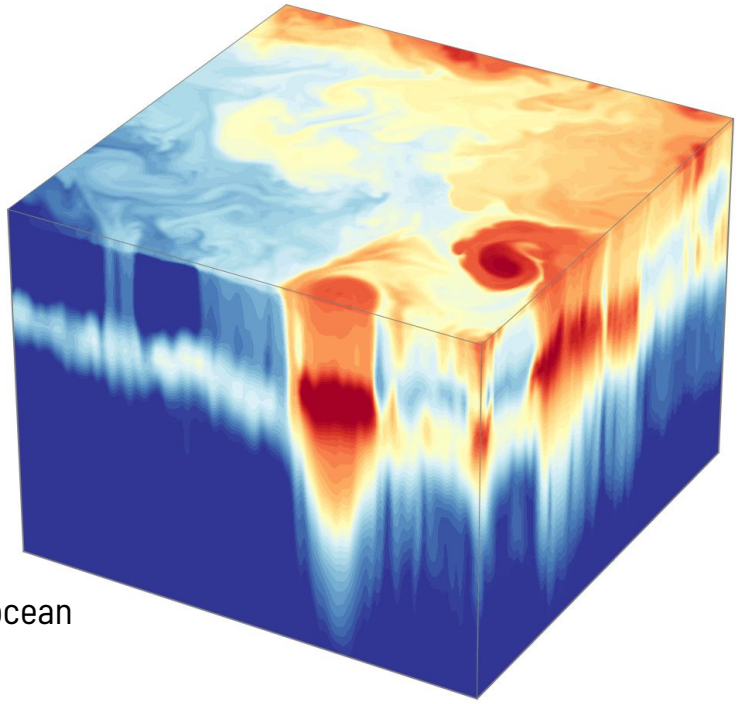
Butterfly Science

Local to Global

Addressing Decadal Survey Question C-4 *"How will the Earth system respond to changes in air-sea interactions?"*

Science Objective 2: Balance the global ocean turbulent heat and moisture flux contributions to the energy and water cycles to within 5%.



ECCO ocean model data showing ocean eddies off British Columbia

Some examples of .....

atmosphere forcing the ocean

SST/wind ▬ correlation

Coastal Upwelling: Wind ↑ Ocean Temp ↓

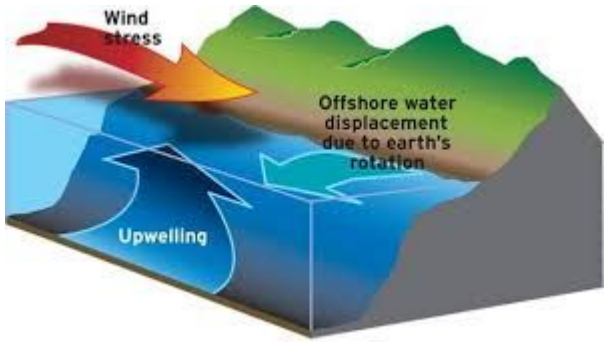
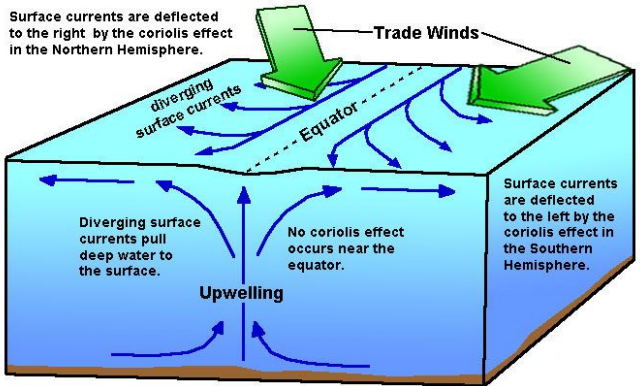


Image: (top) Gentemann et al. 2019; (bottom) NOAA NFSC

Equatorial Upwelling: Wind ↑ Ocean Temp ↓

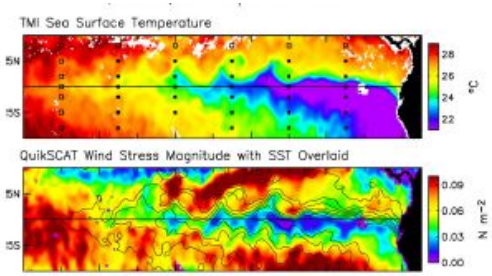


ocean forcing the atmosphere

SST/wind ✚ correlation

Boundary layer stability: Wind ↓ Ocean Temp ↓

Boundary layer stability: Wind ↑ Ocean Temp ↑



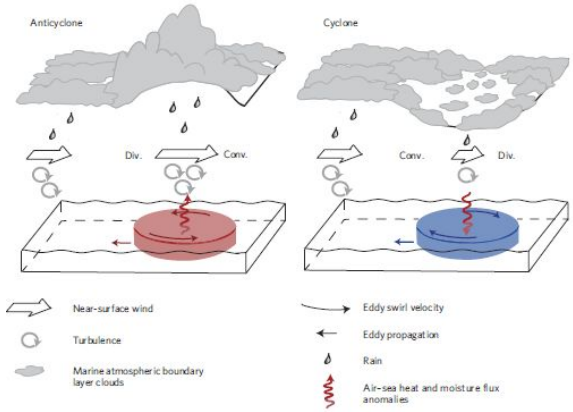


Image: (top) Chelton et al. 2001; (bottom) Frenger et al. 2013