Observational Perspective on Bulk Air-Sea Flux formula

Elizabeth Thompson (NOAA PSL), with input from many:

Jim Edson, J. Thomas Farrar, Momme Hell (WHOI)

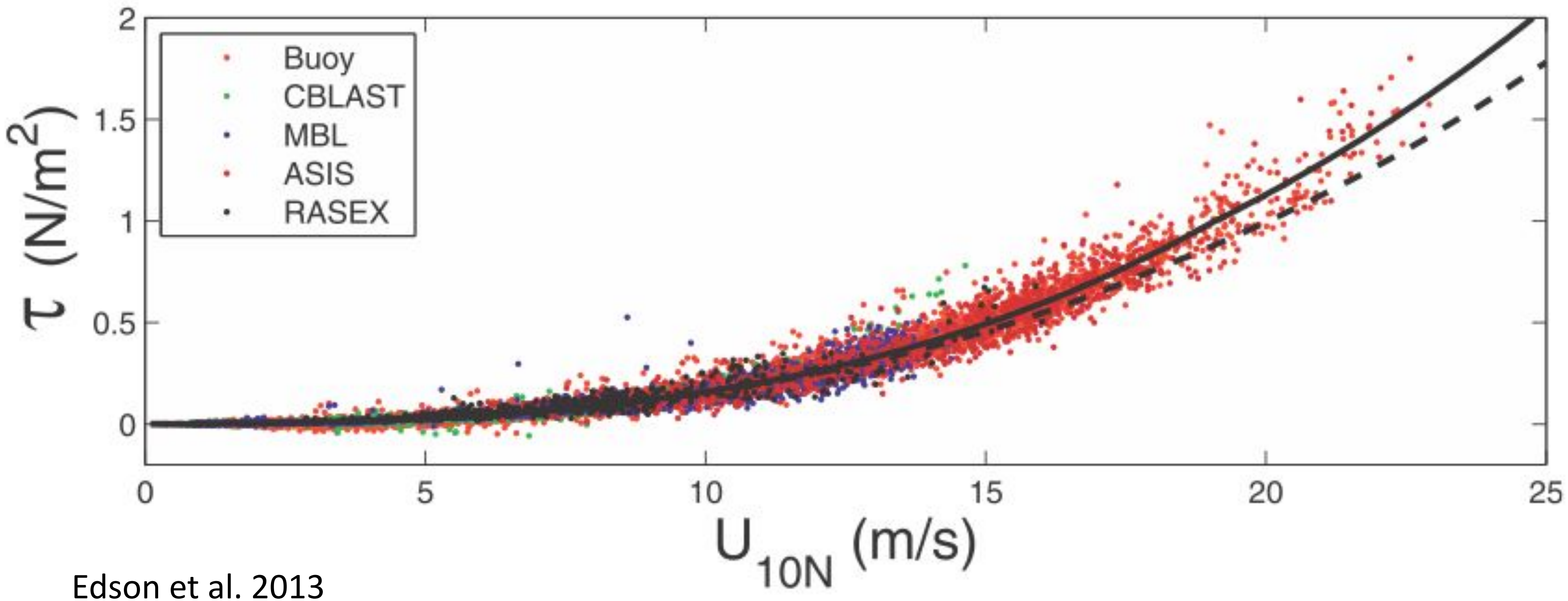
Seth Zippel (OSU)

Lucas Harris, Andrew Wittenberg, Brandon Reichl (NOAA GFDL)

Chris Fairall (formerly NOAA PSL)

Frank Bryan (NCAR)

Bulk Formula is a great **mean fit to obs** across the world, in all stability states and latitudes



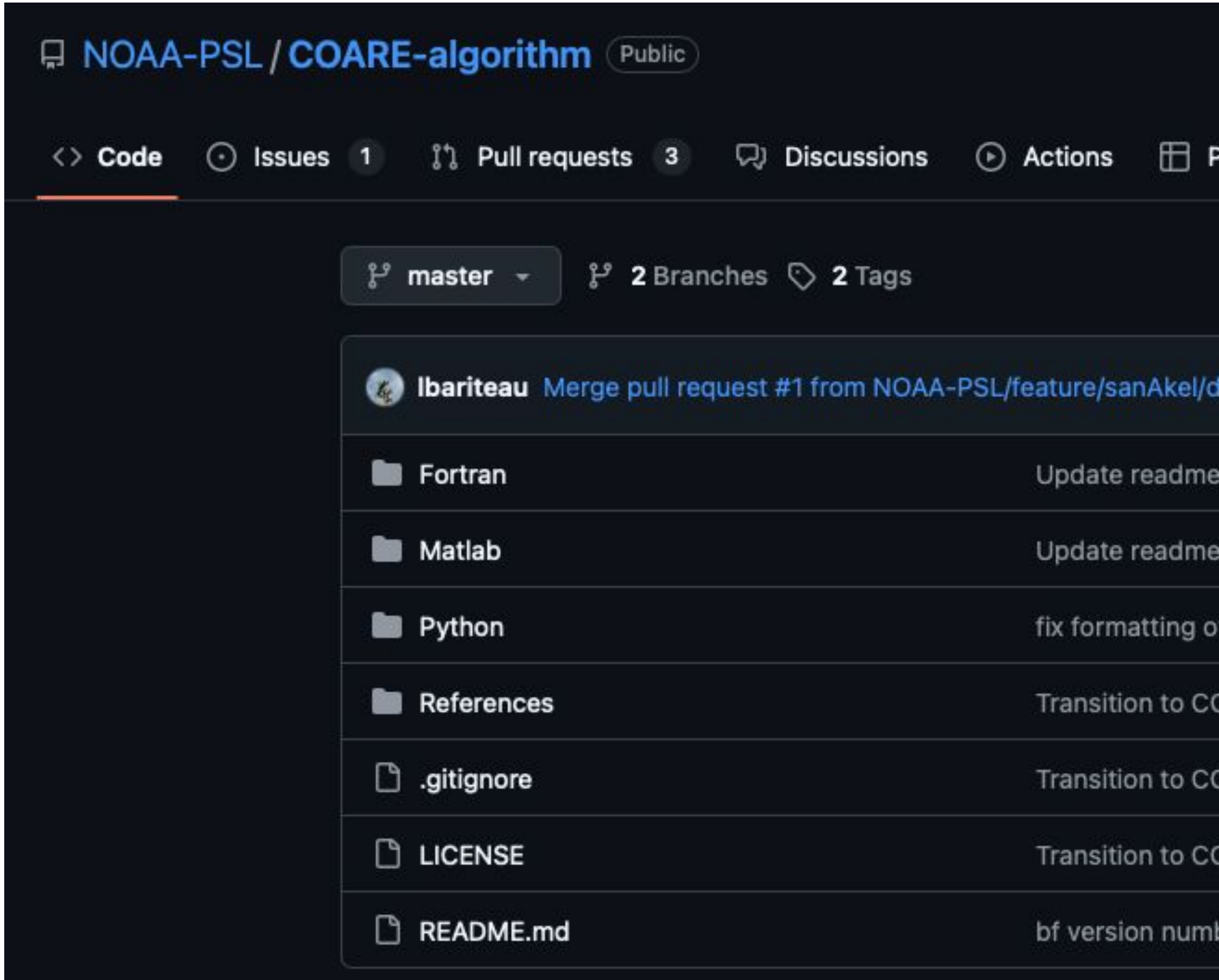
Edson et al. 2013
COARE v3.5… 4.0 coming soon

COARE Bulk Air-Sea Flux Algorithm GitHub

https://github.com/NOAA-PSL/COARE-algorithm

v3.6 in Matlab, Python, Fortran

v4.0 expected soon



NOAA PSL: myself, Ludovic Bariteau
WHOI: Jim Edson

Bulk Formula don't *fully* capture *all* small-scale flux dependencies or variability

- **Waves and/or currents misaligned with wind** (adjustment suggested by Sauvage et al. 2024)… but roughness responds to the shortest waves, which reach equilibrium very fast, so disequilibrium area/time is very small in obs (Iyer et al. 2022a,b, Chang et al. 2025)
- **Limited data collected at high-winds (> 30 m/s)** … Davis et al. 2024, Davis in prep, Barr in prep, Butterworth in prep: what we should expect given the obs we have
- **Sea spray** (adjustments are possible as indicated by Barr et al. 2023, and in review)
- **Subgrid scale spatial gradients** *(e.g. use caution averaging over the entire Gulf Stream)*
- **Rain's impact on cool skin** (Witte et al. 2023), + other **cool skin** details (Fairall, in prep)

*** missing physics, particularly waves/spray become more important at high wind speed / flux values, which are inherently important (impactful)

*** these are still all second or third order effects to the flux formula

*** if datasets are collected of all training variables, we can adapt COARE to fit it -> like we've done with stress in the context of wave age

*** we don't update COARE unless a suggested fix offers improvement (better fit) in describing our *global* dataset

The time scale, variance, and height of interest must be taken into account

- ***Gustiness factor***
  - Time and height dependent
  - Some papers are in preparation on this
  - Should adapt as wind speed (PBL dynamics) get more complex

- Flux observations used to train COARE were collected at the surface (2-17 m), so their formulas cannot be applied to 1-2 km satellite retrievals with confidence, or above any decoupled internal boundary layers (but *within* shallow stable surface layers, COARE works well)

Application of COARE at the finest temporal and spatial scales (e.g. LES) is ***FINE***

- COARE transfer coefficients were trained with 10-15 min chunks of 10 Hz data used to compute eddy covariance flux, that were then hourly averaged, and lumped together across the world to compute the transfer coefficients (Cd, Ch, Ct) (Fairall et al. 1996, 2003, Edson et al. 2013)
- Shear length scaling suggests Δx of 4 m is about the limit of applicability of bulk flux physics, with stability dependence: Zippel in prep, Scully et al. 2011, Bariteau and Fairall 2016)
  - flux theory should hold at scales much larger than the co-spectral roll-off (kappa*z ~ 4.1 m for 10m winds)
- We haven't observed un-COARE (un-MOST) like behavior, even at these smallest scales (1 min or a few meters wide), so long as your data are within the surface layer (< 50 m)
- Simply stated, evaporation doesn't work fundamentally different at 4 m scale than it does at 1 km m scale… it's still a ventilation / gradient process (*Evaporation into the Atmosphere,* Brutsaert 1982)
- Resolved vs. unresolved turbulence, and comparable vertical/horizontal scales of motion, at fine LES scales would still need to be addressed or a subject of related research (Juliano et al. 2022)
- *Try and find out:* It's difficult or expensive to measure in practice, but you could try with two stations located close together with fast response time; or systematically add variance to bulk formula in models and test for significance in model output; account for stochasticity…

Notes from the field: S-MODE

“If COARE was wrong at fine scales, coupled and uncoupled LES using COARE would produce unrealistic features; it doesn’t” (Peter Sullivan et al. 2025, & prior work)

“I appreciate the conceptual difficulty with how we apply boundary conditions for high-resolution models. It is theoretically an issue, but, as you note, it can't be an order-one effect -- that is, it can't be any bigger than the disagreement between COARE and eddy-covariance fluxes” [which is relatively well constrained] –Tom Farrar

“MOST wasn’t guaranteed to work at small (LES) scales, but it surprisingly does” – Momme Hell

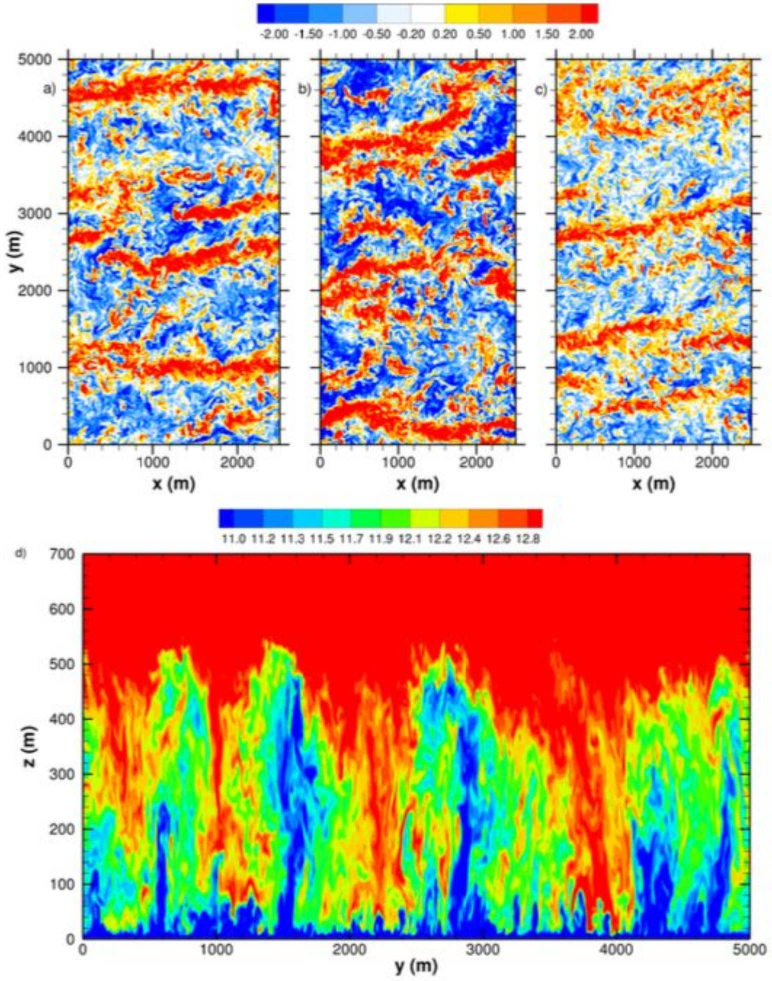


FIG. 2. Snapshot of vertical velocity w showing typical ABL turbulence shear-convective rolls (SCR) from simulations with geostrophic winds $U_g = (10, 10, 15)$ m s,$^{-1}$ run names ($U10, U10C, U15$) shown in a), b), c)

The largest 2 sources of flux/surface model errors when using bulk formula are…

1. **Mean biases in near-surface met + ocean state variables**
   - Air pressure, temp, humidity, wind speed, ocean currents, wave age, SST, SSS, rain rate, solar downwelling radiation, IR downwelling radiation
   - Exchange coefficient variability is small relative to variance in the mean inputs
2. **Ocean and atmosphere boundary layer parameterizations**
   - Including the cloud, entrainment, microphysics, etc. parameterizations that feedback to PBL

- It's fine to keep **improving/researching the bulk formula**, and being interested in small scale physics… but expect further refinements to be **minor and special cases**;
- It's more important <u>*now*</u> to **address longstanding model mean state biases** in models, reanalyses, and similarly for satellite retrievals (for Tair and qair, Yu 2019)
- stress errors may be larger due to quadratic nature, unlike heat fluxes

LHFLX Bias in AMIP Ensemble

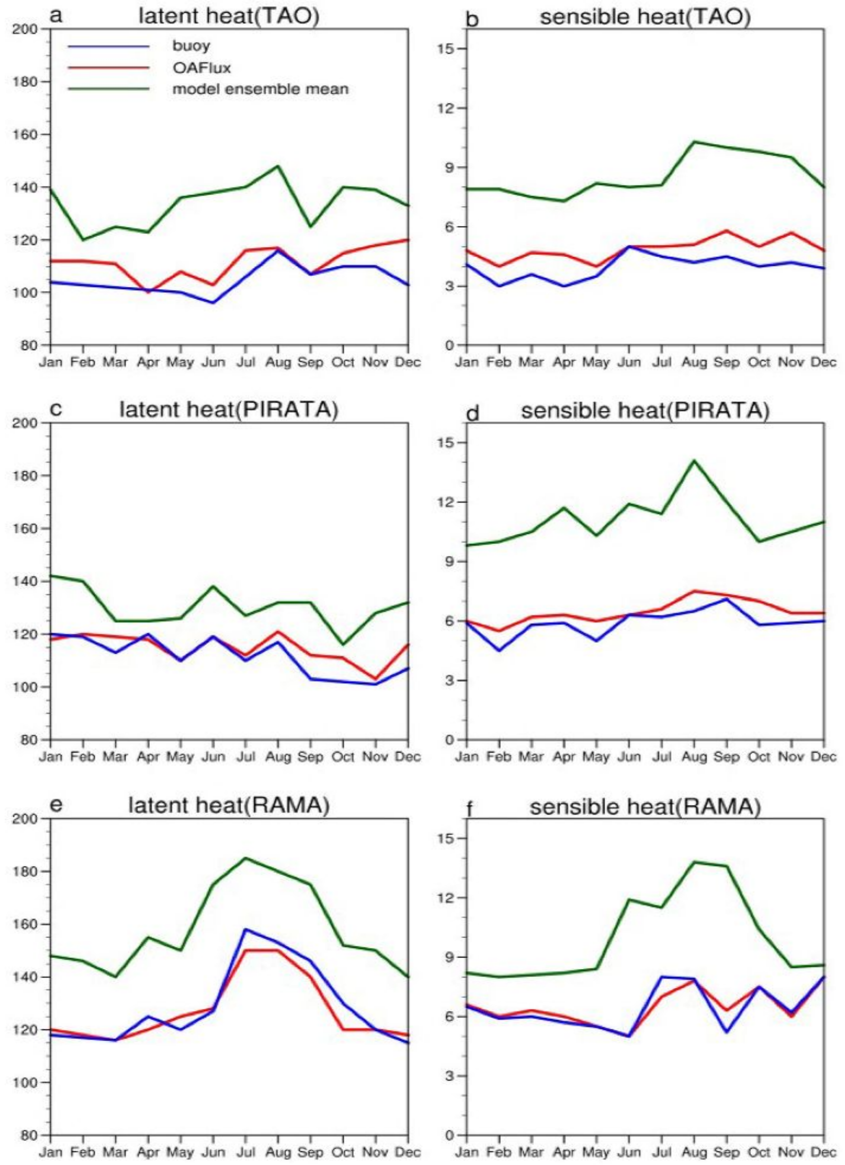
Model ensemble mean
OAFlux (satellite+reanalysis)
Buoy

Climate Dynamics (2020) 55:2957–2978
https://doi.org/10.1007/s00382-020-05431-y

Understanding the bias in surface latent and sensible heat fluxes in contemporary AGCMs over tropical oceans

Xin Zhou[1] · Pallav Ray[1] · Bradford S. Barrett[2] · Pang-Chi Hsu[3]

(iii) The models, in general, overestimated sea-air humidity ($q_s - q_a$) and temperature ($T_s - T_a$) differences. Since the AMIP models all used the same values of observed SST (T_s), it is clear that the models underestimated q_a and T_a. This is possibly due to the stronger mixing in the boundary layer that brings drier and cooler air from above to the near-surface area (e.g., Garratt 1994). Thus, the mixing in the model boundary layer may be too strong. The drier near-surface humidity could also be at least partially due to stronger downdraft (Rahaman and Ravichandran 2013) that brings colder and drier air from the above to the surface leading to underestimation of q_a and T_a in the models.



Pacific

Atlantic

Indian

c/o Frank Bryan

Geophysical Research Letters

RESEARCH LETTER

10.1029/2020GL091169

Key Points:

- Fifth Coupled Model Intercomparison Project Atmospheric Model Intercomparison Project simulations disagree on the magnitude of the present-day global mean precipitation rate by 13%

Lower Tropospheric Processes: A Control on the Global Mean Precipitation Rate

Jacob M. Hendrickson[1], Christopher R. Terai[1,2], Michael S. Pritchard[1], and Peter M. Caldwell[2]

[1]Department of Earth System Science, University of California, Irvine, CA, USA, [2]Lawrence Livermore National Laboratory, Livermore, CA, USA

Provides link between longstanding model flux biases to model biases in amplified global hydrologic cycle

Abstract The spread in global mean precipitation among climate models is explored in two ensembles using the complementary perspectives of surface evaporation and energy budgets. Models with higher global mean precipitation have stronger oceanic evaporation, driven by drier near-surface air. The drier surface conditions occur alongside increases in near-surface temperature and moisture at 925 hPa, which point to stronger boundary layer mixing. Correlations suggest that the degree of lower tropospheric mixing explains 18%–49% of the intermodel precipitation variance. To test this hypothesis, the degree of mixing is indirectly varied in a single-model experiment by adjusting the relative humidity threshold that controls low-cloud fraction. Indeed, increasing lower tropospheric mixing results in more global mean precipitation. Energetically, increased precipitation rates are associated with more downwelling longwave radiation to the surface and weaker sensible heat fluxes. These results highlight how lower-tropospheric processes must be better constrained to reduce the precipitation discrepancy among climate models.

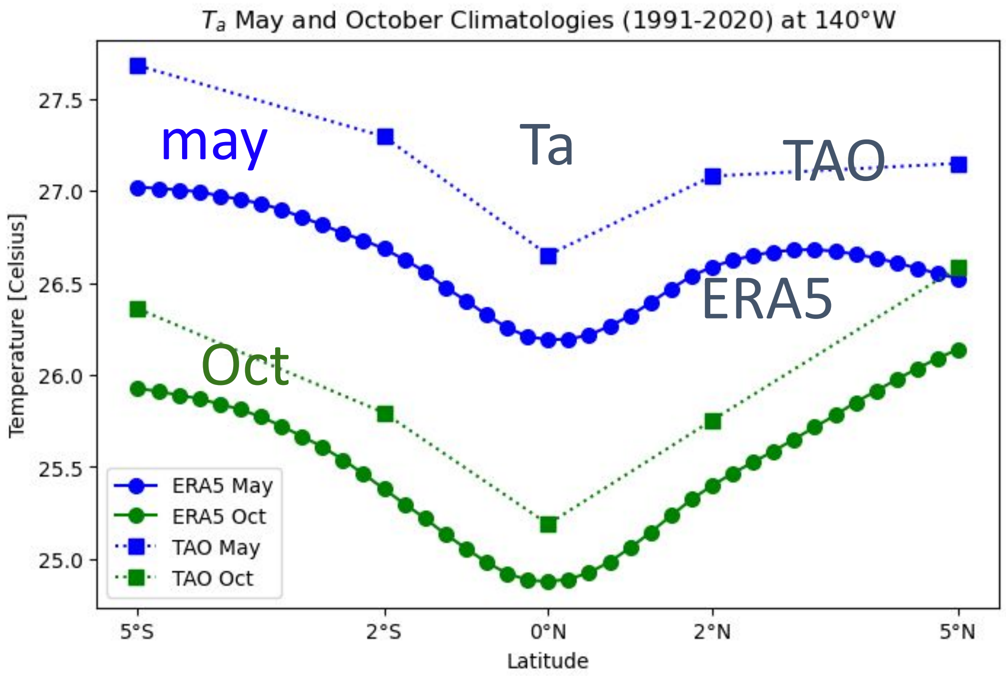
c/o Frank Bryan

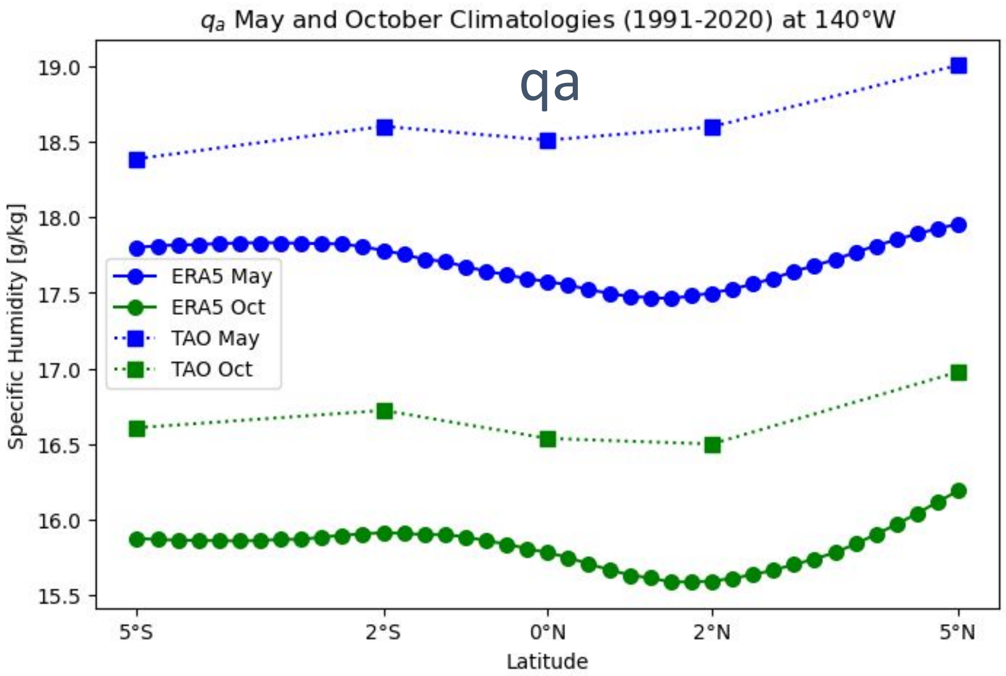
Global buoy network and radiosonde locations show **systematic reanalysis biases in near-surface Ta, qa, sensible/latent heat flux**, despite getting wind and SST correct

-> suggests PBL parameterization problems & inconsistent surface energy balance

-> satellite and reanalysis cloudiness and PBL height estimates disagree here

30-yr of TAO data: Pacific Cold Tongue



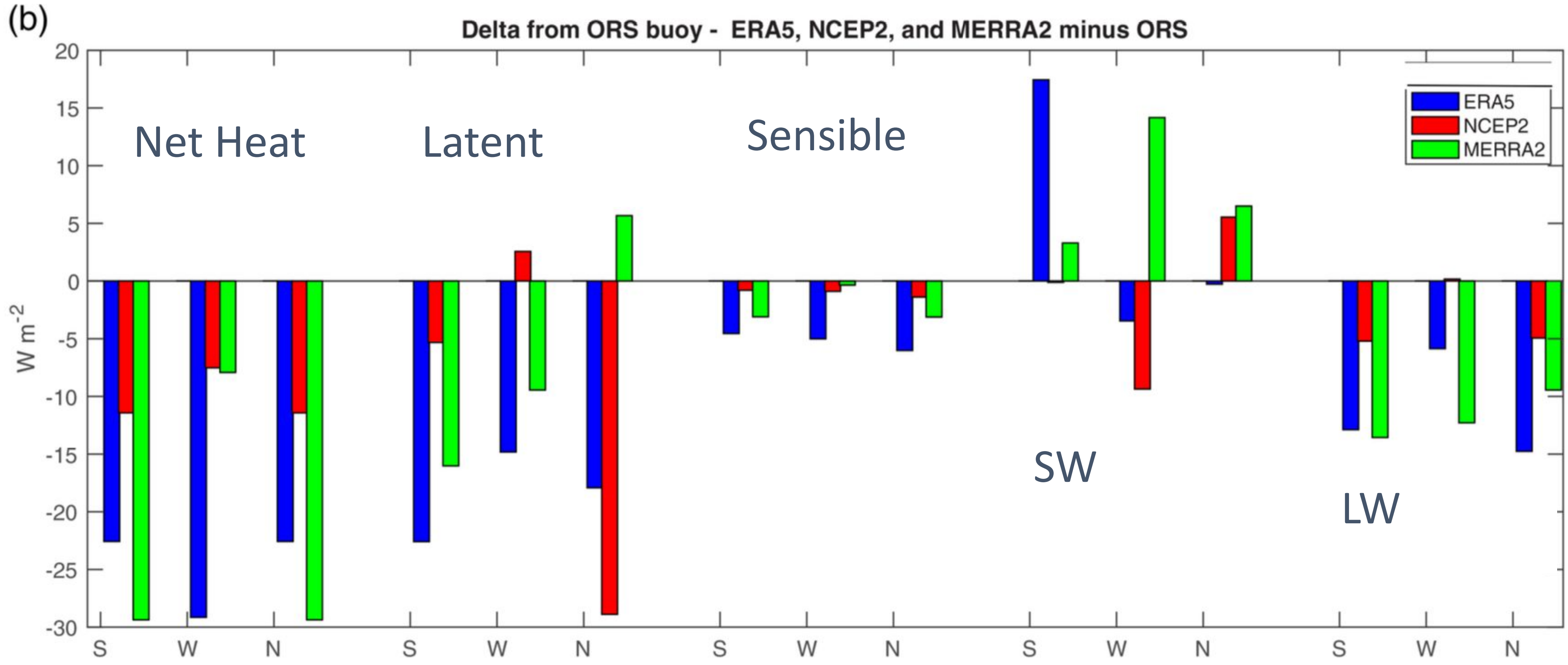


Jackson et al. in prep;

also confirmed **globally** with NCAR CESM2: finds systematic latent heat flux bias (Frank Bryan)

Global buoy network and radiosonde locations show **systematic reanalysis biases in near-surface Ta, qa, sensible/latent heat flux**

-> suggests PBL parameterization problems & inconsistent surface energy balance

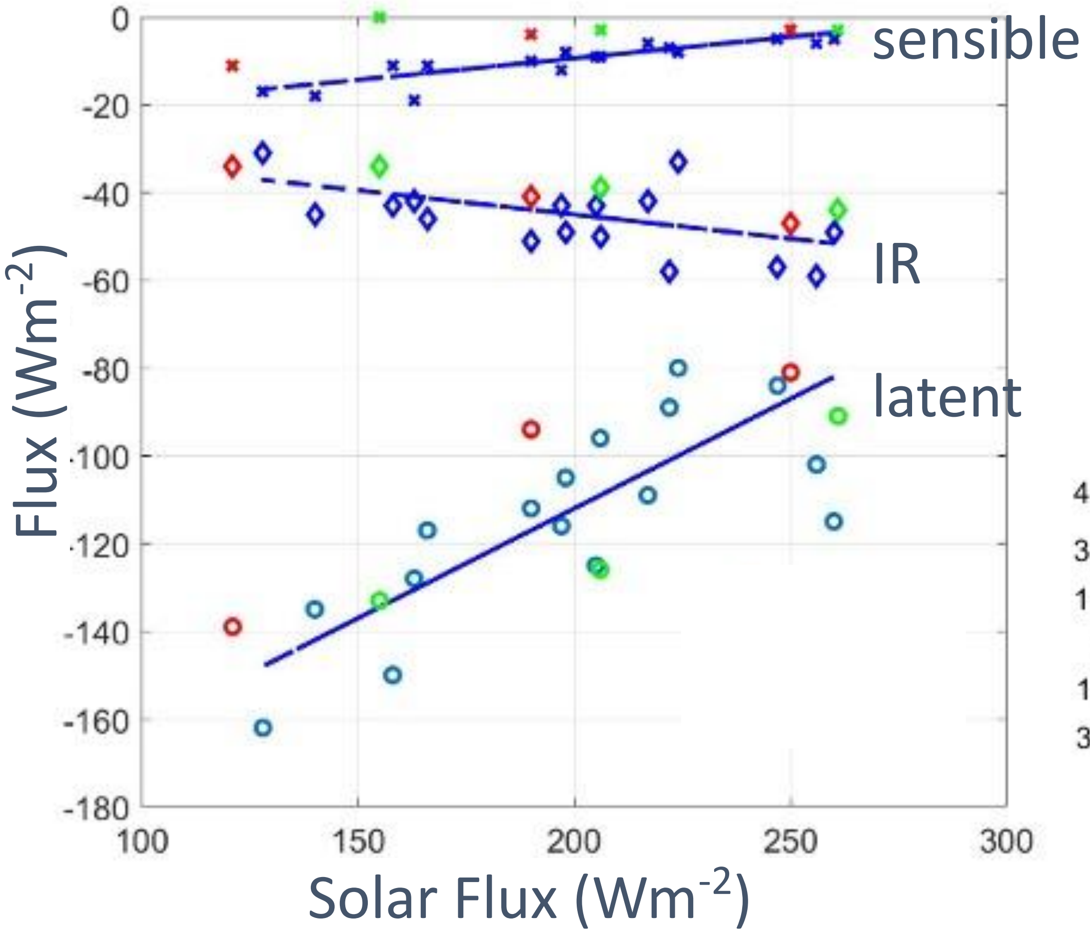


20+ years of 3 Ocean Reference Site research-quality buoys

Weller et al. 2022 BAMS

Toward getting the *right surface fluxes* for the *right reasons*

- universal relationship found between turbulent and radiative surface fluxes in tropics, a different relationship is found for subtropics

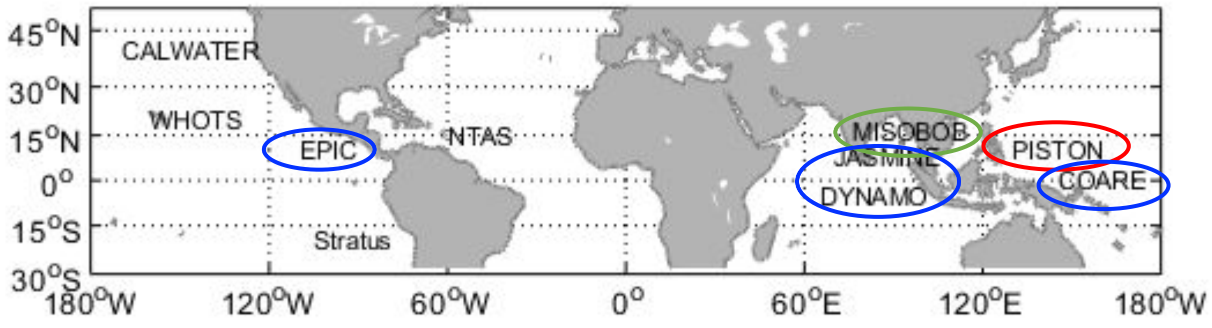


30-40 day cruise mean values

COARE, JASMINE, EPIC, DYNAMO

PISTON

MISOBOB



Wolding et al. in prep

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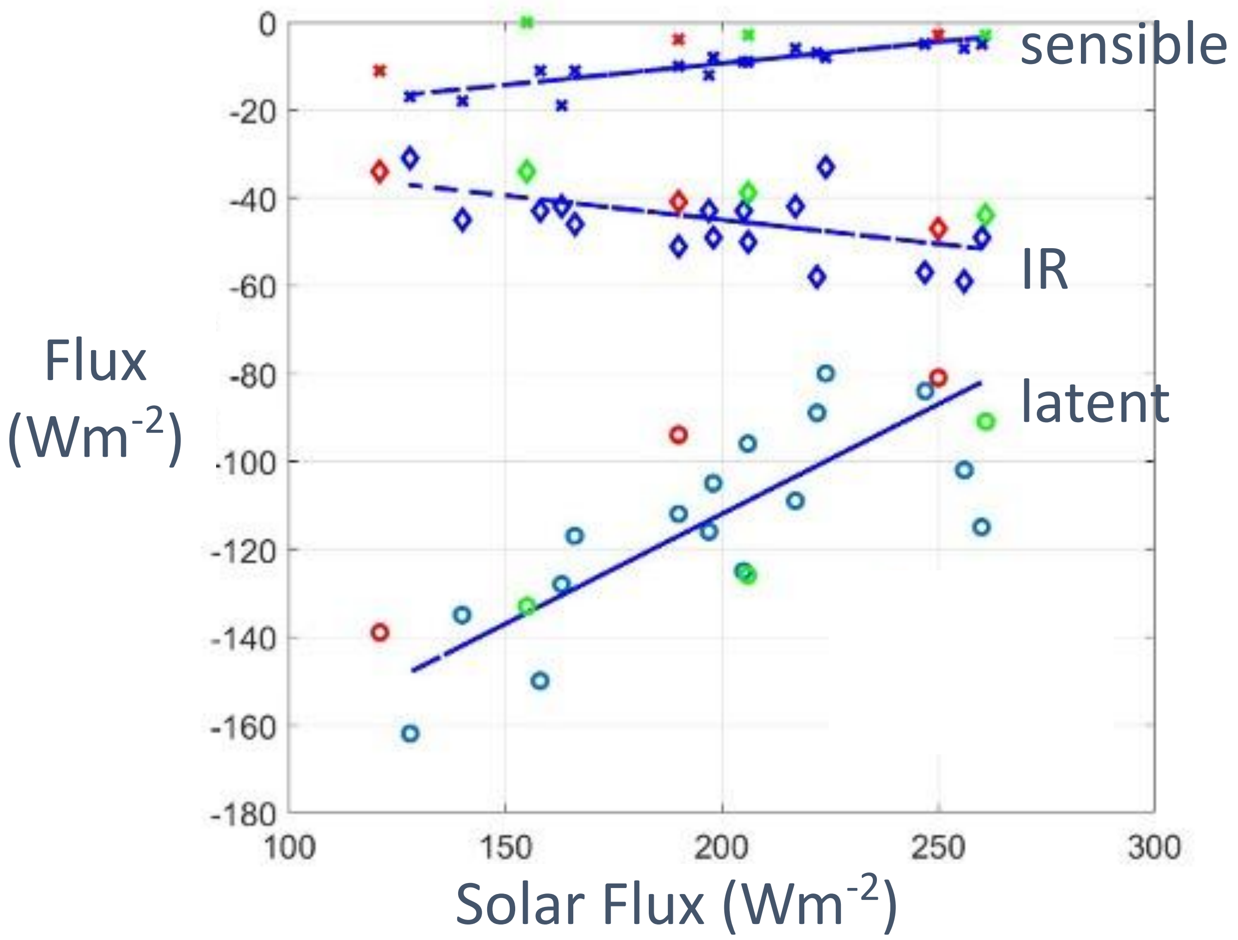
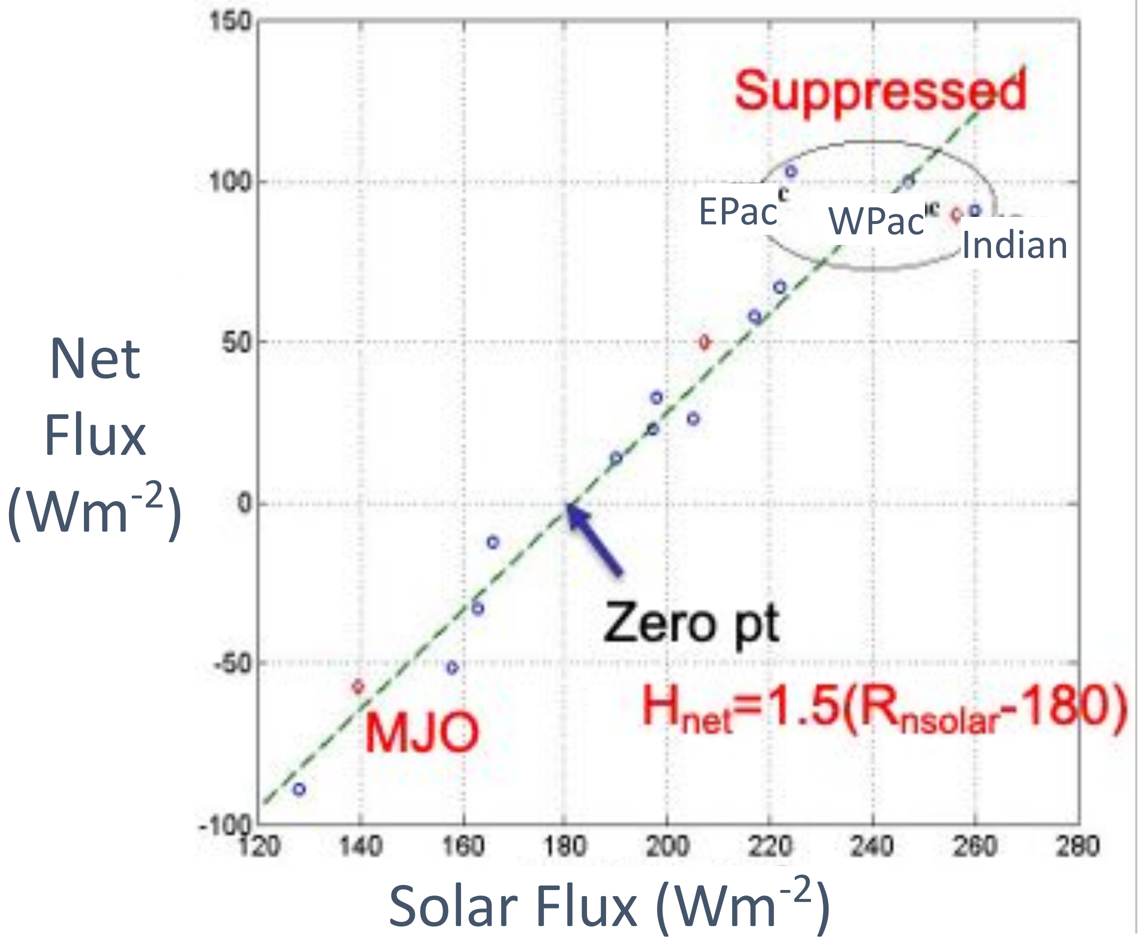




Netcdf PSL Field Campaign Data Archive -> model diagnostics (also see OOI and ORS buoys, not shown)

- netCDF **data** on our NOAA PSL "cruises" site: https://psl.noaa.gov/data/cruises/ & https://downloads.psl.noaa.gov/psd3/cruises/
- PSL Synthesized netCDF Flux Database search "synthesis" at URLs above

  59+ cruises

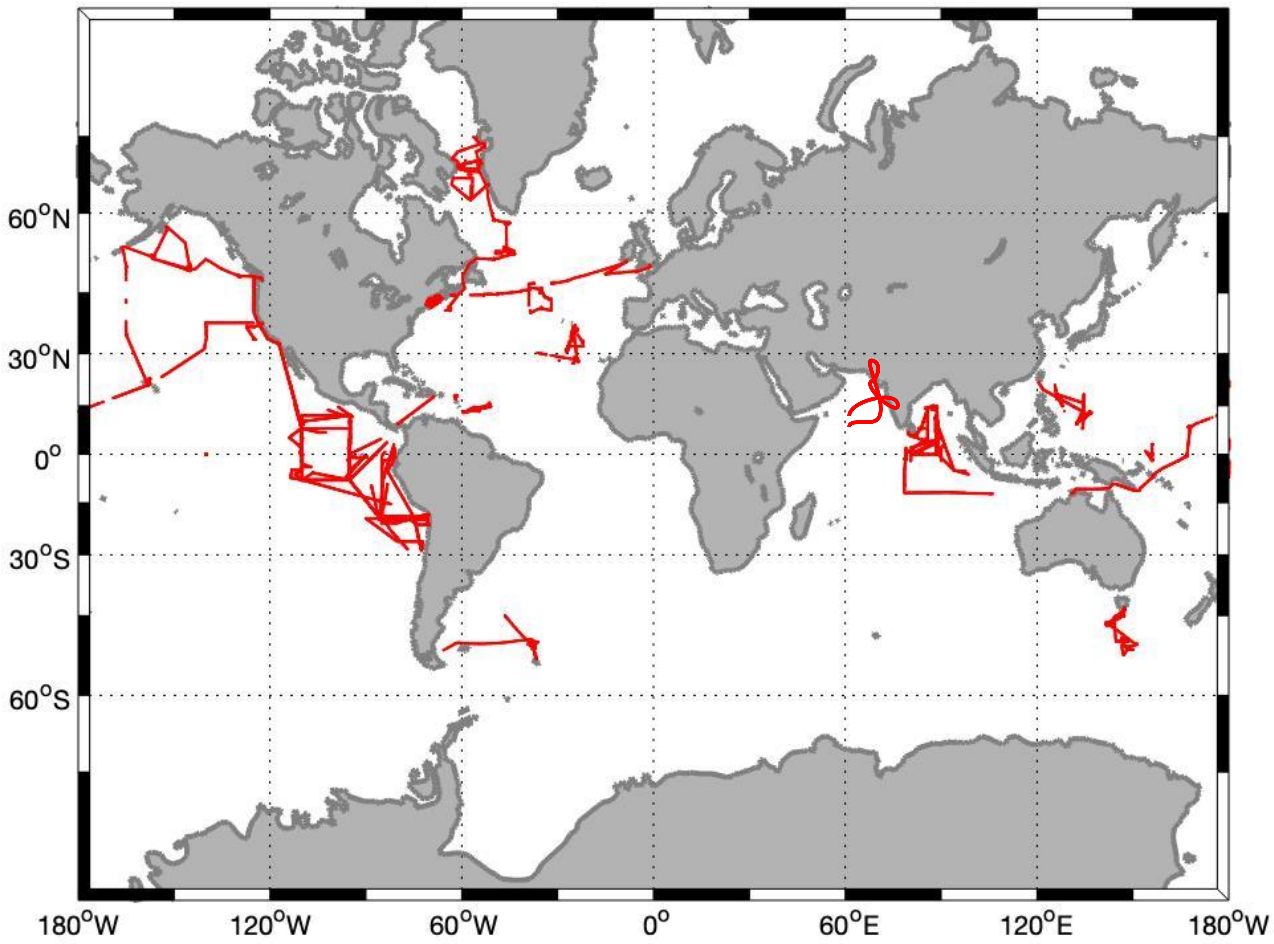
  33 years

  20K+ hrs of "good data"

  @ 1 hr, 10 min

  surface ocean + atmos., fluxes

- Also ERDAPP: https://marineflux-erddap.coaps.fsu.edu/erddap/index.html



Bulk Flux Conclusions and Recommendations from Observational Point of View

- COARE bulk flux formula are well-constrained with observations; many updates have been made since TOGA-COARE (Fairall et al) 1996, 1997 (v3.0 Fairall et al. 2003, v3.5 Edson et al. 2013, v4.0 soon)
  - All stability states; all latitudes; higher and lower winds; small-scale physics
  - Check out our github: https://github.com/NOAA-PSL/COARE-algorithm (NOAA+WHOI)
  - Gustiness factor can be more sophisticated, scale-aware, height aware (we're working on it)

- COARE physics holds even at smallest scales (several meters) according to observations, and theory backs up that experience (just stay near surface, e.g. < 50 m)

- More focus should be placed now on **improving coupled air-sea boundary layer parameterizations (and other schemes that impact them)** that lead to longstanding biases **near-surface model mean state variables**
  - How would our models behave if we got the *right fluxes* for the *right reasons*? -> obs provide model diagnostics
  - Proposed Butterfly satellite mission targeted improved mean state inputs to COARE: https://nasa-butterfly.github.io
  - We need more observations of high-vertical/temporal resolution vertical profiles through atmosphere, above ocean/flux data from remote sensing
- … and in **using LES and single column models with confidence to bridge scales** between process-level physics/observations and seasonal to subseasonal coupled GCMs or medium-range NWP (Chen et al. 2025, Reichl et al. 2024, Zhu et al. 2025), to guide parameterization improvement

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