Satellite Observations at Air-Sea Interface & Value for Ocean Sciences

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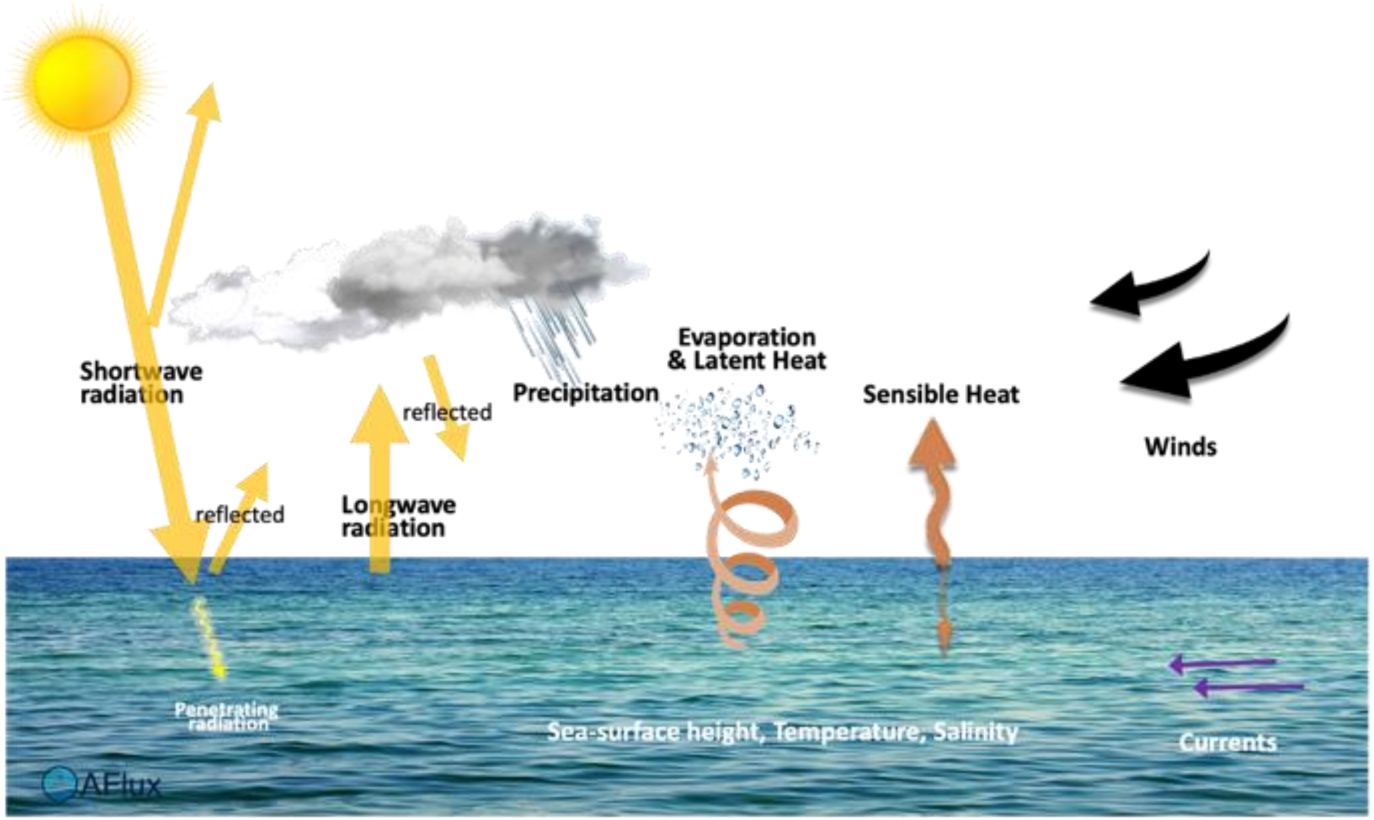
WOODS HOLE
OCEANOGRAPHIC
INSTITUTION

At the ocean surface, heat, moisture, momentum, and gases are constantly exchanged between the atmosphere and ocean.



Yu (2019)

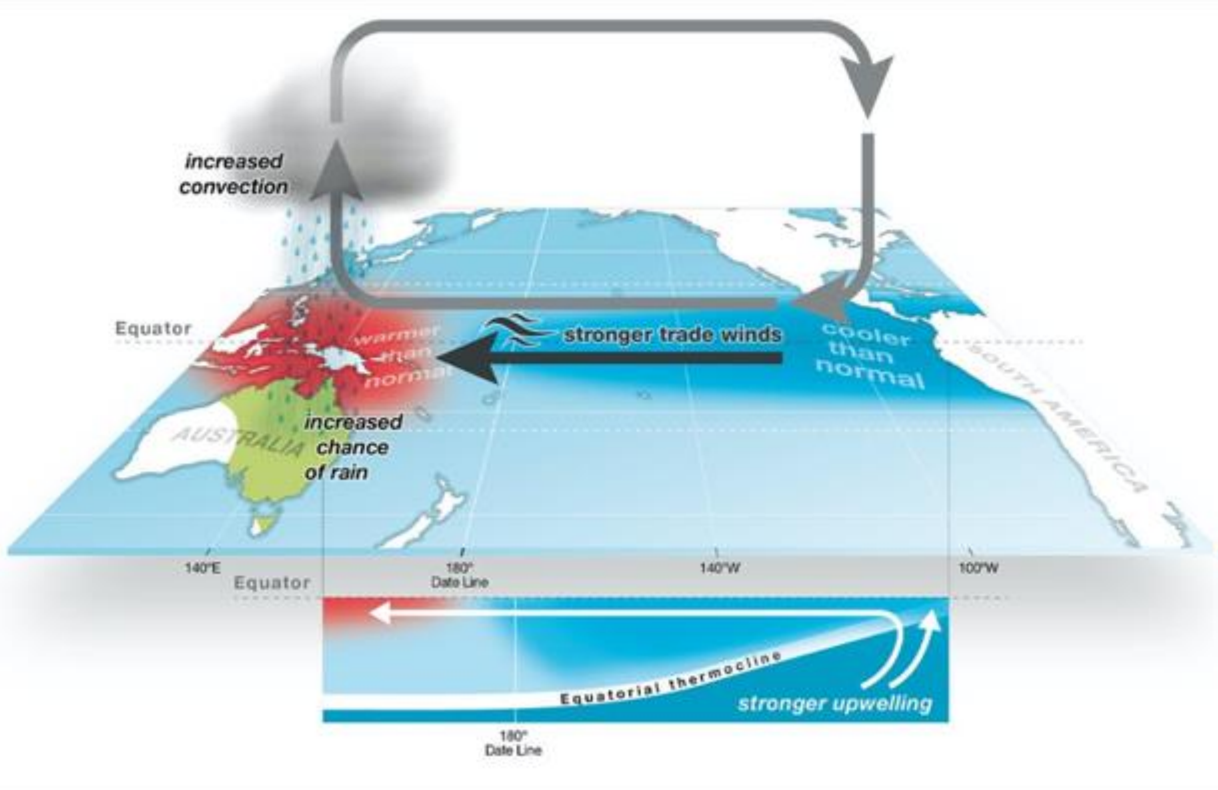
Main topics

1. What are surface fluxes and how are they used in ocean applications?

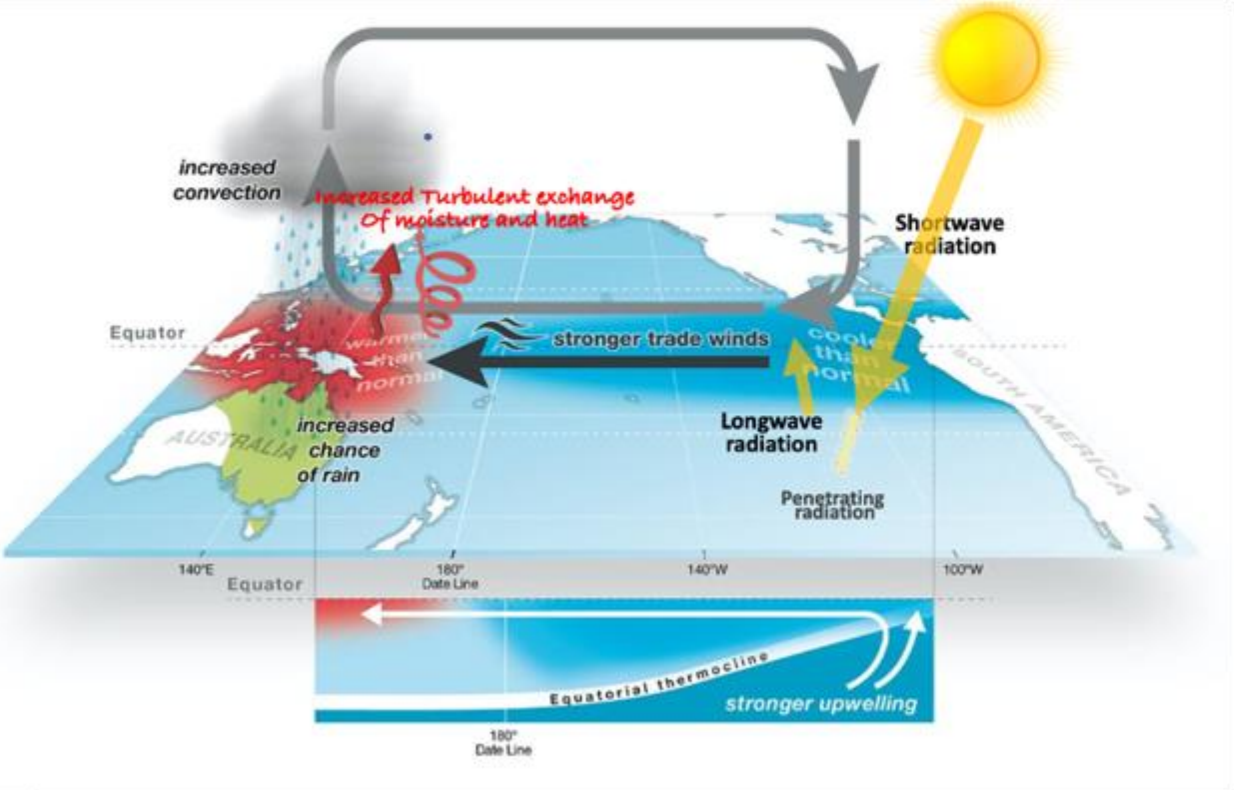
2. How are surface fluxes determined from satellite remote sensing?

3. Observed change and variability of surface forcing in the Indian Ocean and marginal seas.

Wind stress and surface heat exchange (fluxes) are the driver of ocean circulation and variability…… although climate events are most often depicted in terms of changes of SST, wind, convection.

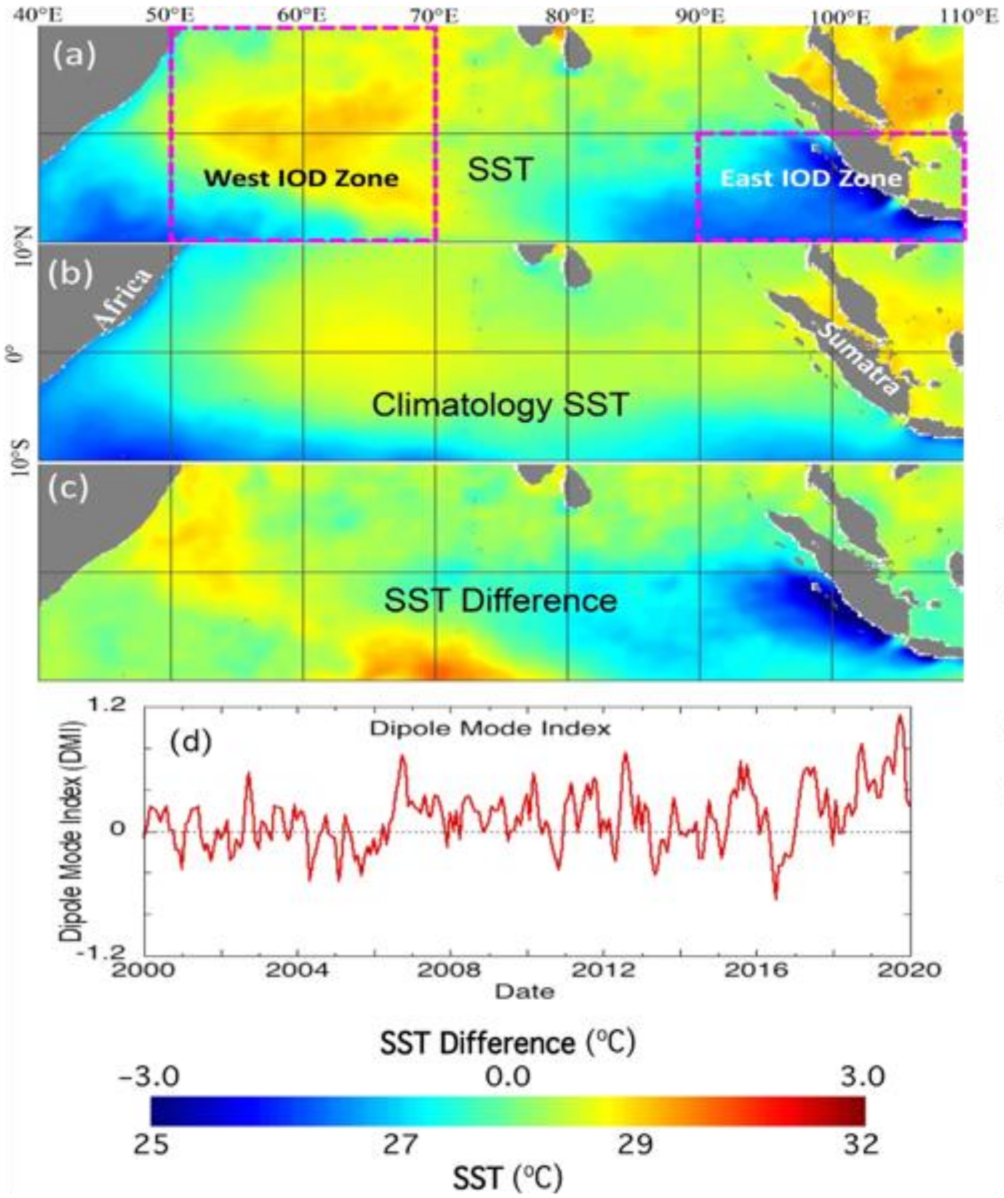


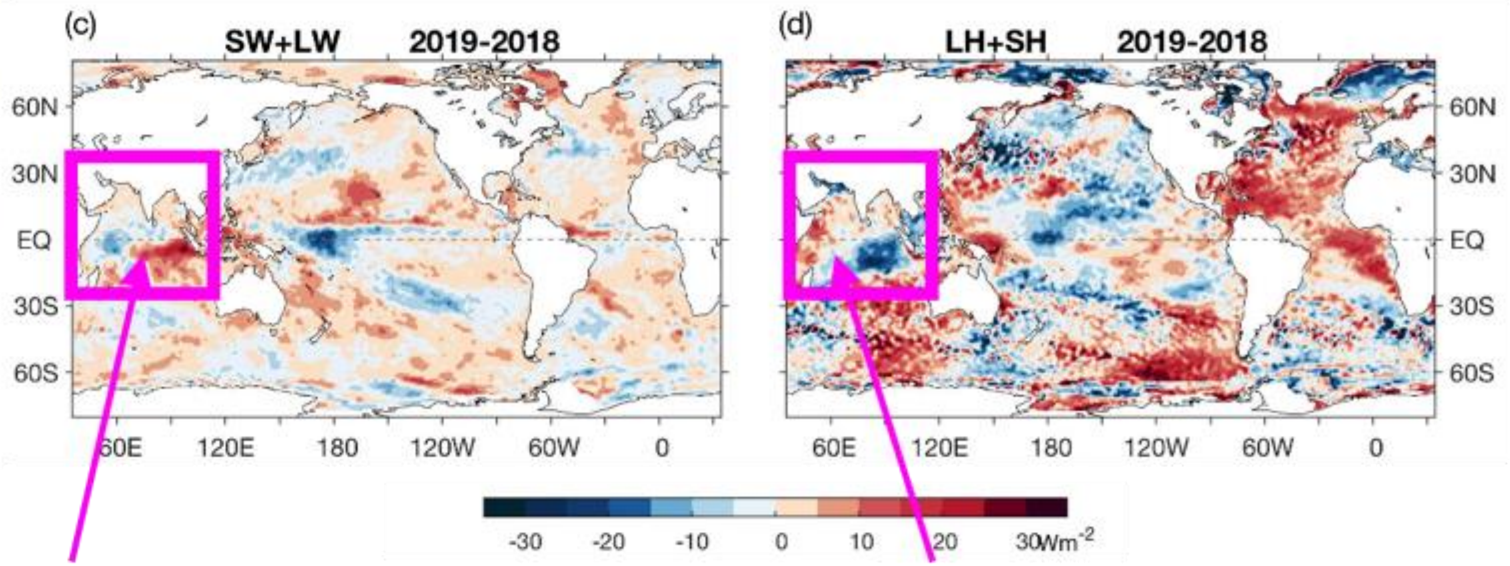
- an Indian Ocean Dipole event



- Inclusion of surface radiative and turbulent fluxes in depiction of an Indian Ocean Dipole event

SST and Surface fluxes during the 2019 IOD





Increased net radiation into the eastern basin due to reduced clouds

Increased turbulent heat loss in the western basin due to increased SST

Shi and Wang (2021)

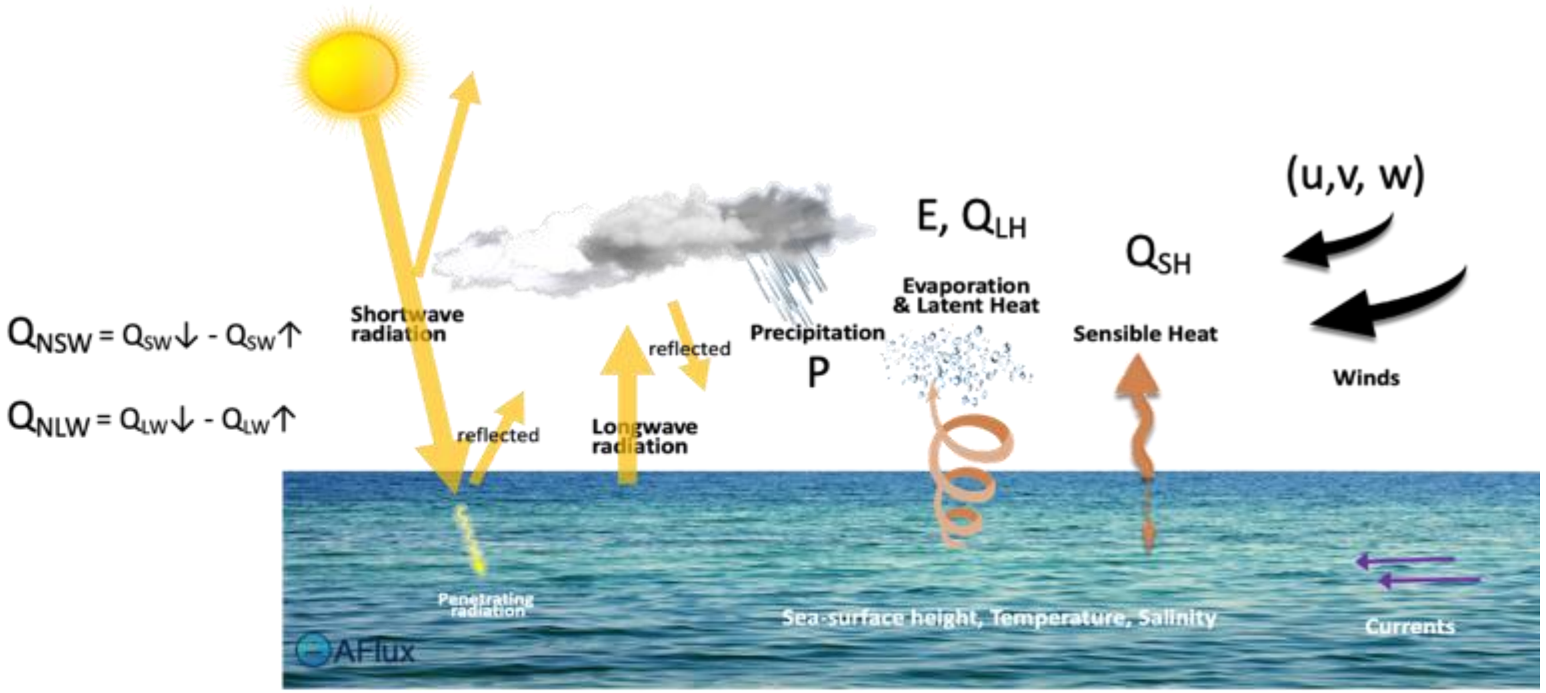
Yu et al. (2020) "State of the Climate in 2019"

Surface heat, freshwater, and momentum fluxes

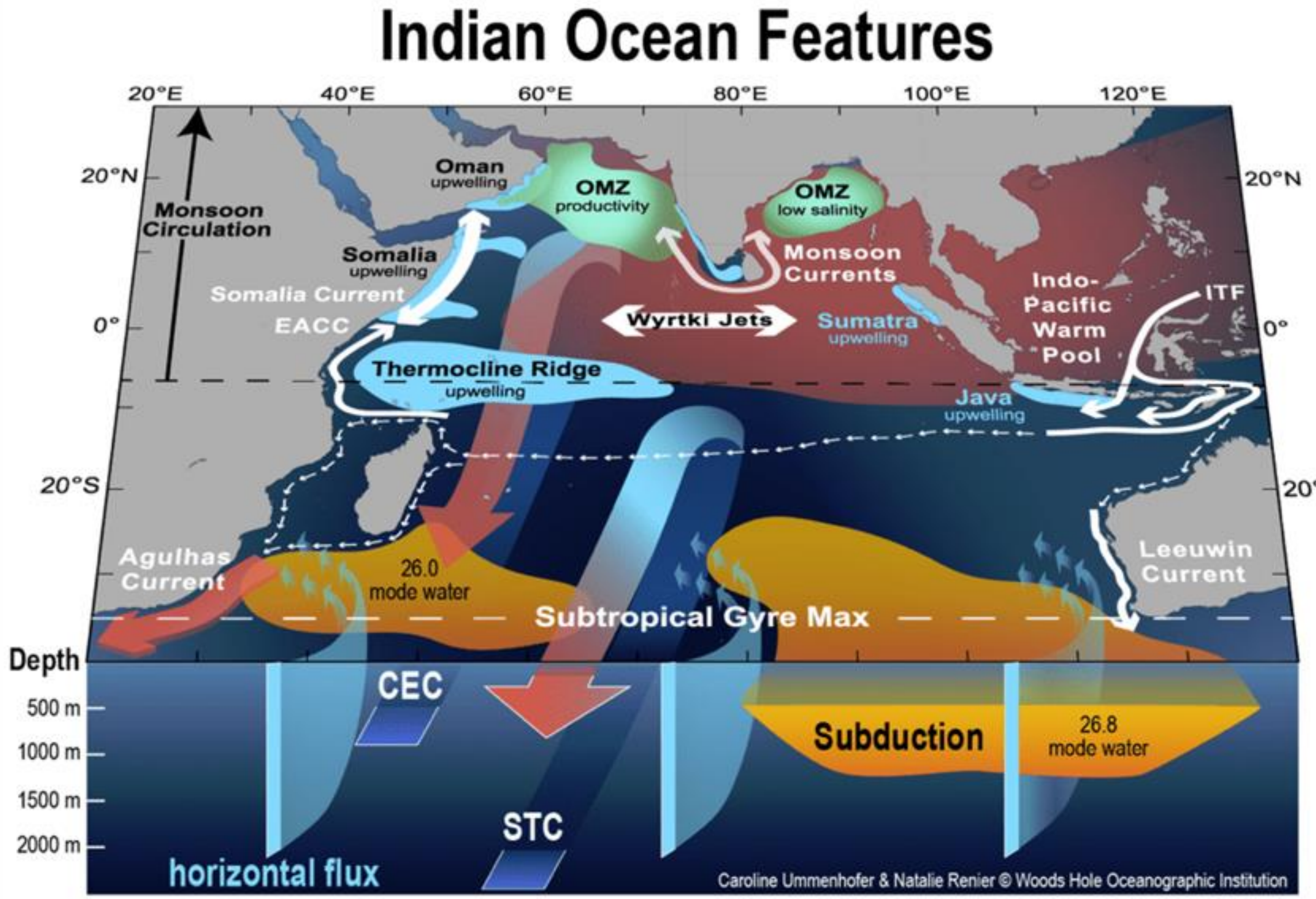
Momentum flux (wind stress): $(\tau_x, \tau_y) = \rho c_d w(u, v)$

Net Freshwater Flux (FW): $FW = E - P$

Net Heat Flux: $Q_{net} = Q_{NSW} - Q_{NLW} - Q_{LH} - Q_{SH}$

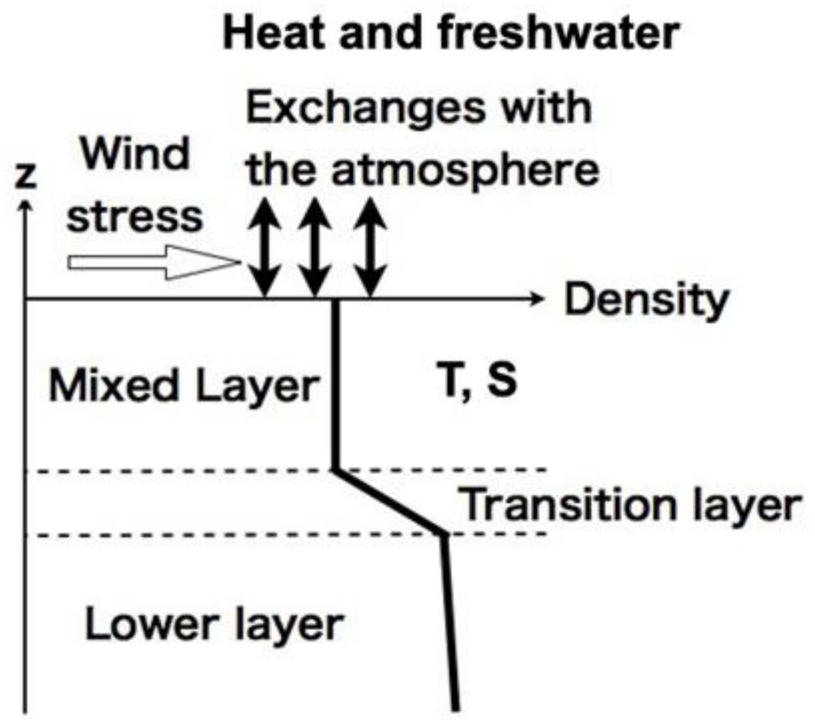


Wind stress and surface fluxes are virtually the forcing for all the processes named in the picture.



“A Road Map to IndOOS-2” (Beal et al. 2020)

Oceanic surface mixed layer is subject to direct wind and buoyancy (heat and freshwater) flux forcing



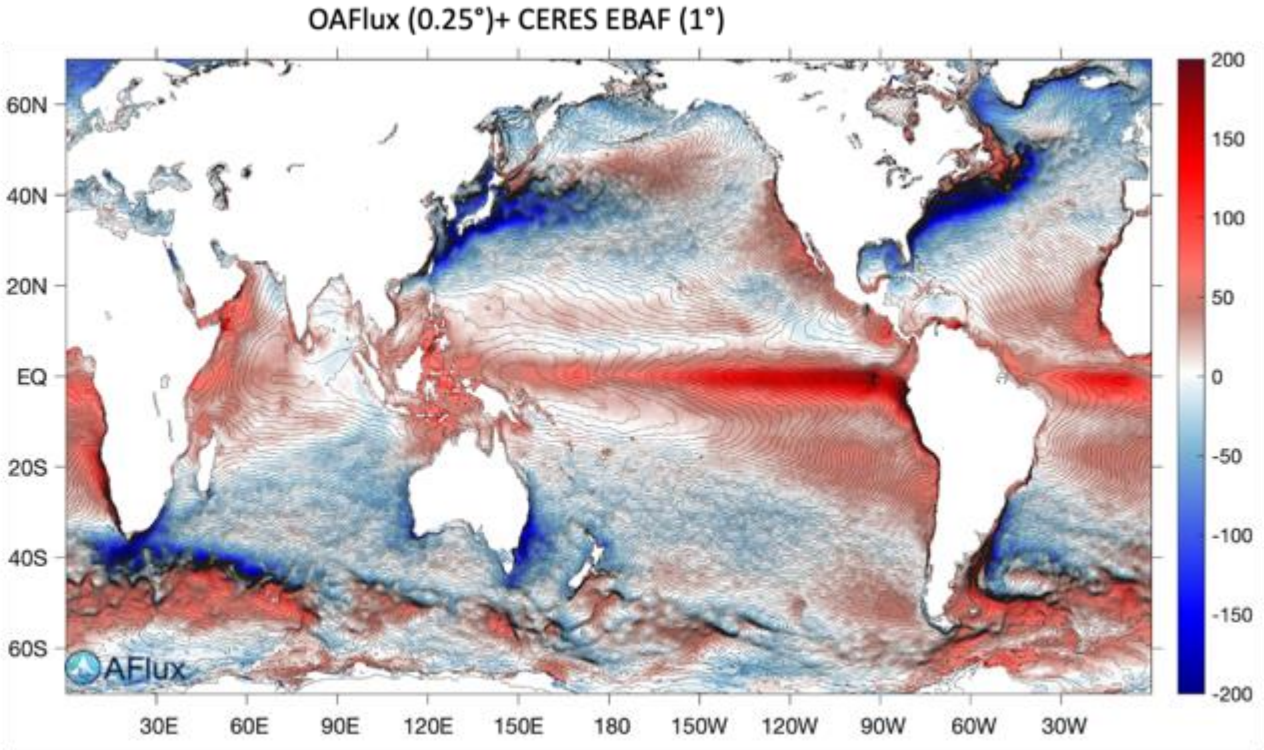
Mixed-layer temperature budget:

$$\frac{\partial T}{\partial t} = - \frac{Q_{net}}{\rho c_p h} - \vec{\mathbf{u}} \cdot \nabla T + R_T$$

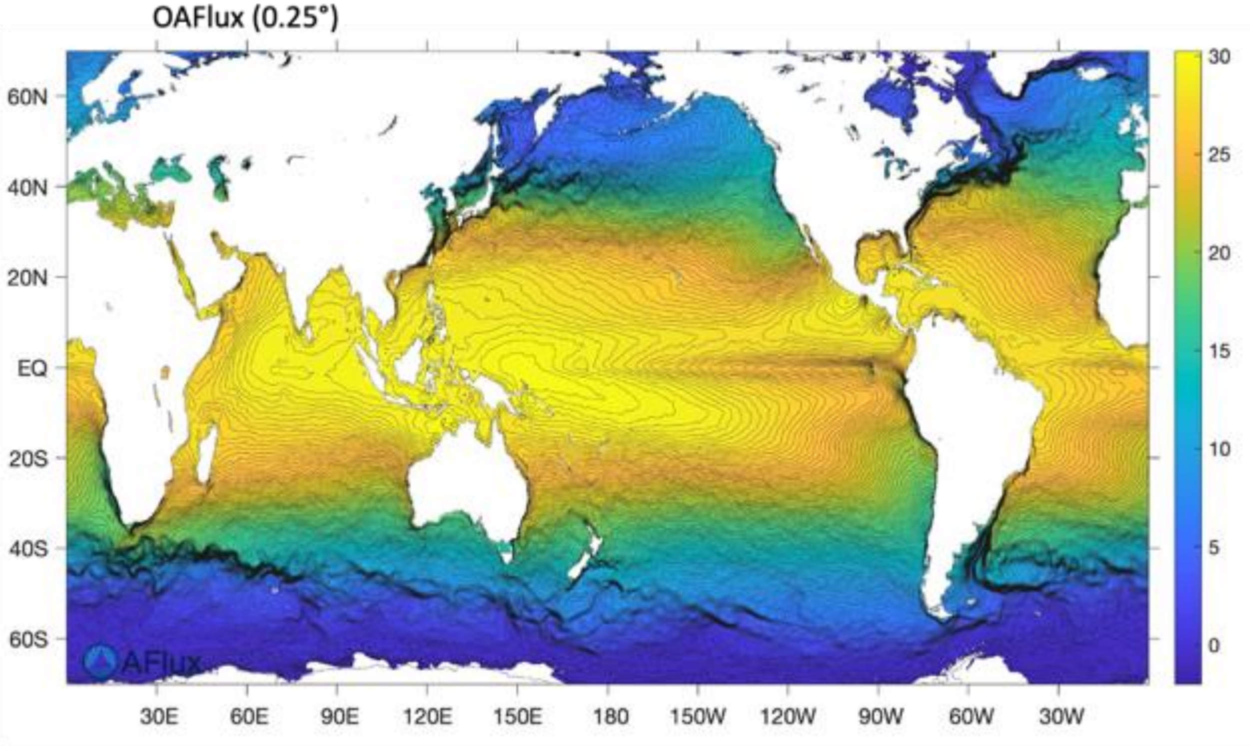
Mixed-layer sallinity budget:

$$\frac{\partial S}{\partial t} = - \frac{S_0(E - P)}{h} - \vec{\mathbf{u}} \cdot \nabla S + R_S$$

Annual Mean
Qnet (colors)+ SST (contours)



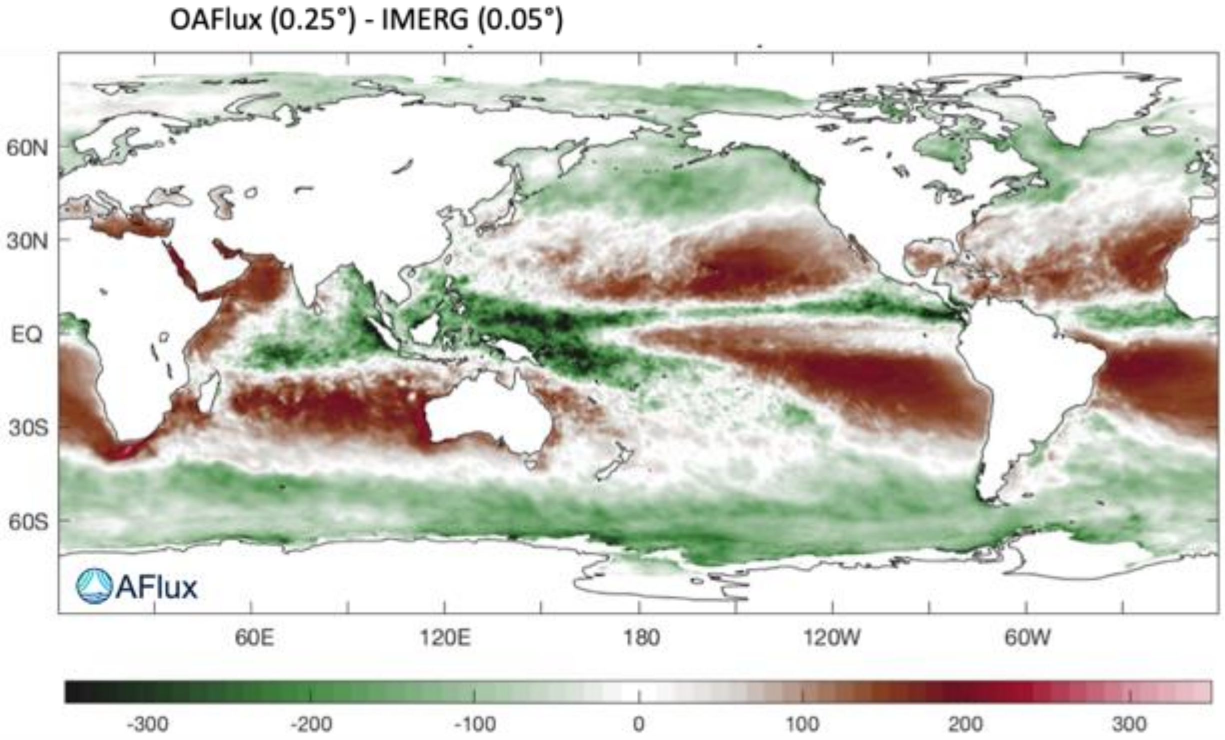
Annual Mean SST



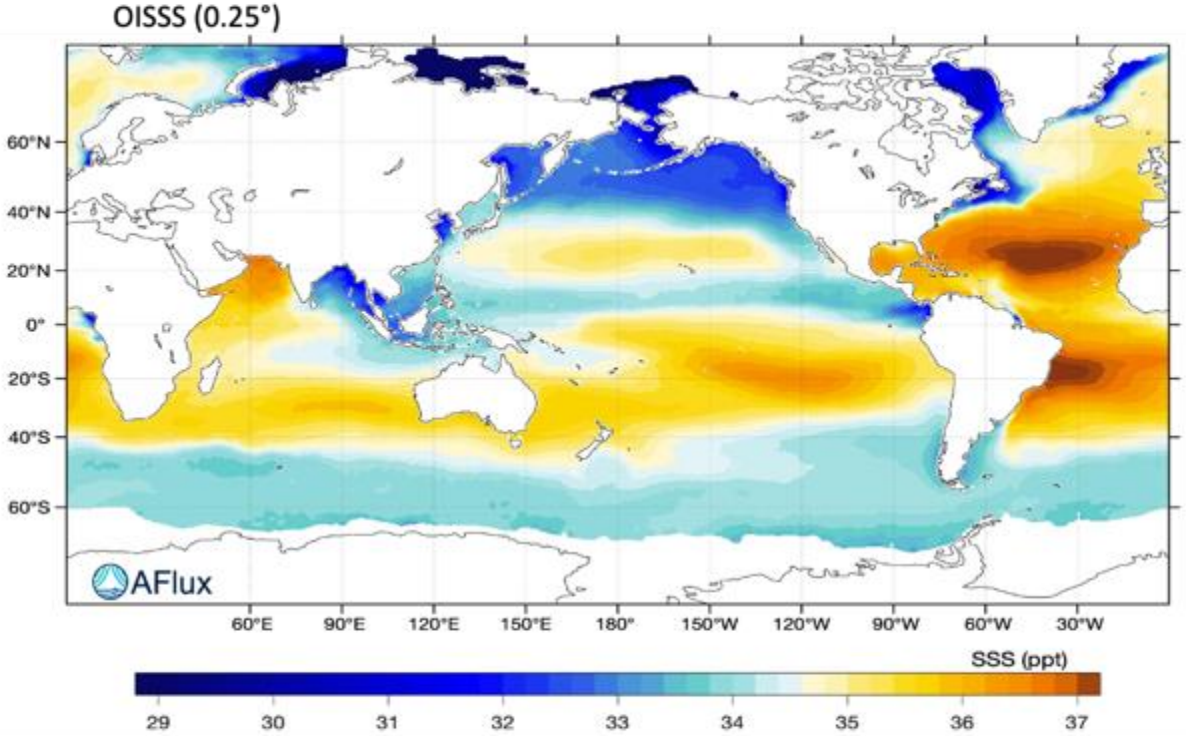
From WHOI OAFlux project (http://oaflux.whoi.edu)

Ocean salinity and water cycle

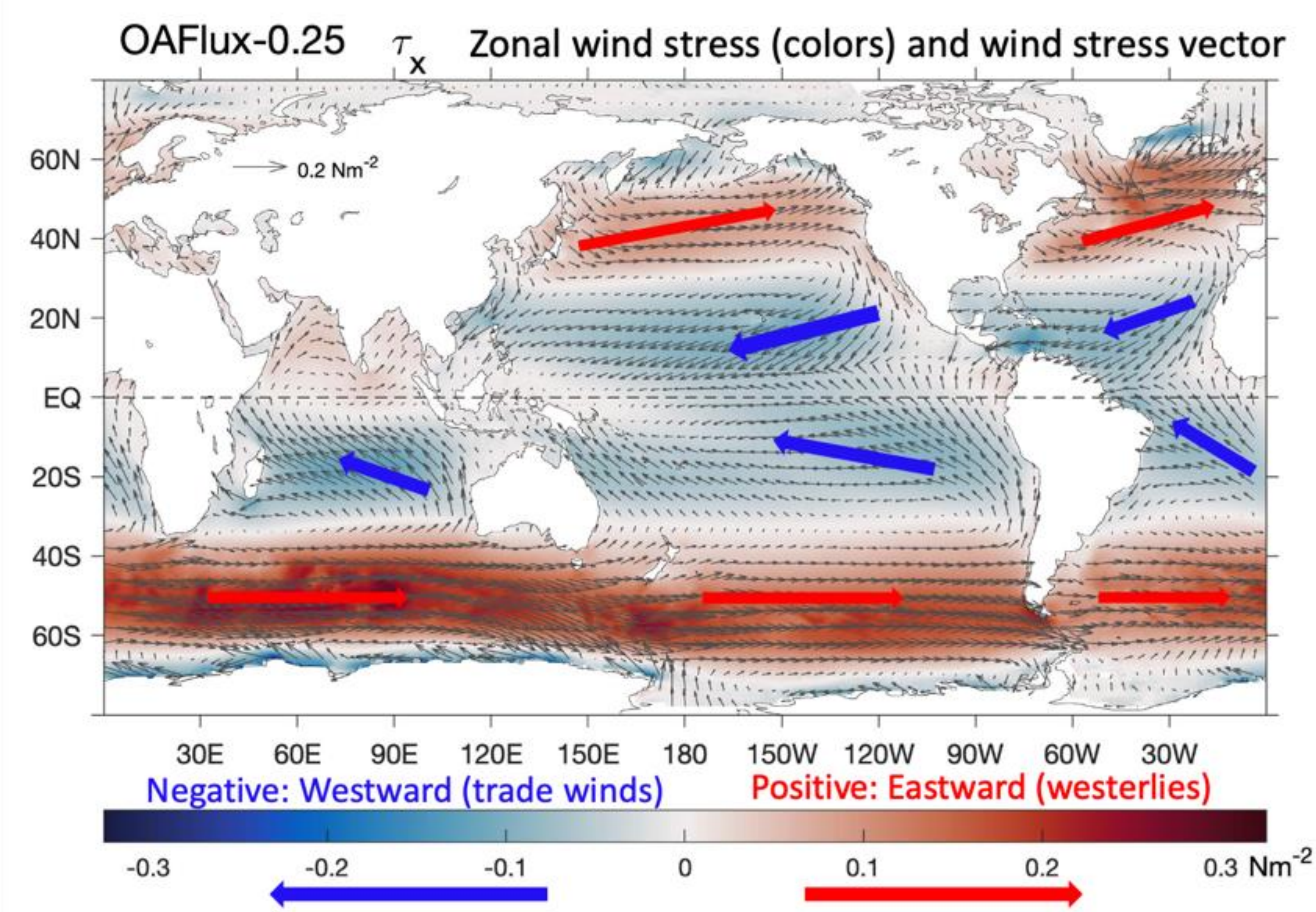
E – P



Sea Surface Salinity



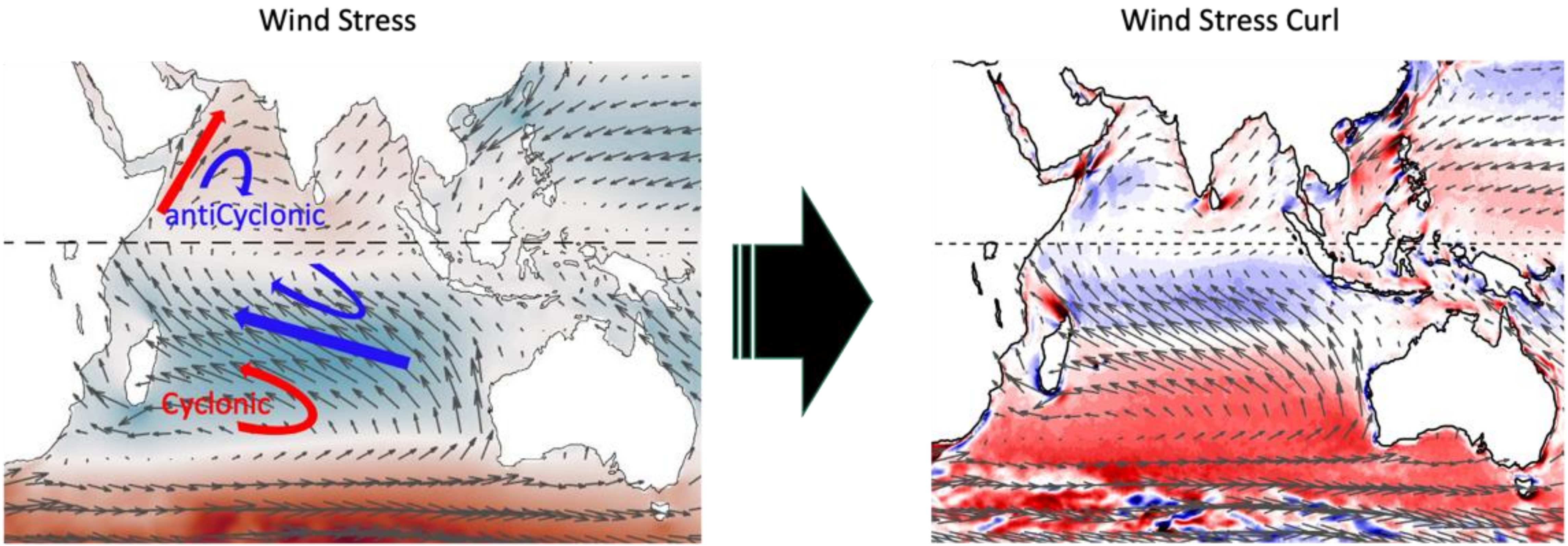
Satellite wind observations



Wind driven circulation: Wind stress curl

Wind stress (τ_x, τ_y) varies spatially. Wind stress curl measures the spin of the wind stress.

- Use your right hand
- Counterclockwise (cyclonic) = thumb up = positive curl
- Clockwise (anticyclonic) = thumb down = negative curl



Wind stress curl and Ekman pumping (w_{EK}): convergence/divergence

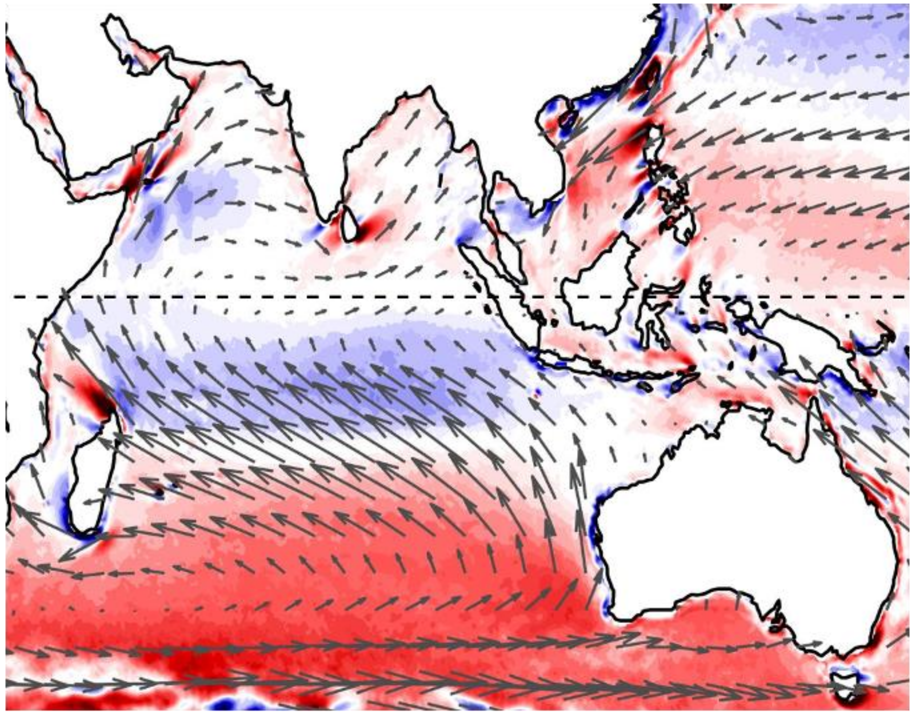
$$w_{EK} = \partial/\partial x(\tau^{(y)}/f\rho) - \partial/\partial y(\tau^{(x)}/f\rho) = \hat{k} \bullet \nabla \times (\vec{\tau}/f\rho)$$

In the Northern hemisphere,

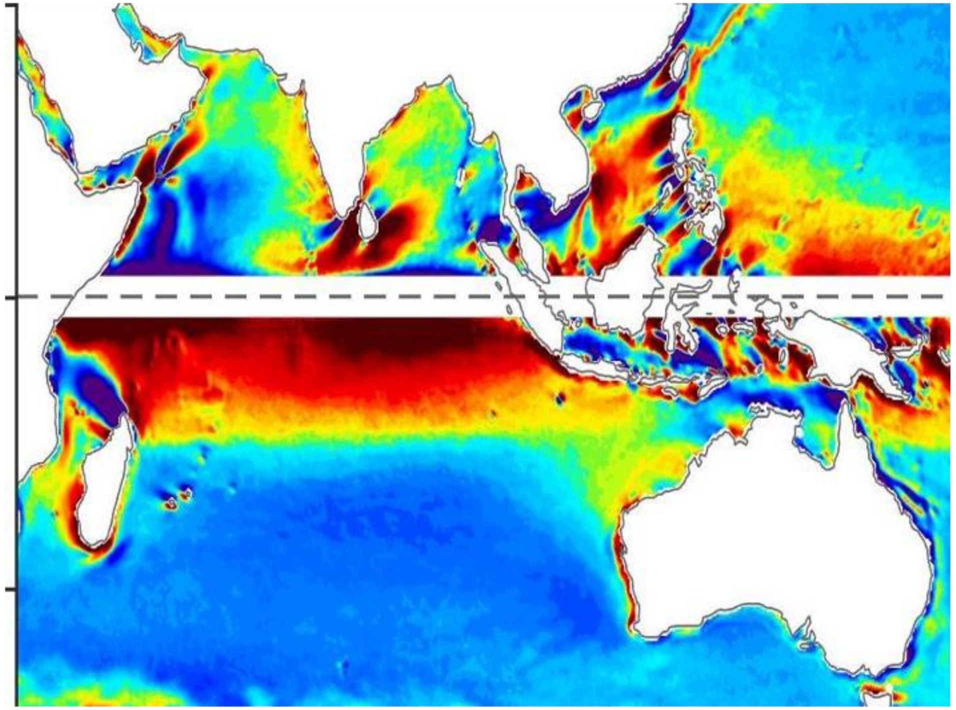
- positive wind stress curl causes surface divergence, inducing upwelling of surface waters → Ekman upwelling (suction), positive
- Negative wind stress curl causes surface convergence, pumping surface waters downward. → Ekman downwelling (pumping), negative

In the Southern hemisphere, the Coriolis parameter changes sign across the equator, giving oppositive directions for Ekman vertical velocity.

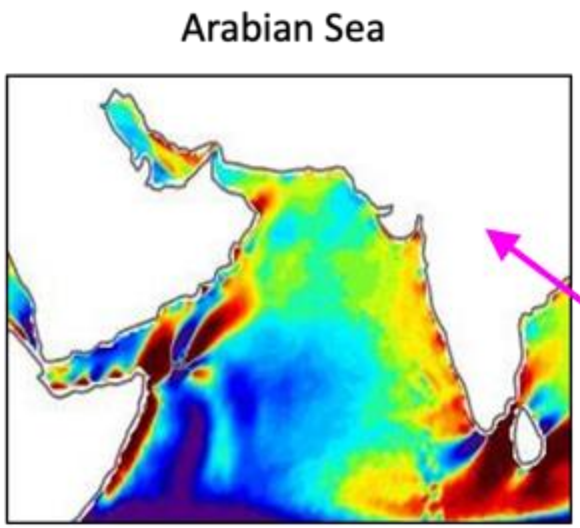
Wind Stress Curl

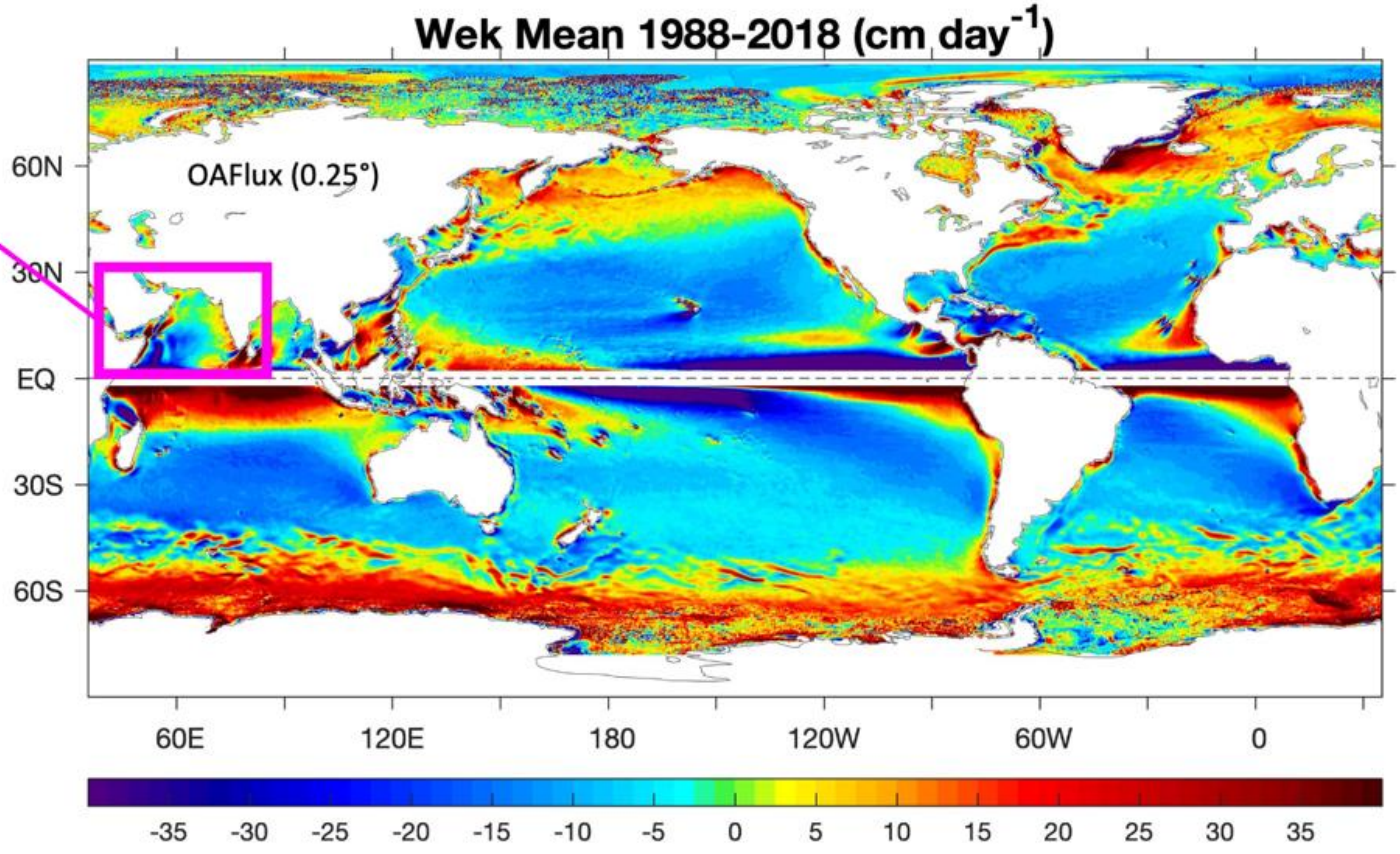


Ekman Upwelling and Downwelling



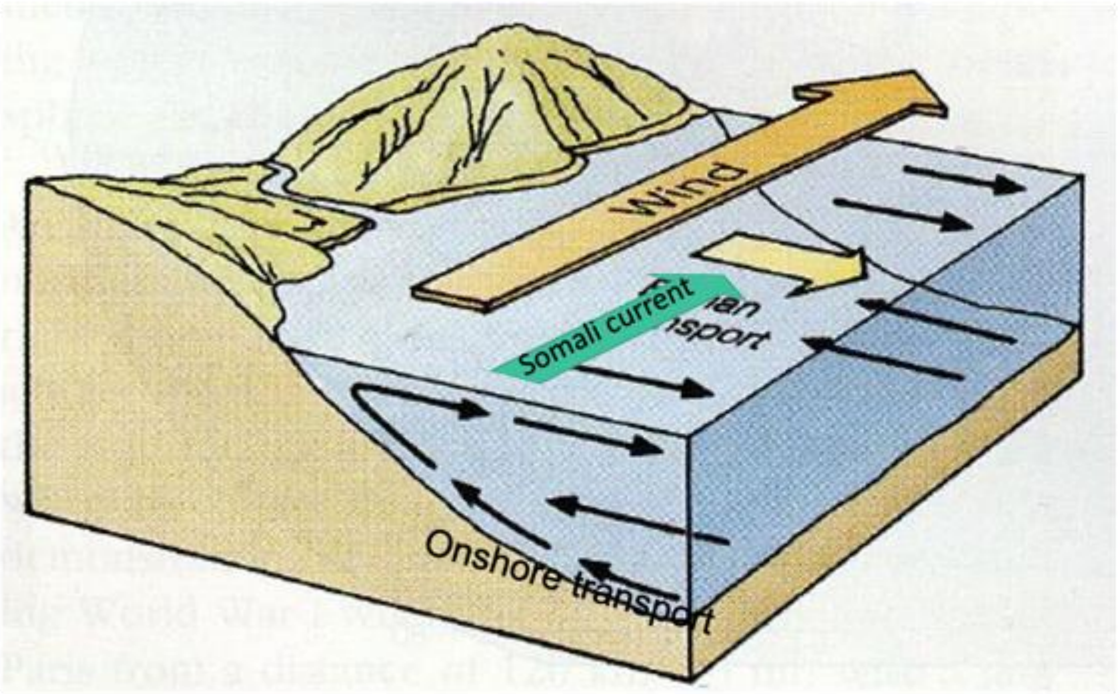
Ekman upwelling (positive) and downwelling (negative)





Wind exerts stress, ($\boldsymbol{\tau}_x$, $\boldsymbol{\tau}_y$), on the ocean surface, driving ocean circulation via frictional Ekman transport

Ekman transport and upwelling



Ekman transport is vertical integral of Ekman flow in the entire Ekman layer

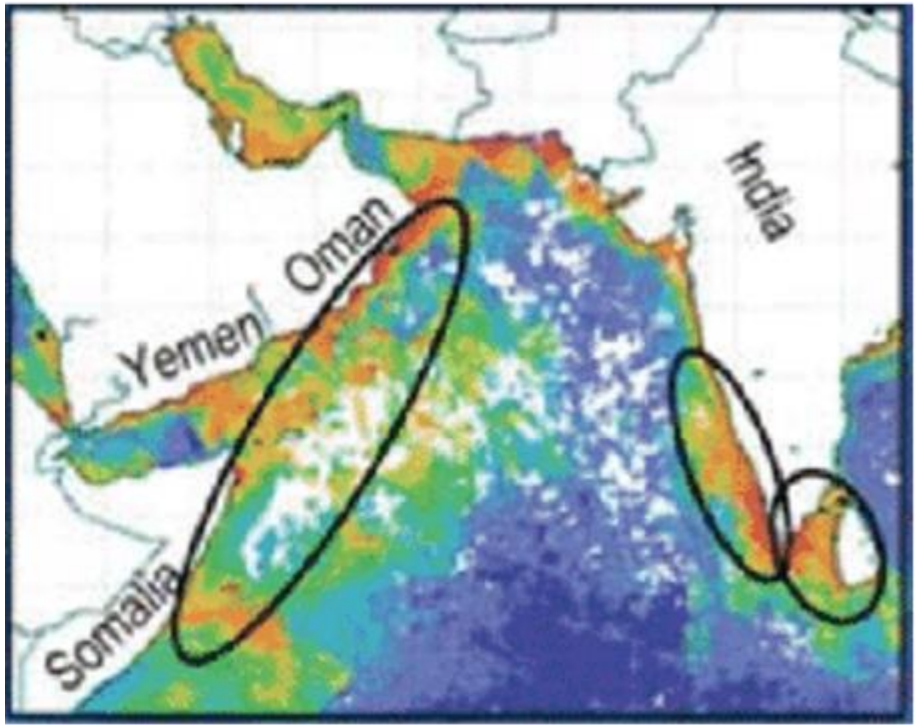
$$U_E = \int_{-H_{mix}}^{0} u_E dz = \frac{\tau^y}{\rho_0 f},$$

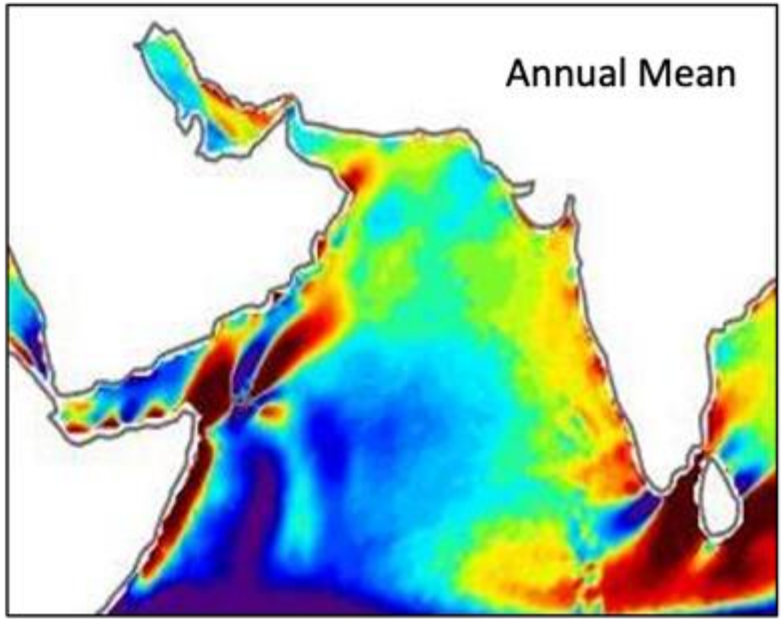
$$V_E = \int_{-H_{mix}}^{0} v_E dz = -\frac{\tau^x}{\rho_0 f}.$$

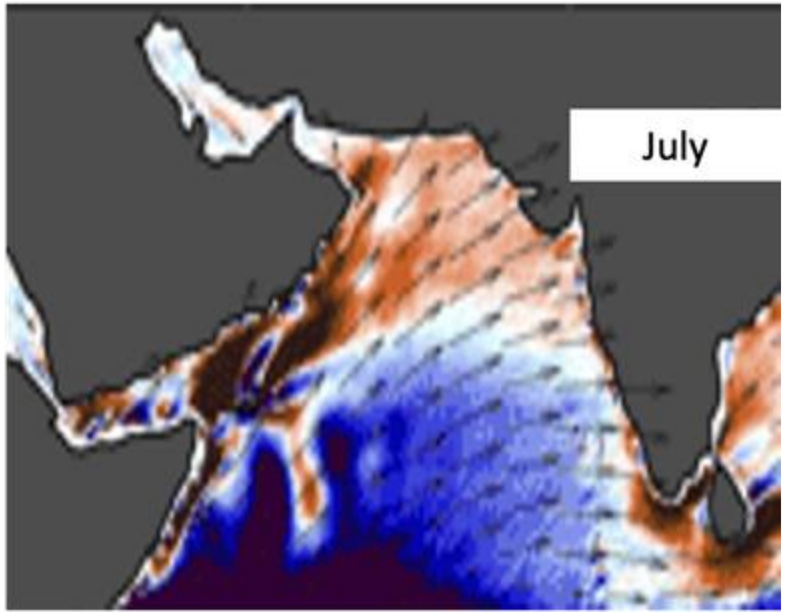
Somali coastal upwelling during the Southwest Monsoon (July – August)

Evidence of Ekman upwelling

Seasonal coastal upwelling regions as seen in satellite-derived elevated chlorophyll-a concentrations. Data source: Giovanni (NASA).

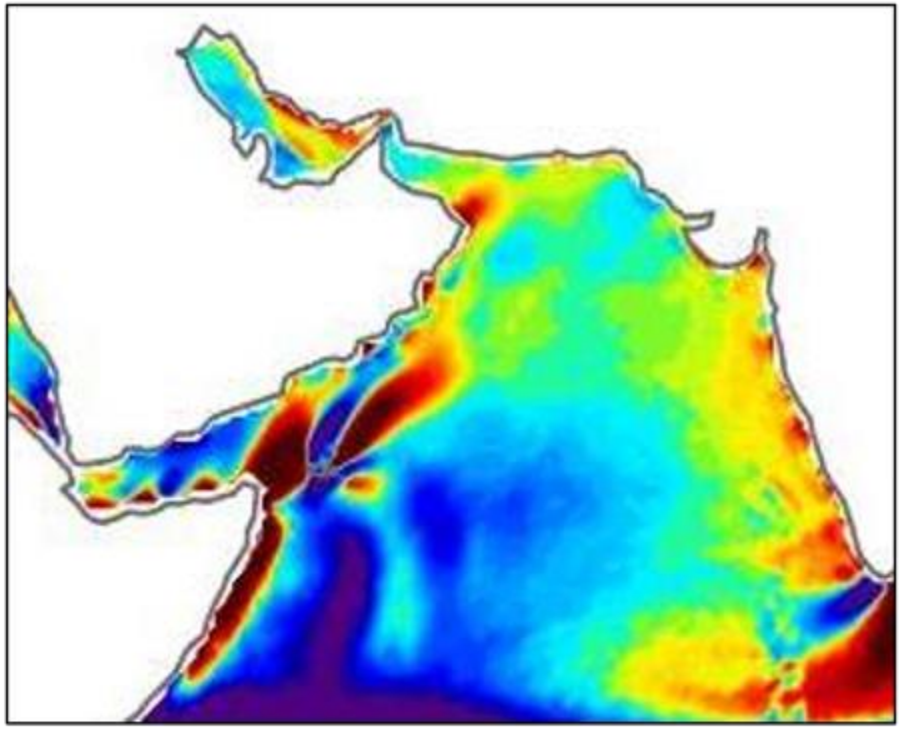




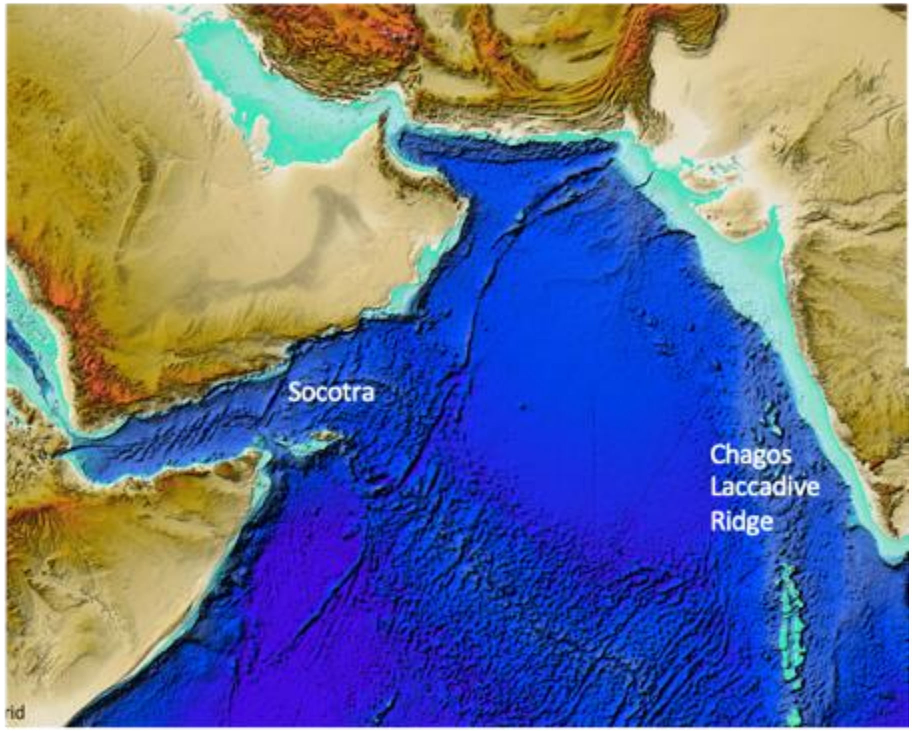


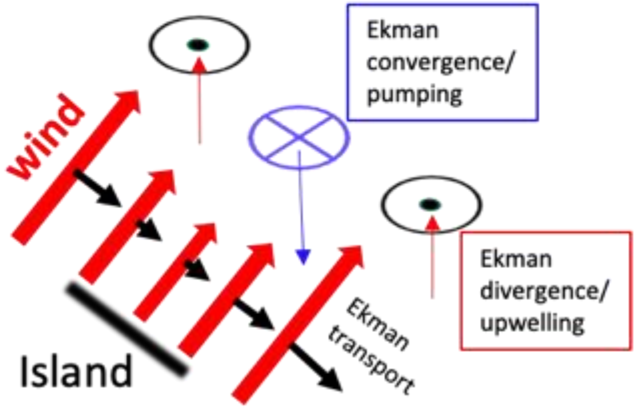
Ekman upwelling (positive) and downwelling (negative): Effect of topography

Annual Mean

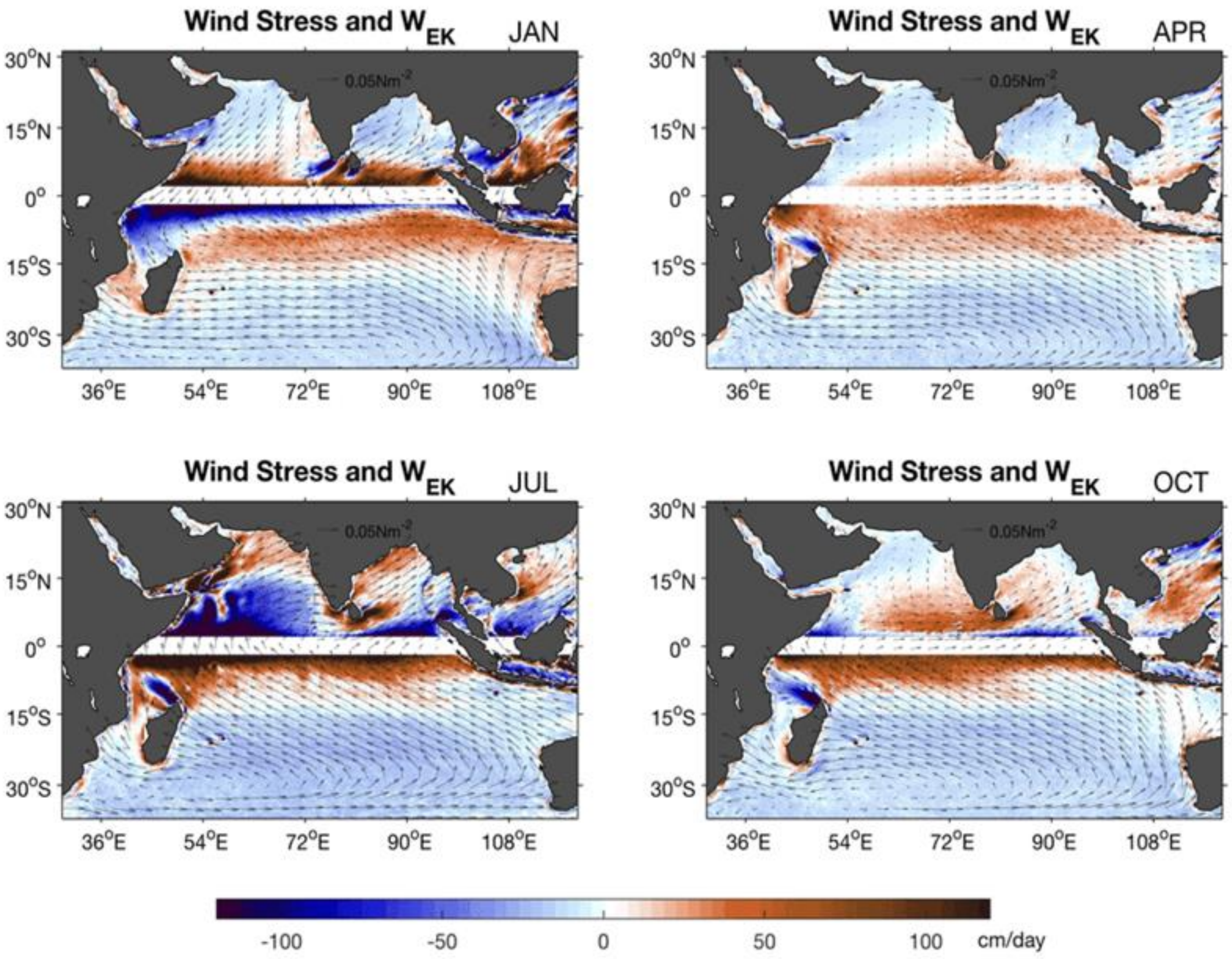


Topography





Seasonal change



Main topics

1. What are surface fluxes and how are they used in ocean applications?

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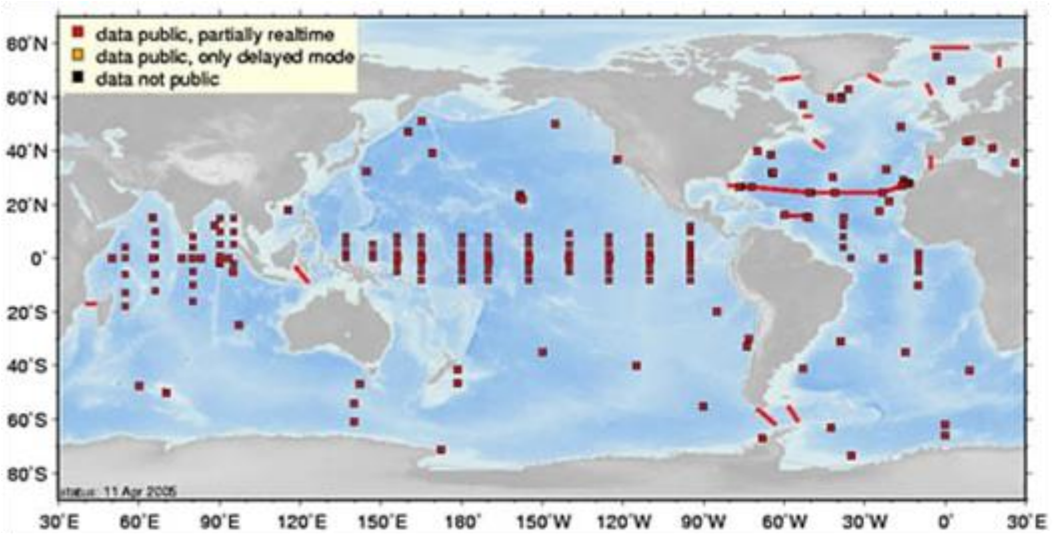
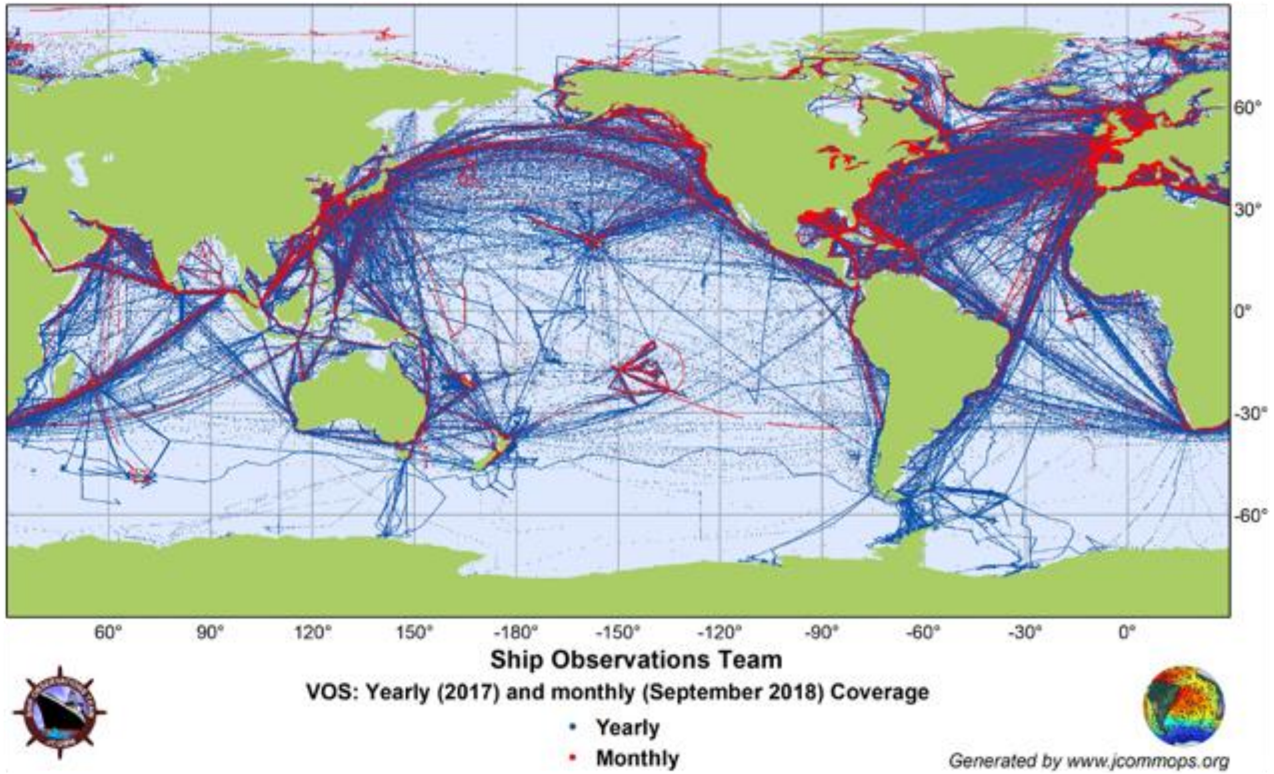
3. Observed change and variability of surface forcing in the Indian Ocean and marginal seas.

Surface air-sea observations from moored buoys and ships



(Bob Weller, WHOI)



Coverage of the ocean vessels participating in the VOS Scheme (including both character-based and BUFR reports) on monthly (red, September 2018) and yearly (blue, 2017) bases. While approximately 2,000 vessels contributed in total, more than 90% of the data are submitted by fewer than 600 ships.

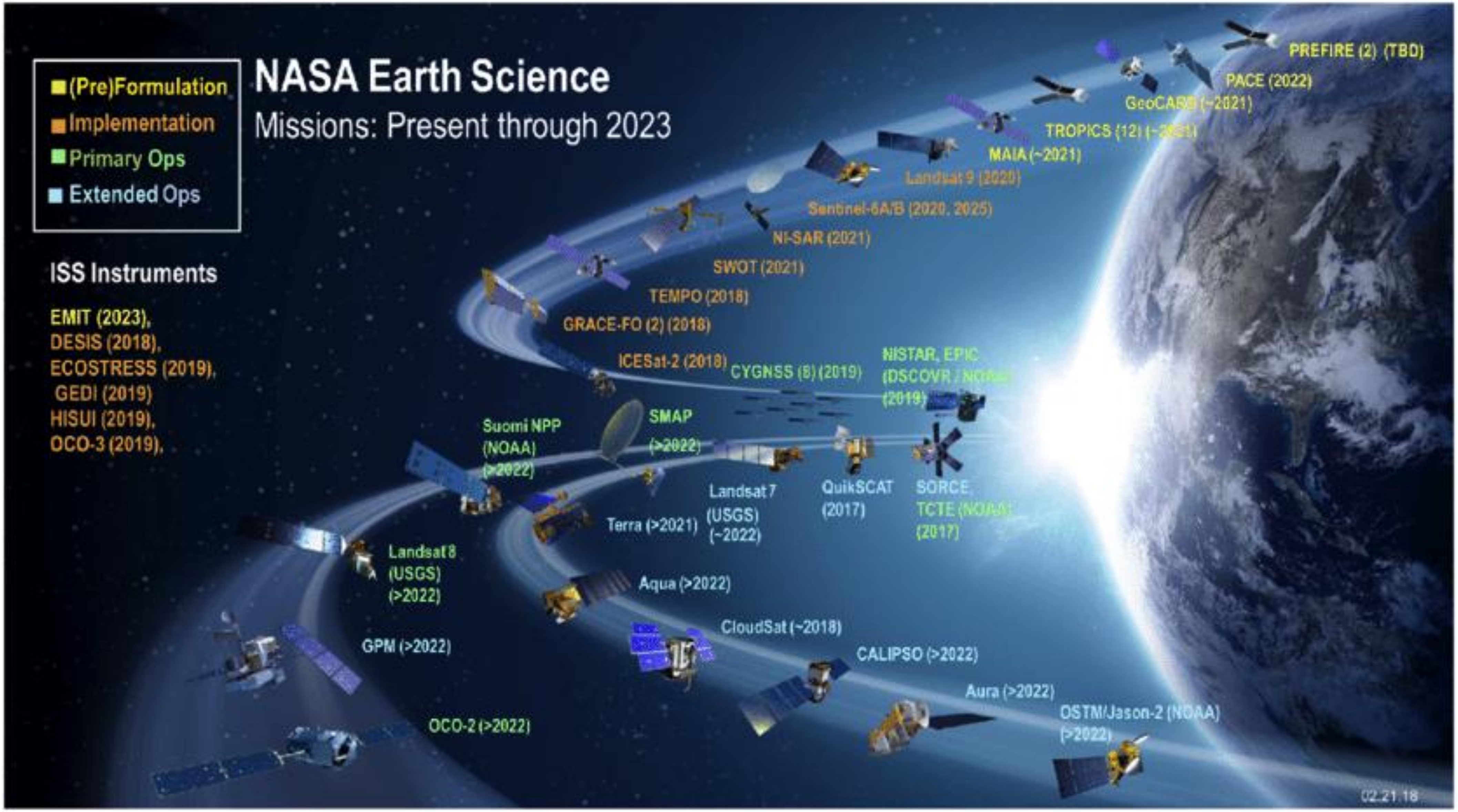
Smith et al. 2019

Example of different types of in situ air-sea observing platforms

Clockwise from upper left: Norwegian weathership Polarfront (image courtesy of Norwegian Meteorological Institute) (Yelland et al., 2009); NOAA ship Ron Brown (from www.noaa.gov); WHOI Air-Sea Interaction Tower (image courtesy Jayne Doucette Woods Hole Oceanographic Institution); RSMAS "ASIS" spar buoy (Graber et al., 2000); Saildrone, Inc., "Saildrone" ASV (image courtesy of Saildrone, Inc.; www.saildrone.com), Liquid Robotics "Wave Glider" ASV (from www.liquid-robotics.com with modifications by UW/APL), UW/APL "SWIFT" drifter (Thomson, 2012); JAMSTEC TRITON buoy (from JAMSTEC, www.jamstec.go.jp); and, in the center, the WHOI SPURS buoy (Farrar et al., 2015).

(from Cronin et al. 2019)

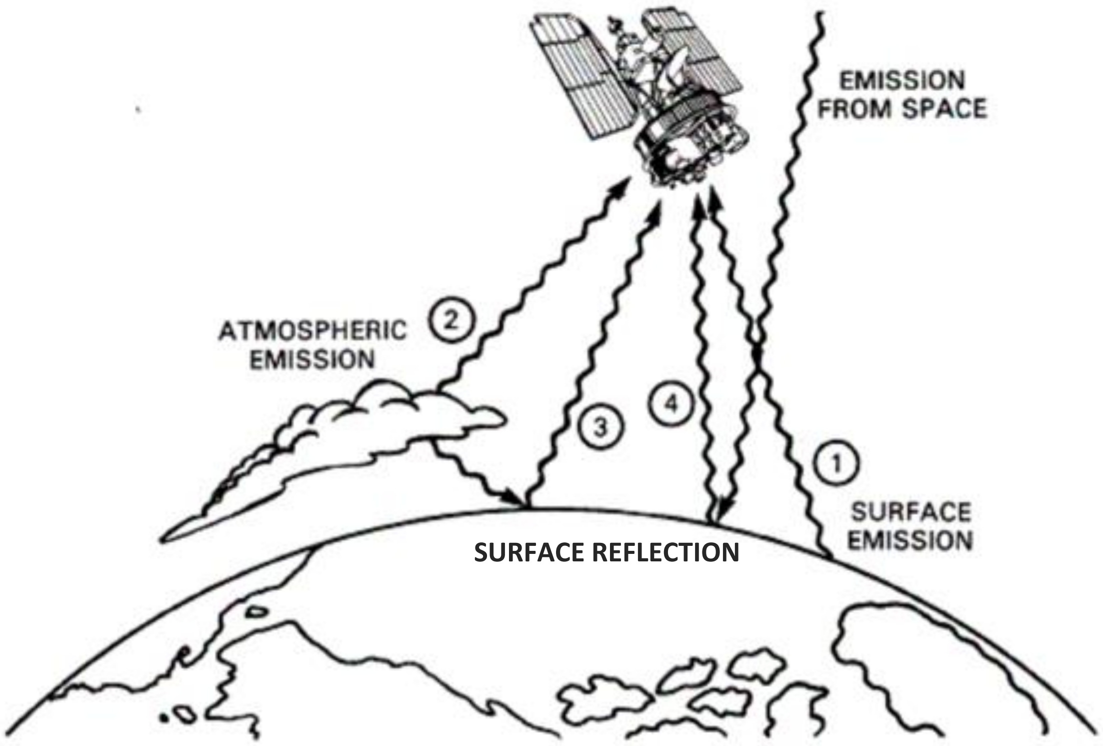
Earth Science Satellite Remote Sensing



Air-sea fluxes are not remotely sensed by satellite.

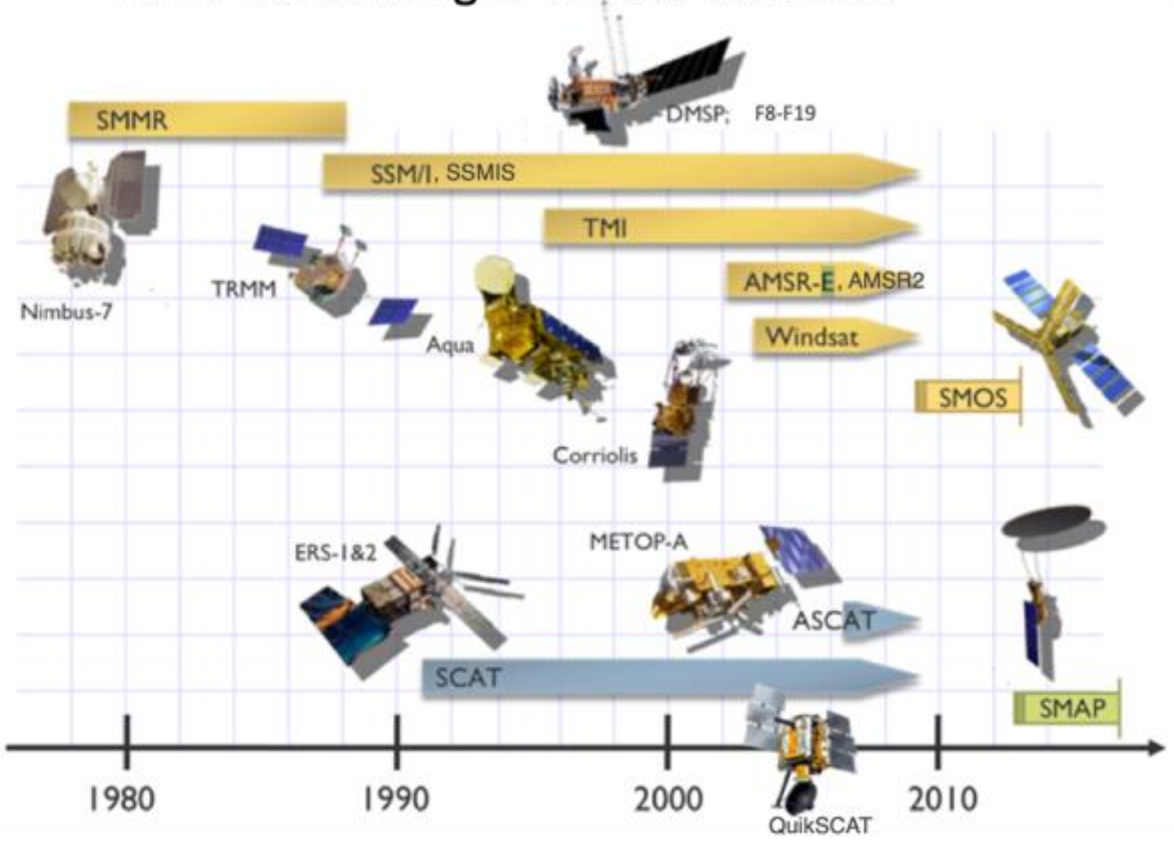
Passive Sensor

measures the self-emission of a **surface**



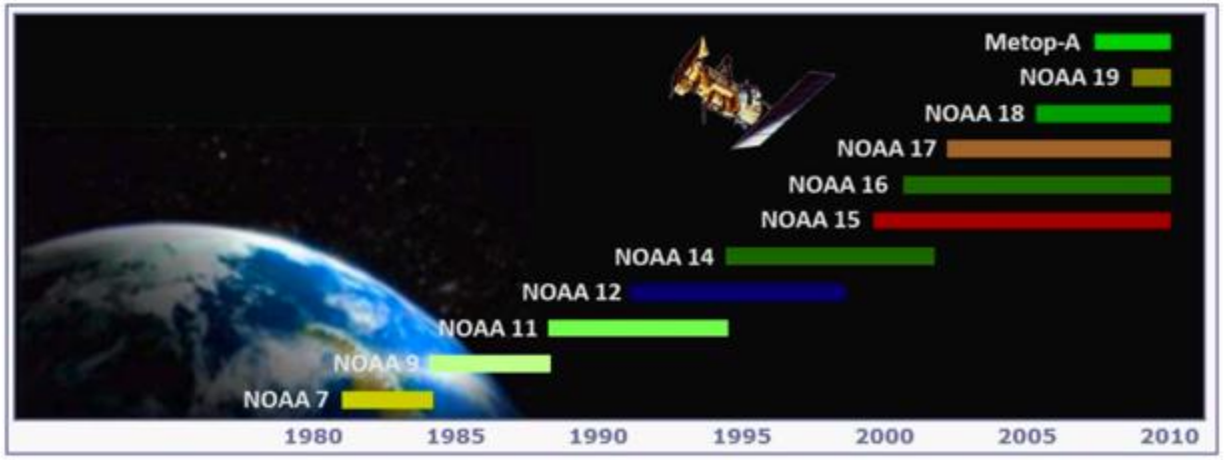
- Air-sea flux occurs when there is a difference (or gradient) in temperature, humidity, momentum, gases, between the sea surface and the near-surface air.
- Satellite passive sensors measure the self-emission of a **surface**. The exchange processes neither emit nor absorb electromagnetic radiation, and so they are not observed by satellite.
- Air-sea fluxes are computed from bulk flux parameterizations using those variables that can be observed: wind, sea and air temperature, relative humidity, barotropic pressure, etc.
- Direct air-sea flux measurements are provided by direct covariance method at limited locations, and these measurements are primarily for improving the flux parameterizations.

Active and passive sensors for long-term monitoring of air-sea variables



Example of different types of satellite sensors that are used in air-sea flux analysis

NOAA Polar Operational Environmental Satellites (POES) series



Advanced Microwave Sounding Unit (AMSU) is flown on NOAA series 15 and onward to provide measurements of atmospheric temperature and moisture profiles

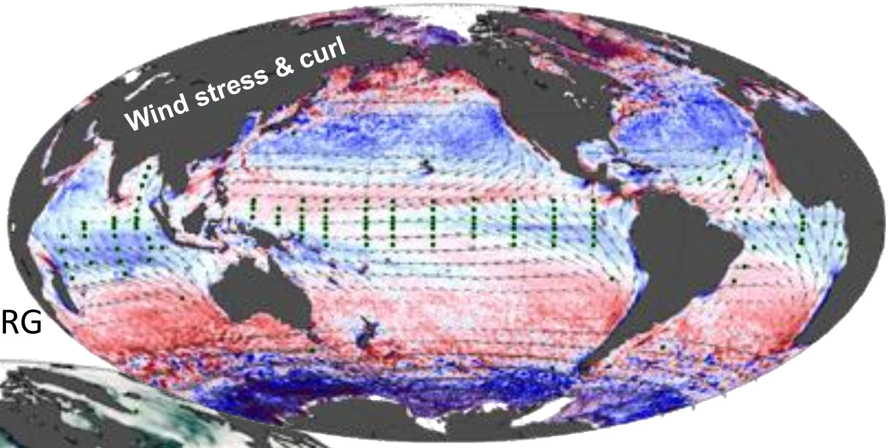
Dataset / Input Variable	GSSFTF v3	IFREMER v3	HOAPS v3	J-OFURO v3	SEAFLUX	OAFllux-1° http://oaflux.whoi.edu	NASA MEaSUREs ESDRs OAFlux-HR
Qa	EOF-based algorithm Chou et al. (1995)	Qa-Tb relation Bentamy et al. (2003)	Qa-Tb relation Bentamy et al. (2003)	Qa-Tb relation Kubota and Hihara (2008)	Qa-Tb relation Roberts et al. (2010)	Objective blending of qa from NCEP1, NCEP2, ERA-Interim	Regime dependent Qa-Tb relation SSM/I, SSMIS, AMSU-A Yu and Jin (2018)
Ta	NCEP1	NCEP1	Estimated from SST assuming 80% constant humidity and 1K difference	NCEP2	Same as Qa	Objective blending of Ta from NCEP1, NCEP2, ERA-Interim	Same as Qa
Ts	OISST	NCEP2	AVHRR	Ensemble median of global SST products	A diurnally varying SST based on AVHRR.	OISST	OISST, OSTIA Adjusted by buoys
W	SSM/I	Scatterometers	SSM/I	Microwave radiometers and scatterometers	CCMP	Satellite synthesis of QuikSCAT, ASCAT A/B, SSMI, SSMIS, AMSRE, AMSR2, WindSat	QuikSCAT, ASCAT A/B/C, OSCAT, SSMI, SSMIS, AMSRE, AMSR2, WindSat Yu and Jin (2012; 2014a; 2014b)
Spatial resolution	0.25ºx0.25º	0.25ºx0.25º	0.5ºx0.5º	0.25ºx0.25º	0.25ºx0.25º	1ºx1º	0.25ºx0.25º
Temporal resolution	Daily	Daily	Twice daily	Daily	3-hourly	Daily	Daily for LH, SH, E 6 hourly for winds
Temporal coverage	Jul. 1987 – Dec.2009	Jul. 1987 – Dec. 2008	Jul. 1987 – Dec. 2008	Jan. 1988 – Dec. 2013	Jan.1998 – Dec. 2007	Jan. 1958 – present	Jul. 1987 – present
Treatment of data gaps	Method Unknown	Method Unknown	Method unknown	Method unknown	Data gaps were filled by interpolating MERRA	Atmospheric reanalysis as background information	Two-step approach: (i) bias-correct ERA-interim using regression (ii)objective synthesis
References	Chou et al. (1995) Shie et al. (2012)	Bentamy et al. (2003)	Andersson et al. (2011)	Kubota et al. (2002)	Roberts et al. (2010; 2012)	Yu and Weller (2007) Yu et al. (2008)	Yu and Jin (2012; 2014a; 2014b); Jin and Yu (2013) Jin et al. (2015); Yu (2019)

There have been many efforts on constructing surface fluxes from satellite observations of air-sea variables. The most recent effort is OAFlux – high resolution analysis supported by NASA MEaSUREs (Making Earth System Data Records (ESDR) for Use in Research) program.

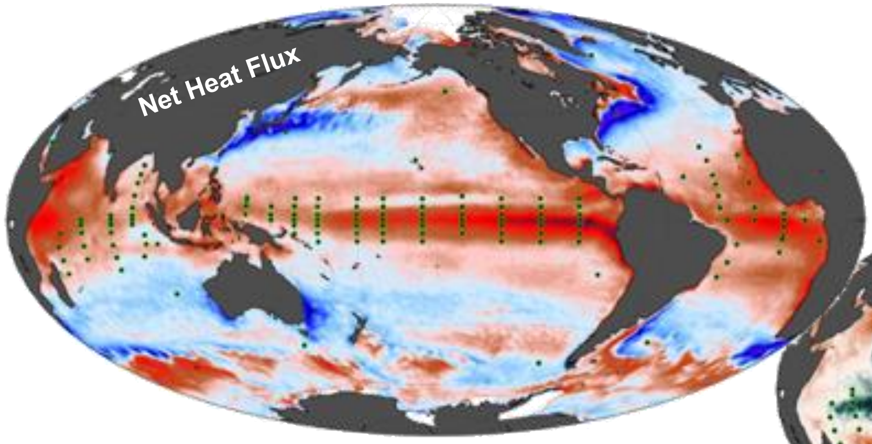
Earth System Data Records of
Air-Sea Heat, Freshwater, Momentum Fluxes
Anchored on the Global Moored Buoy Observations

OAFlux (Objectively Analyzed air-sea Fluxes)

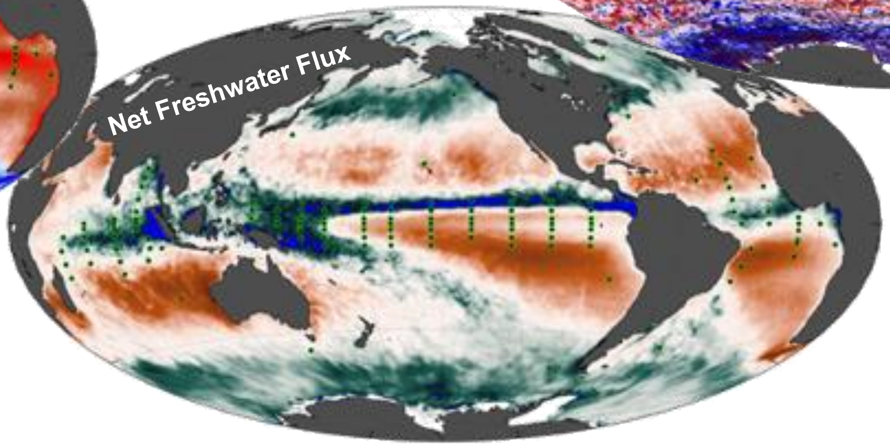
Woods Hole Oceanography Institution



OAFlux+CERES EBAF



OAFlux+IMERG



NOAA PMEL Buoy

WHOI Buoy

Project Objectives

This proposed work is to produce, validate, and distribute ESDRs of air-sea variables and turbulent fluxes on 0.25° spatial resolution for the period from 1988 onward (~35 years by the end of the project).

The specific air-sea variable ESDRs include

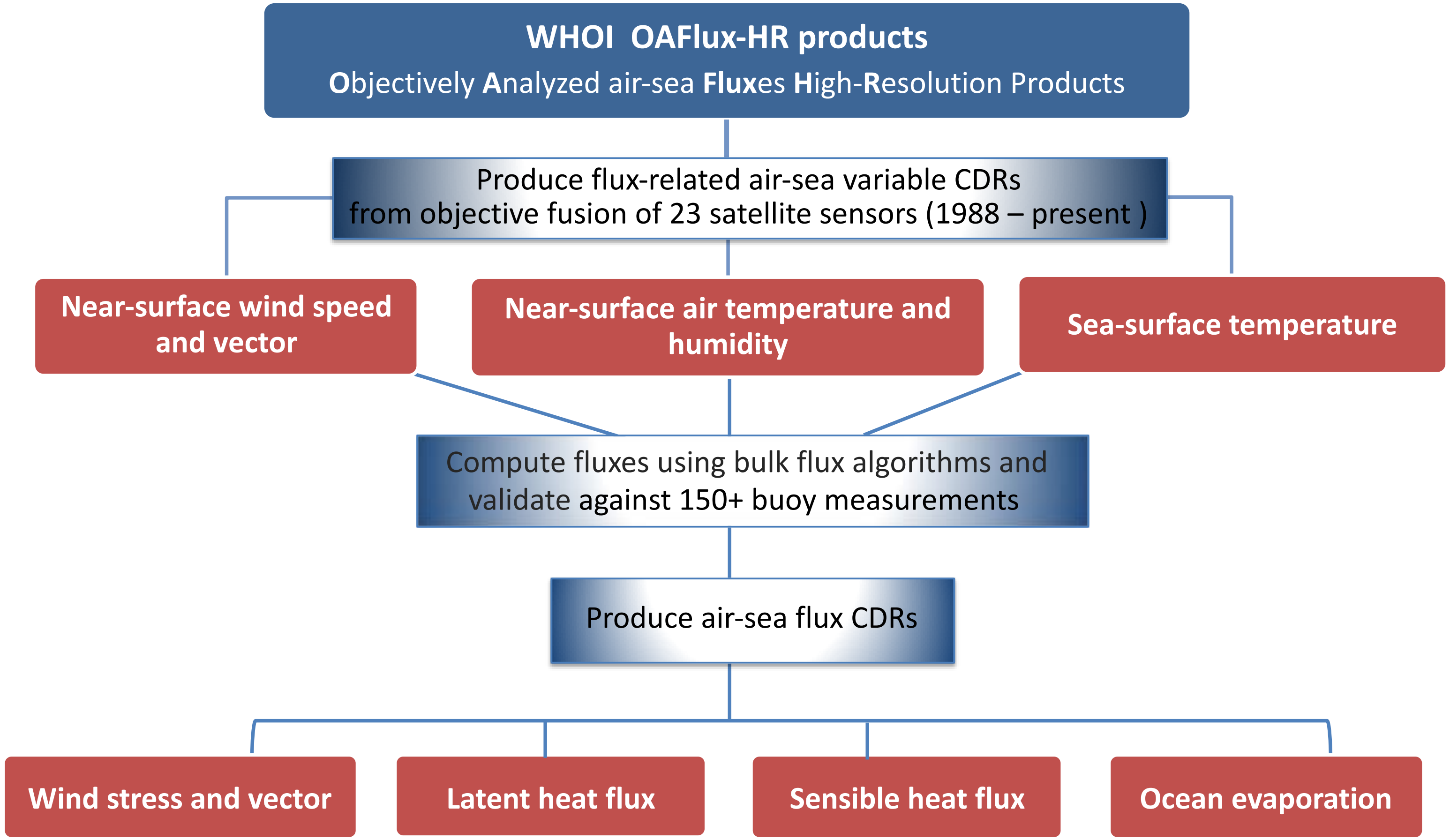
- near surface wind speed and direction merged from scatterometers and microwave radiometers;
- near ocean-surface air temperature (Ta) and specific humidity (qa) retrieved and merged from microwave scanners and sounders;
- SST calibrated with buoys

The air-sea fluxes ESDRs include

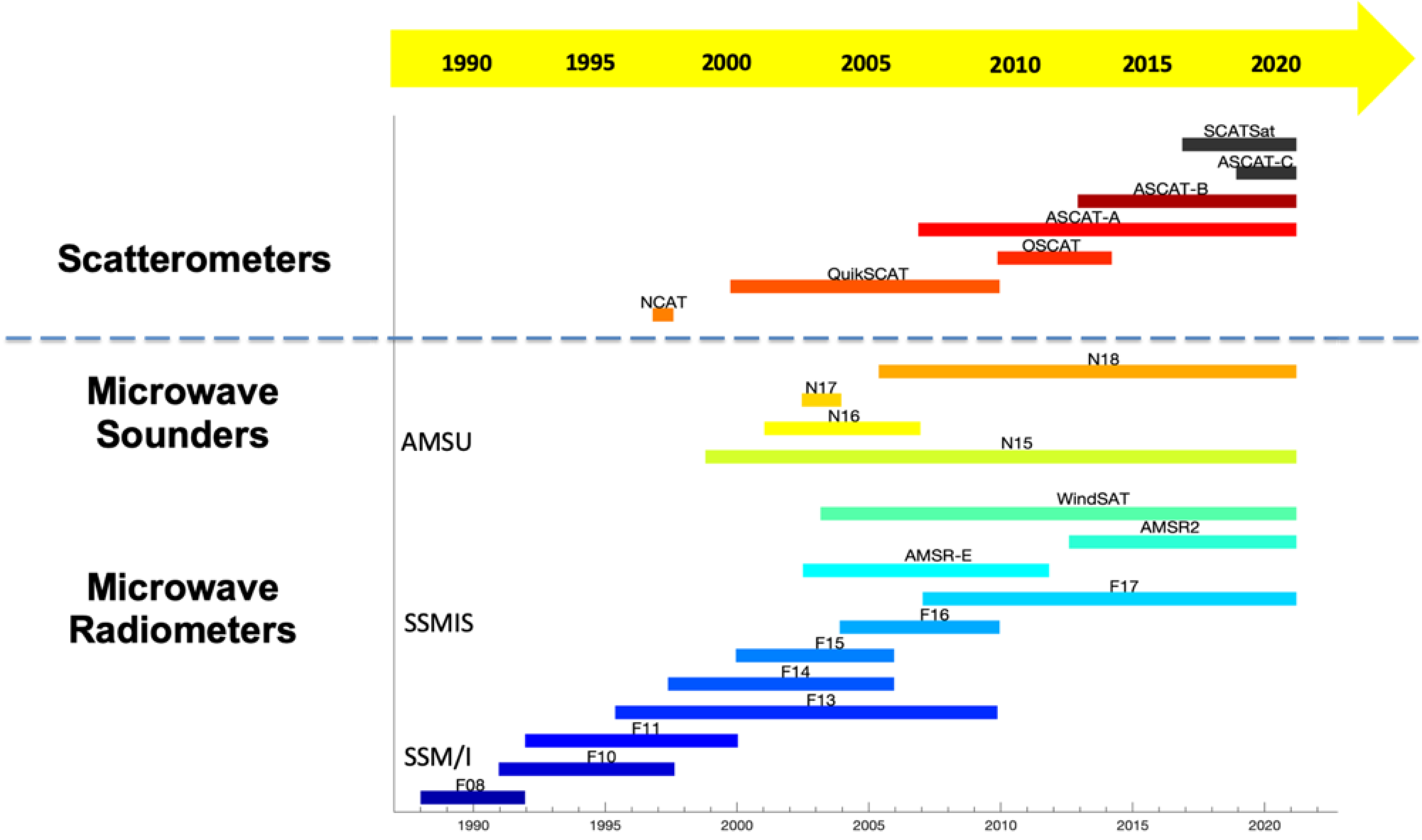
- turbulent momentum fluxes
- turbulent latent and sensible heat fluxes
- turbulent moisture flux (evaporation)

computed from the state-of-the-art bulk flux parameterizations.

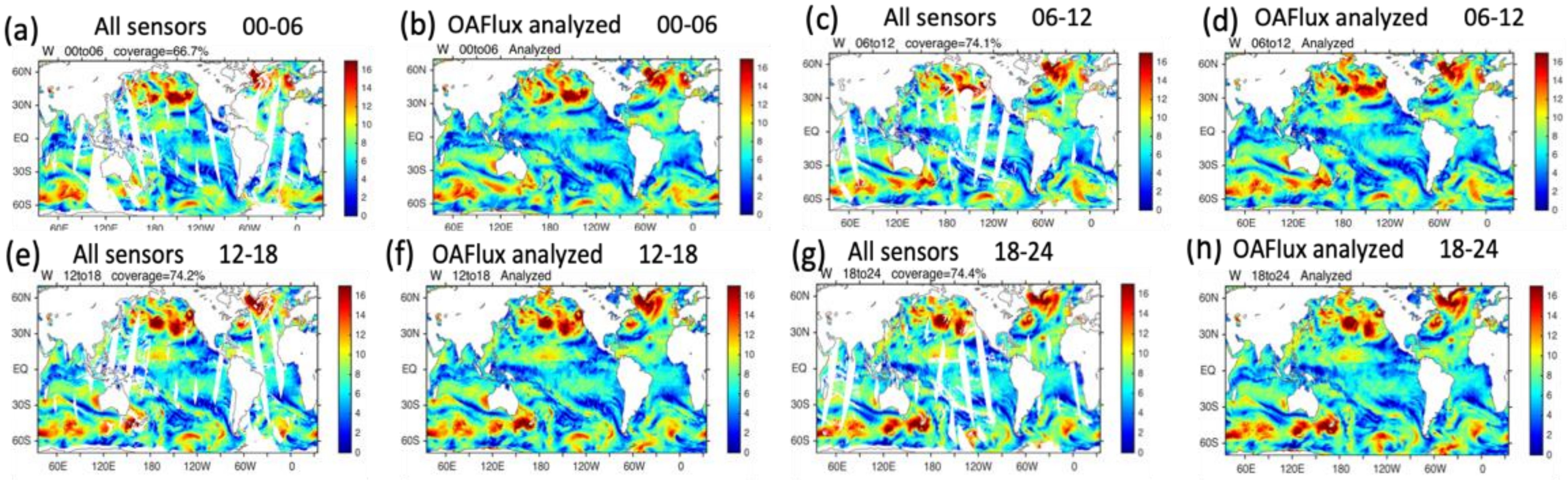
Structure of the project

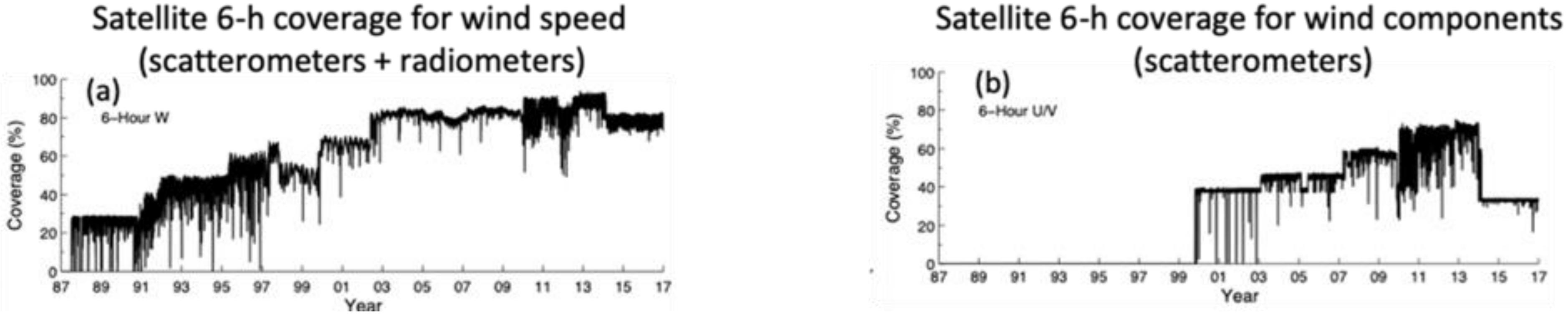


Satellite Sensors commonly used for satellite-based flux estimates

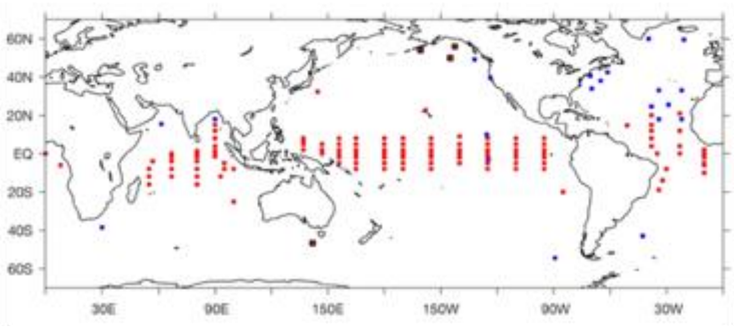


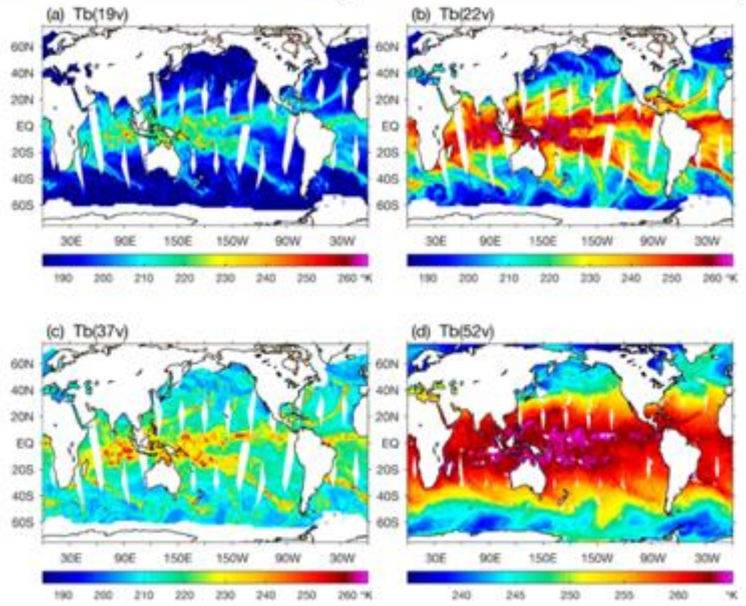
6-hourly synthesis of satellite scatterometers (wind vector) and radiometers (wind speed)



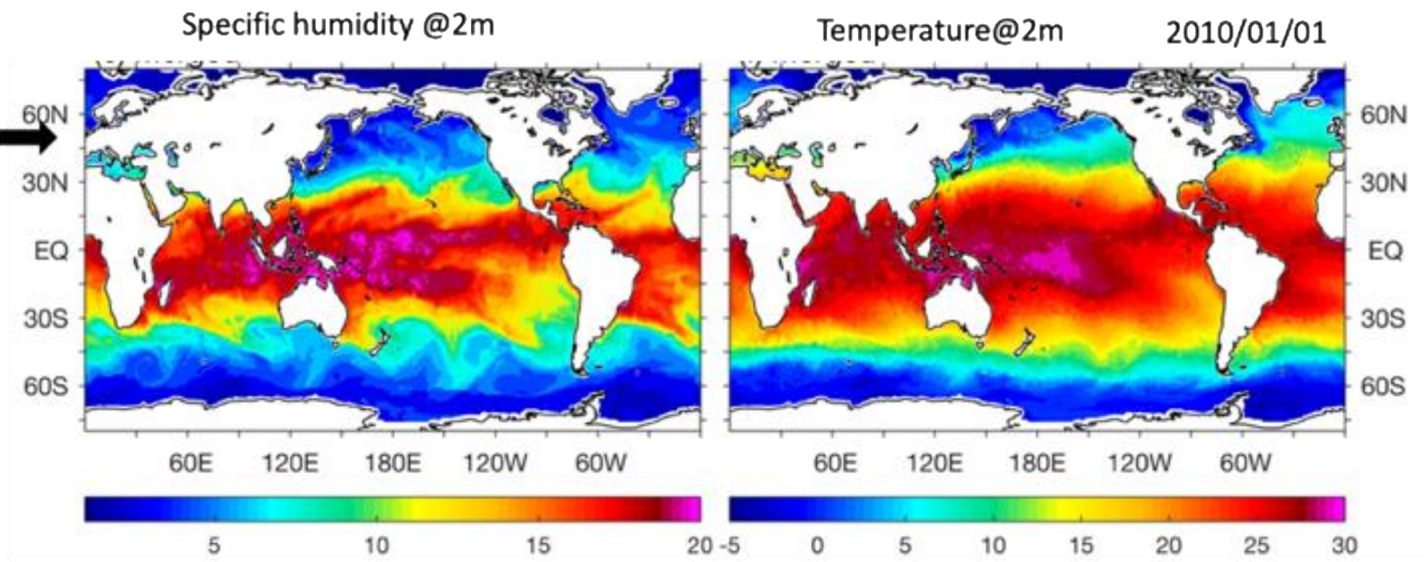


Air humidity (qa) and temperature (Ta) retrievals



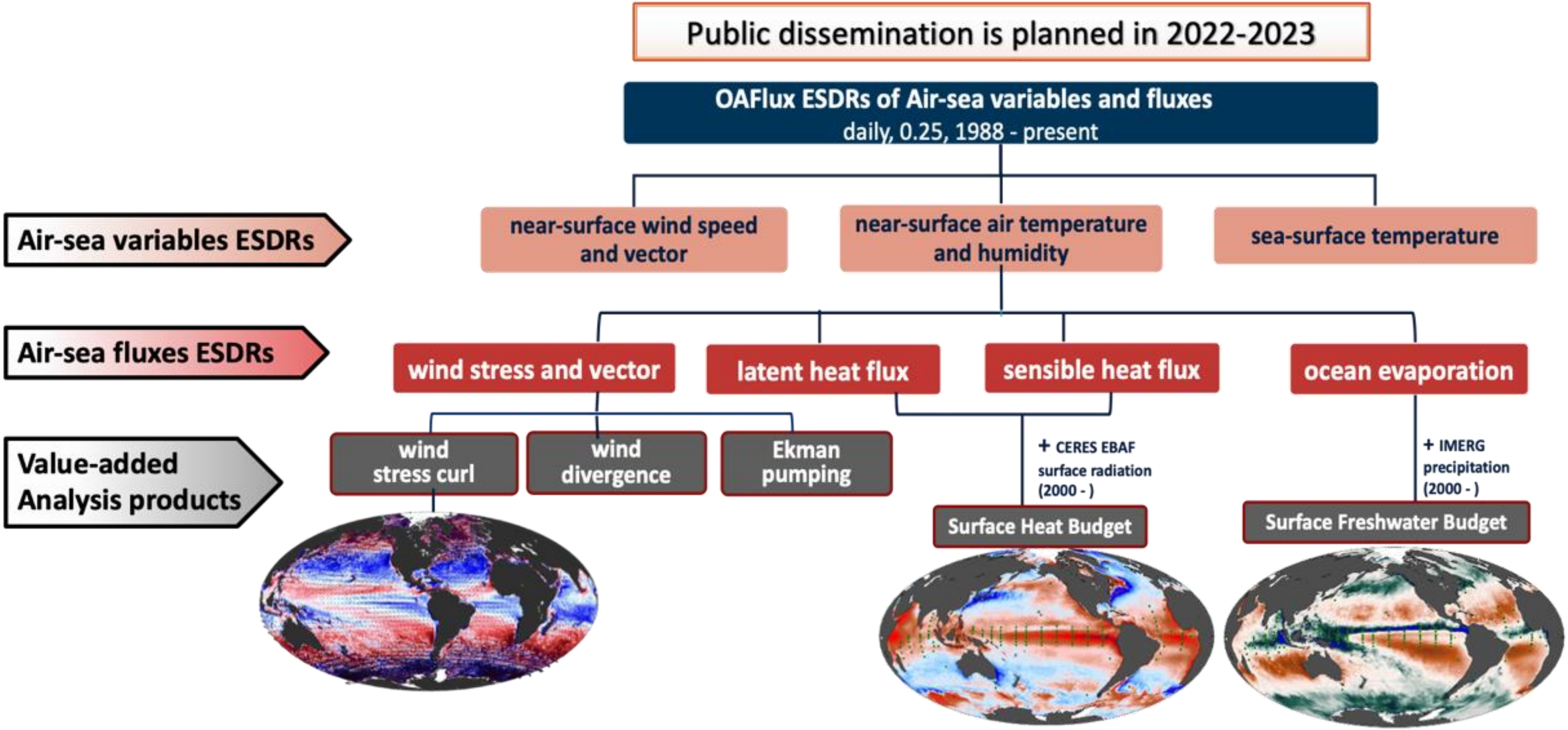


Qa/Ta retrievals are retrieved from multilinear regression developed from 3-h collocated satellite buoy pairs



Yu, L., and X. Jin, 2018: A regime-dependent retrieval algorithm for near-surface air temperature and specific humidity from multi-microwave sensors. Remote Sens. Environ., 215, 199–216.

Expected OUTPUT ESDRs



Main topics

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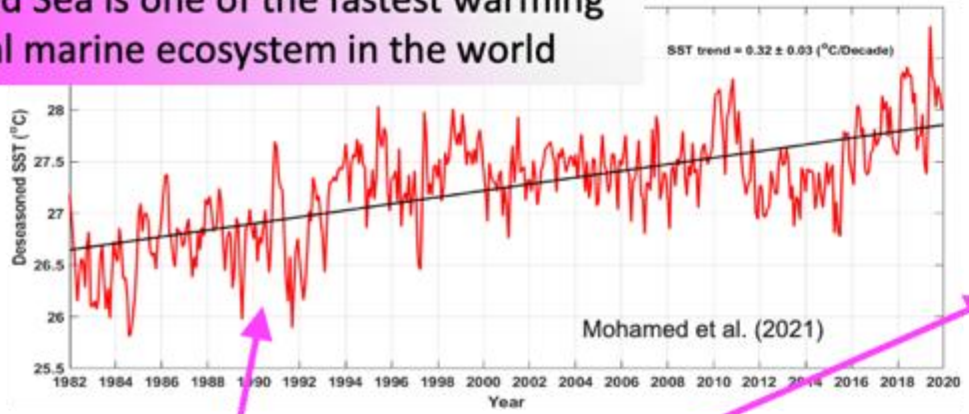
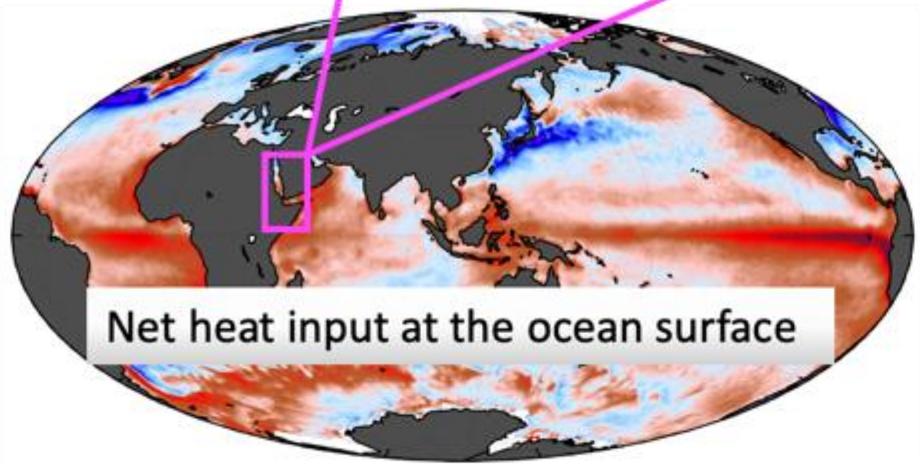
High-resolution insights: Qnet in the Red Sea

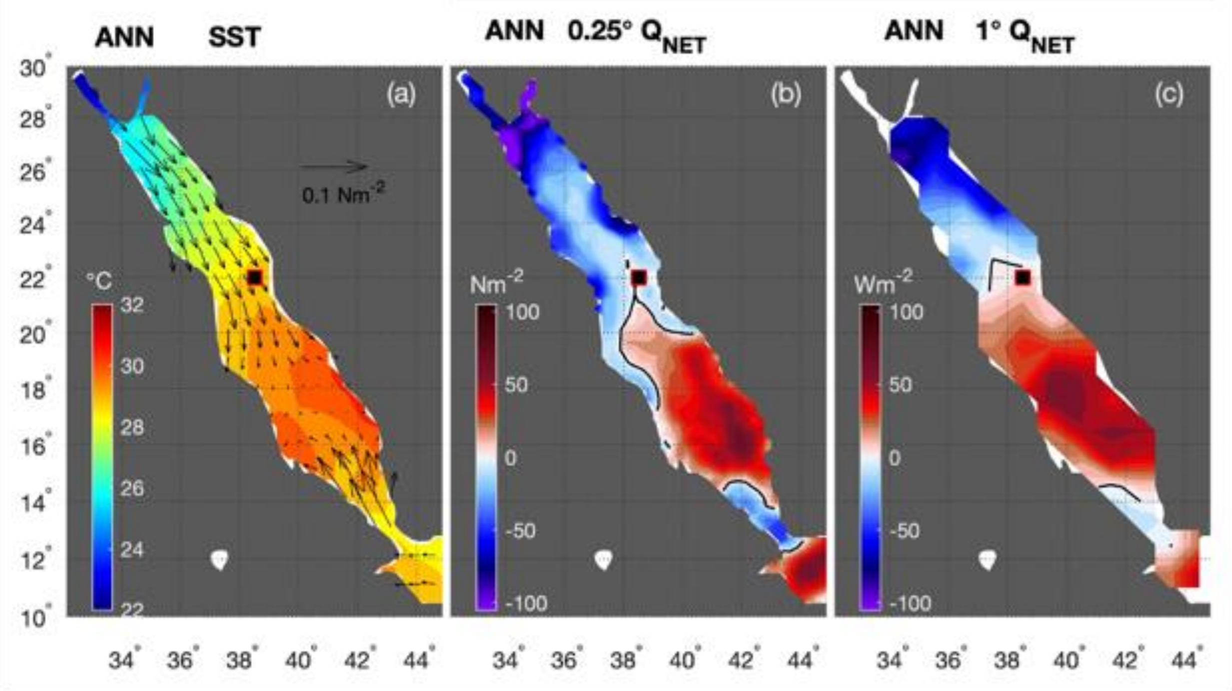
The Red Sea is one of the fastest warming tropical marine ecosystem in the world





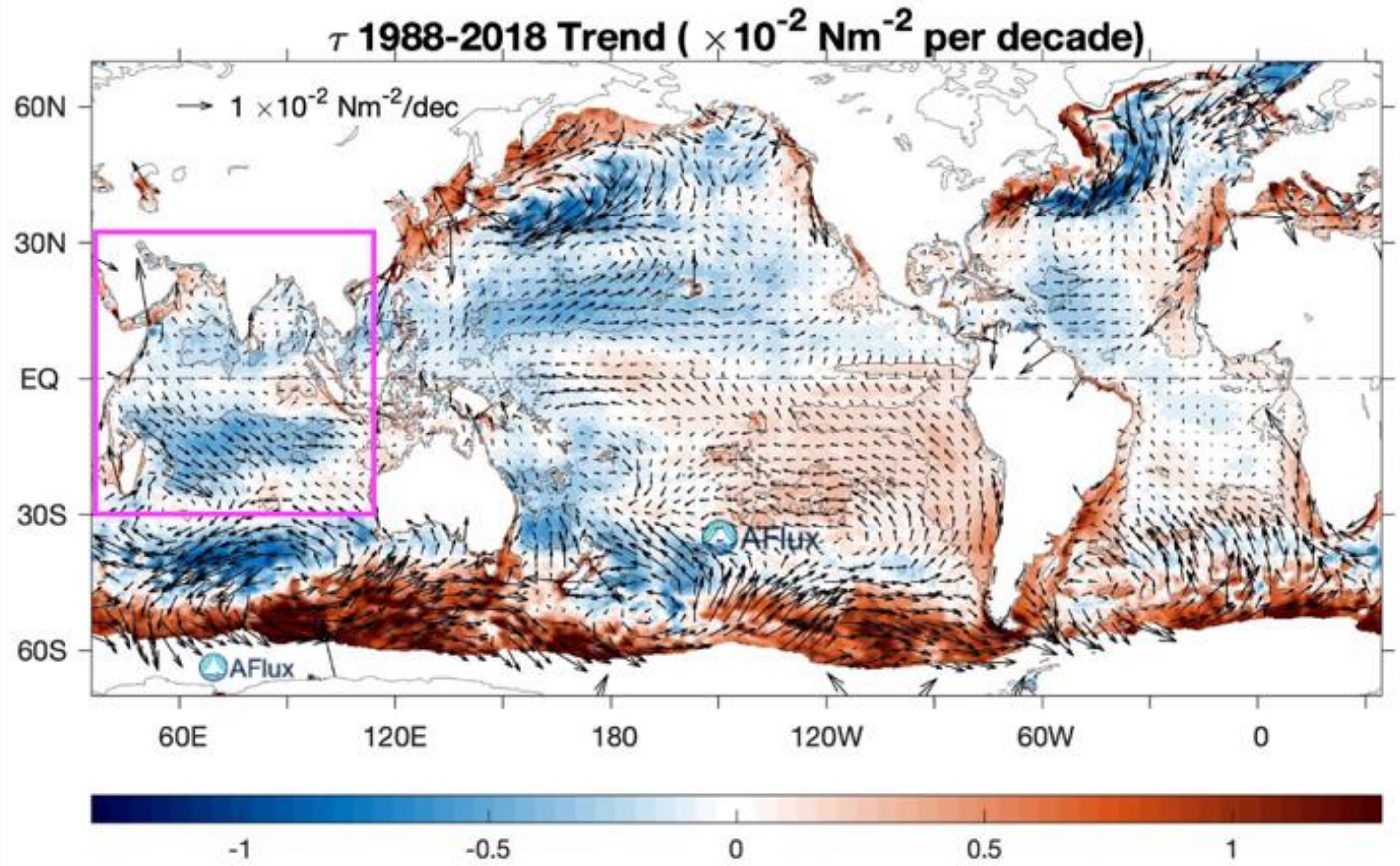
Net heat input at the ocean surface

Annual mean net heat input (Qnet) 0.25° vs 1°



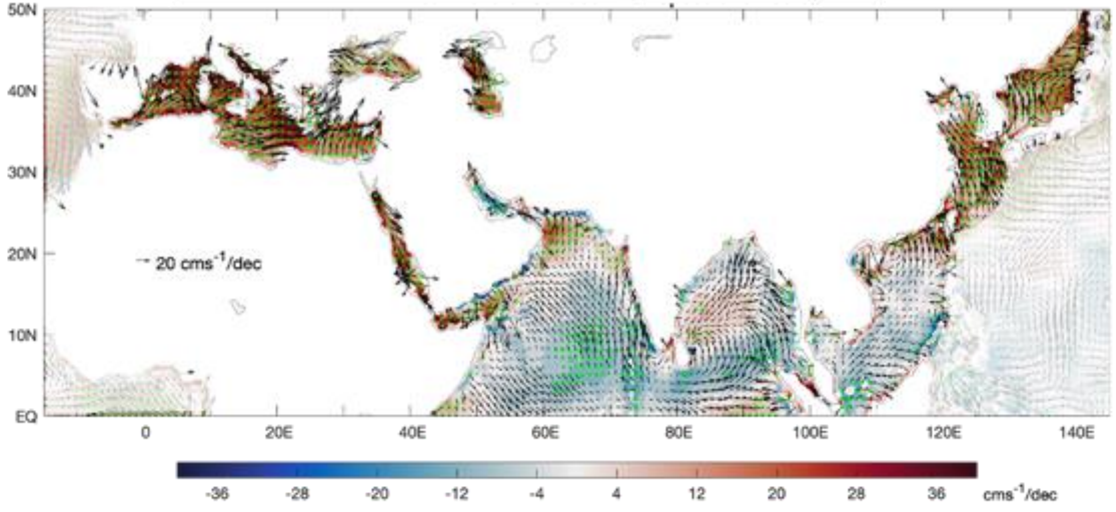
- High-resolution heat flux analysis produces improved representation of the spatial distribution of heat fluxes, particularly, the large heat loss near the Northern tip in the Red Sea.
- The improved mapping of the heat flux mesoscale features improves the estimate of the net heat budget in the sea, allowing more accurate quantification of the role of Qnet in the Red Sea warming.

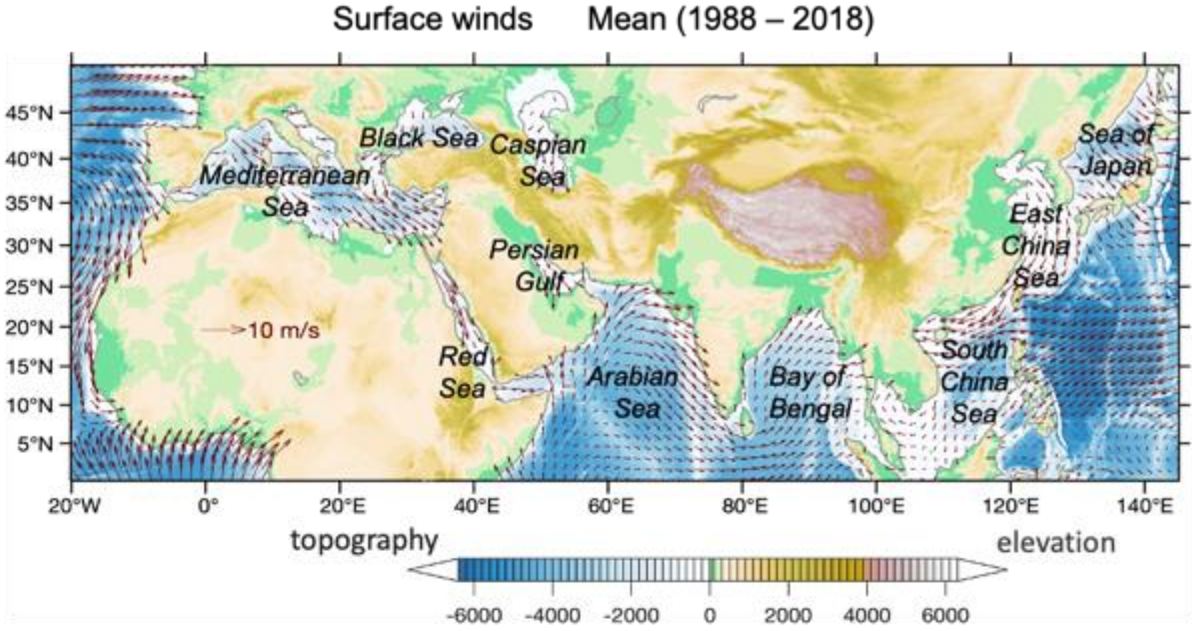
Climate trends in ocean-surface winds

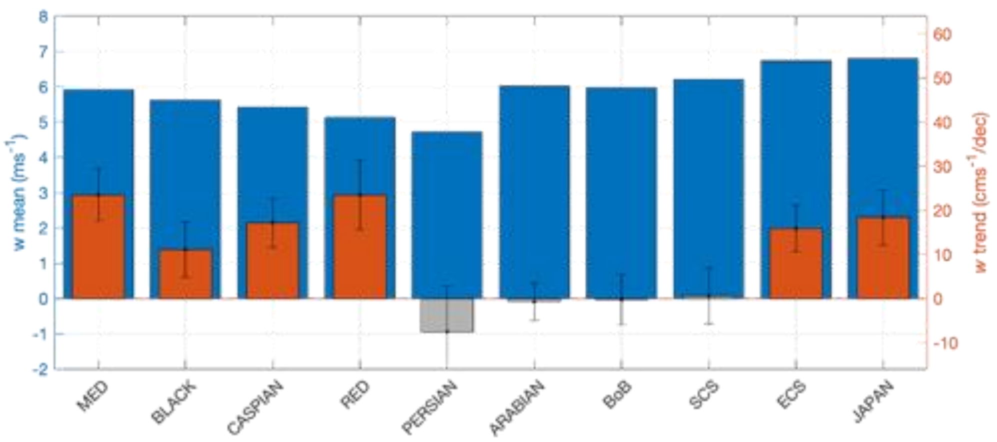


- Surface winds have been changing along with the climate warming in past three decades.
- Winds have weakened in the Indian Ocean.

Winds in Marginal Seas have increased.





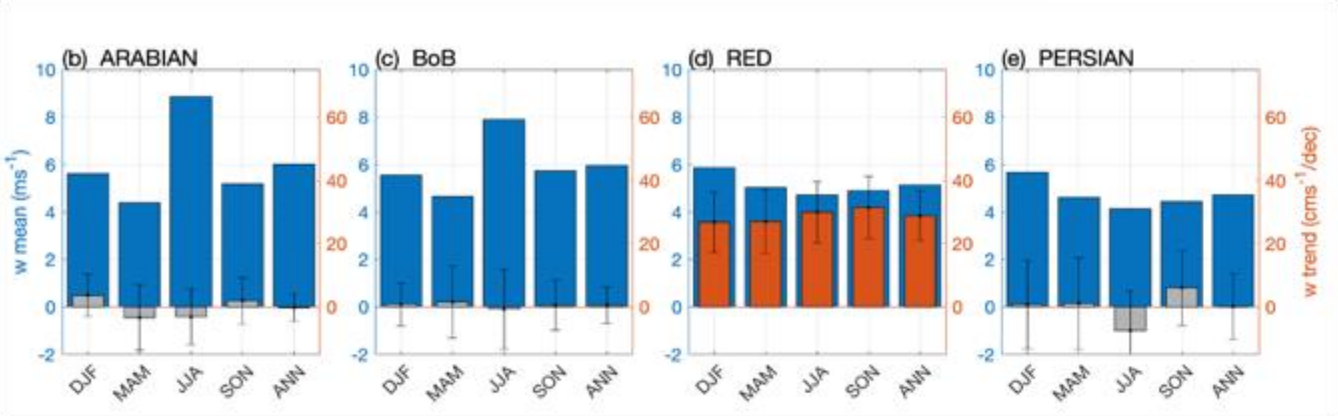


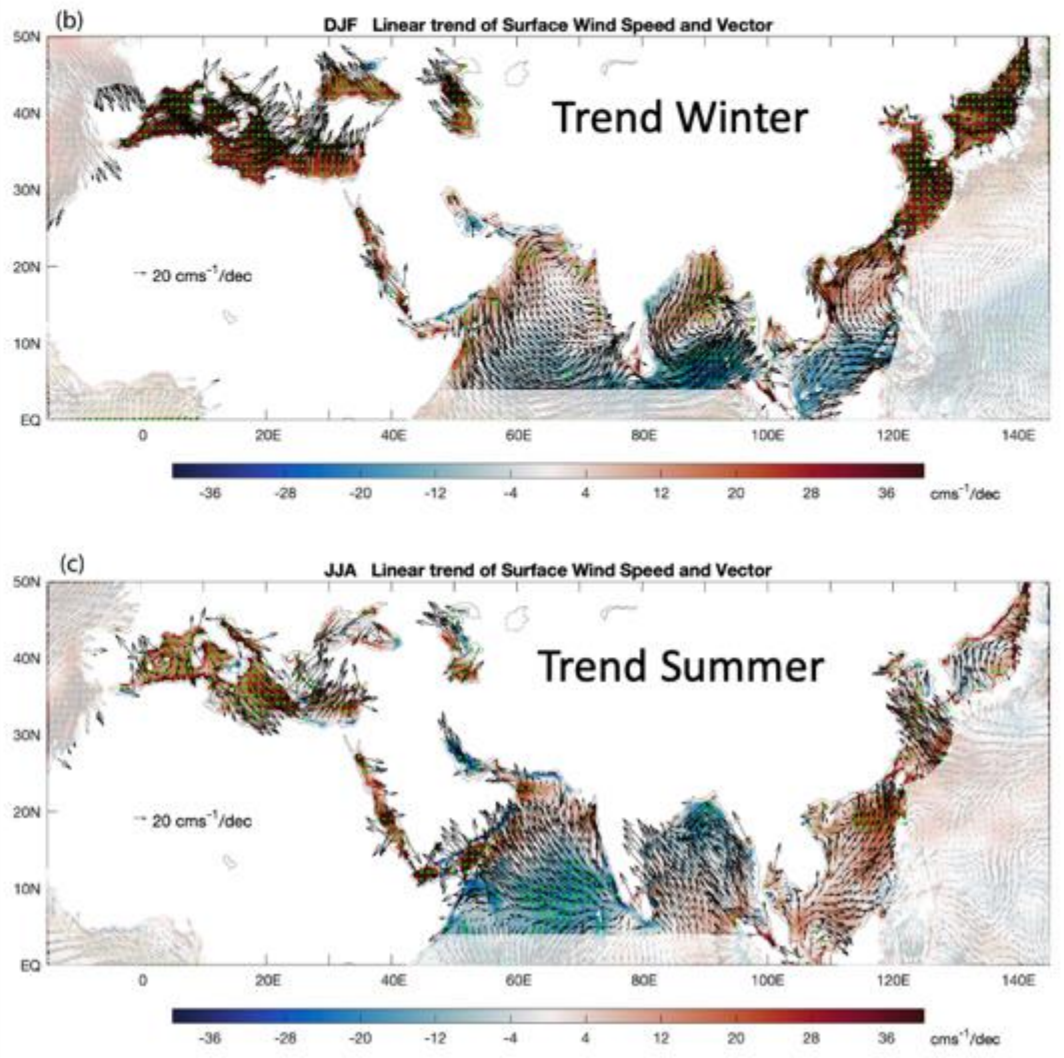
- The marginal sea winds are a result of complex interactions between the atmosphere, ocean, and land; and this complexity demonstrates the importance of long-term satellite data records in identifying and understanding the climate change and impacts at a regional scale.

Yu 2021. Emerging Pattern of Wind Change over the Eurasian Marginal Seas Revealed by Three Decades of Satellite Ocean-Surface Wind Observations. *Remote Sens.* **2021**, *13*, 1707. https://doi.org/10.3390/rs13091707

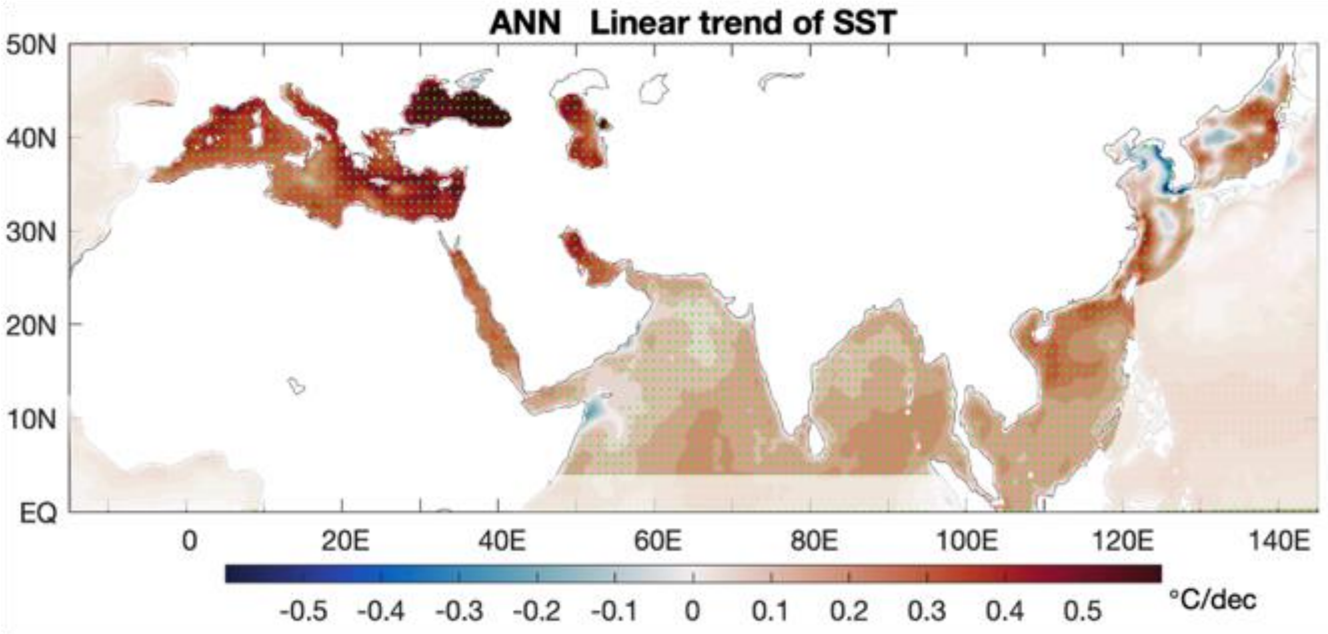
Trend Characteristics: Seasonal differences

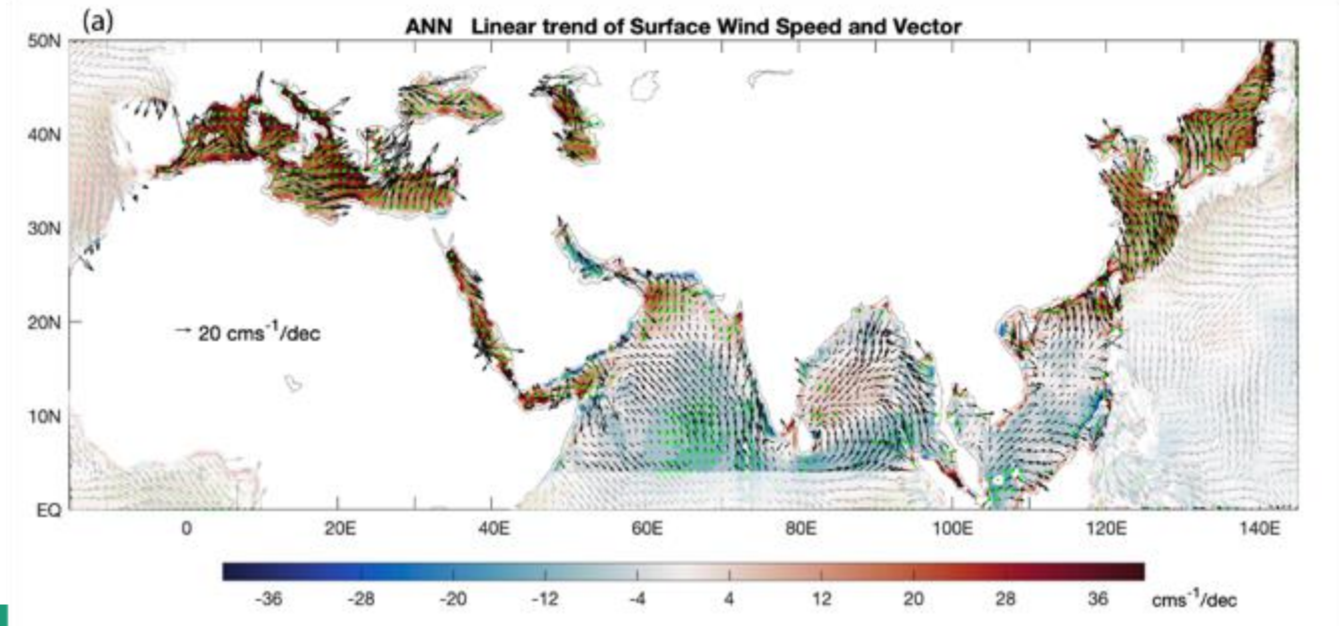
Seasonal + annual trends averaged over four basins



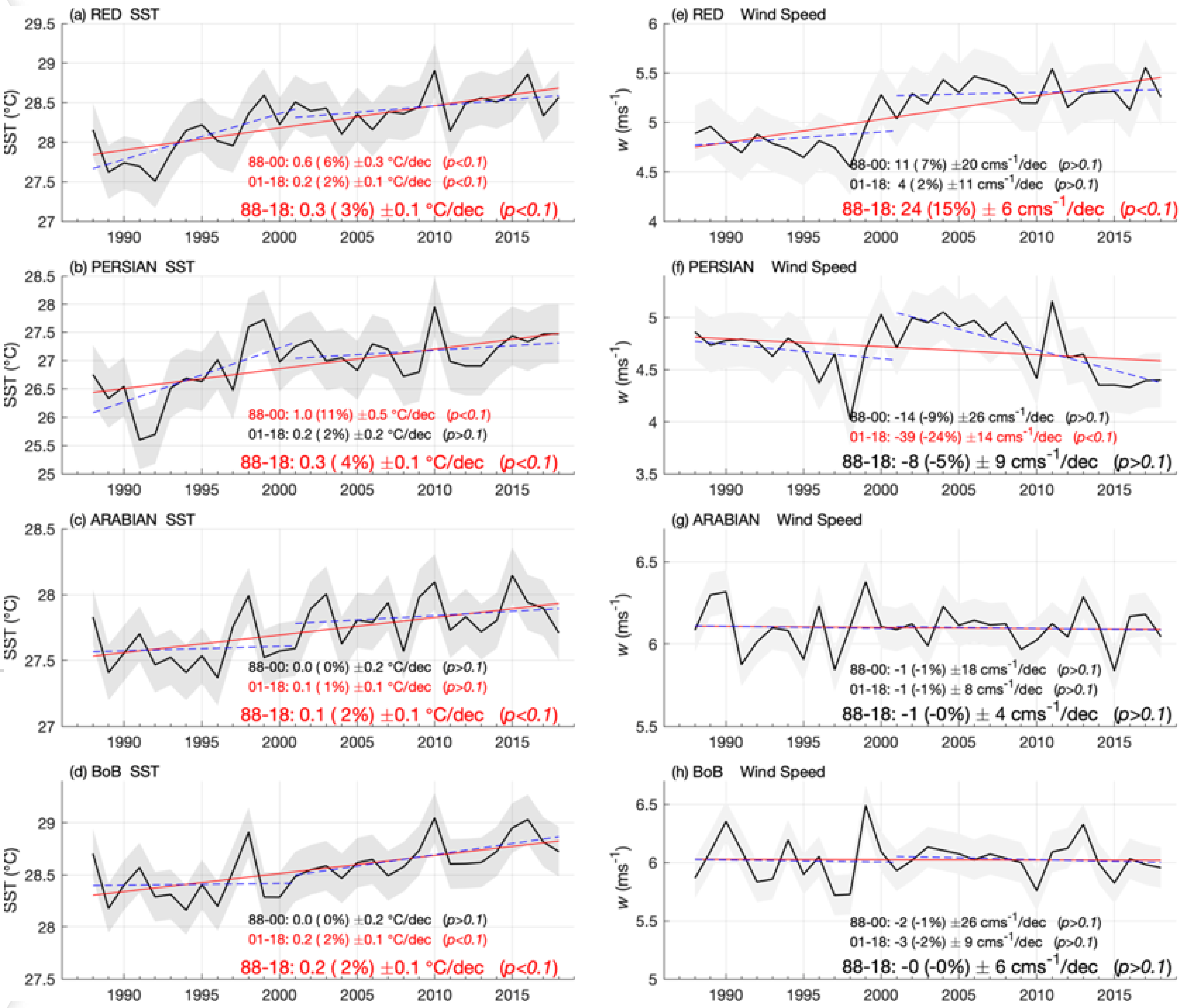


Trends:
Wind vs. SST





Trend characteristics: Decadal differences



Summary

1. What are surface fluxes and how are they used in ocean applications

Air-sea exchange of heat, moisture, and momentum constitutes the surface forcing that drives ocean circulation and variability.

2. How are surface fluxes determined from satellite remote sensing?

Surface fluxes cannot be directly observed from satellite.

They are computed from bulk flux parameterizations using air-sea variables retrieved from satellite.

3. Observed change and variability of surface forcing in the Indian Ocean and marginal seas.

The Indian Ocean and marginal seas have warmed faster than the global mean averages. Meanwhile, the wind circulation has slowed down. Impacts of the weakened winds on the regional ocean circulation warrant further investigation.

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