Air-Sea Interactions over the Tropical Ocean and Earth System Modeling: Progress, Challenges, and Ways Forward

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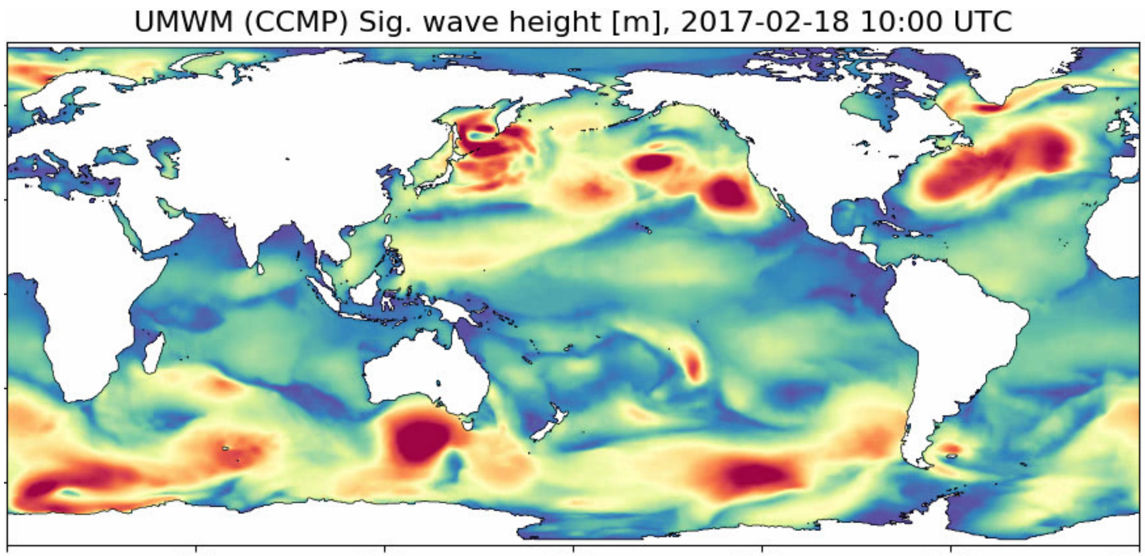
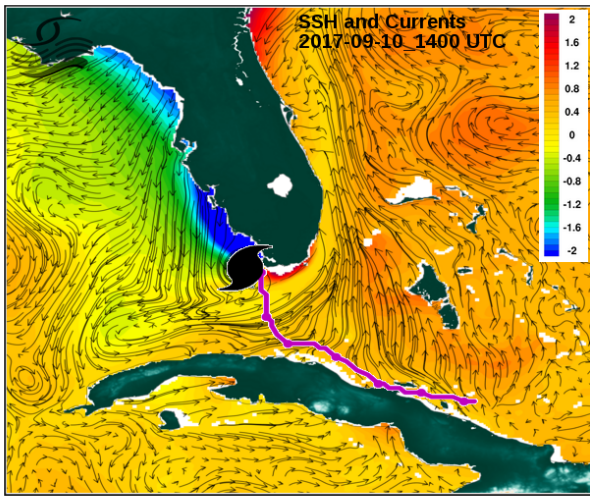


Hurricane Irma



Hurricanes and Coupled Modeling Group

(CLIVAR Workshop, Boulder, CO, 7-9 May 2019)

Overall goals:

- Understand the physical processes of air-sea interaction in global weather and climate system
- Develop a physically based and computationally efficient coupling at the air-sea interface for Earth System coupled atmosphere-wave-ocean-land models

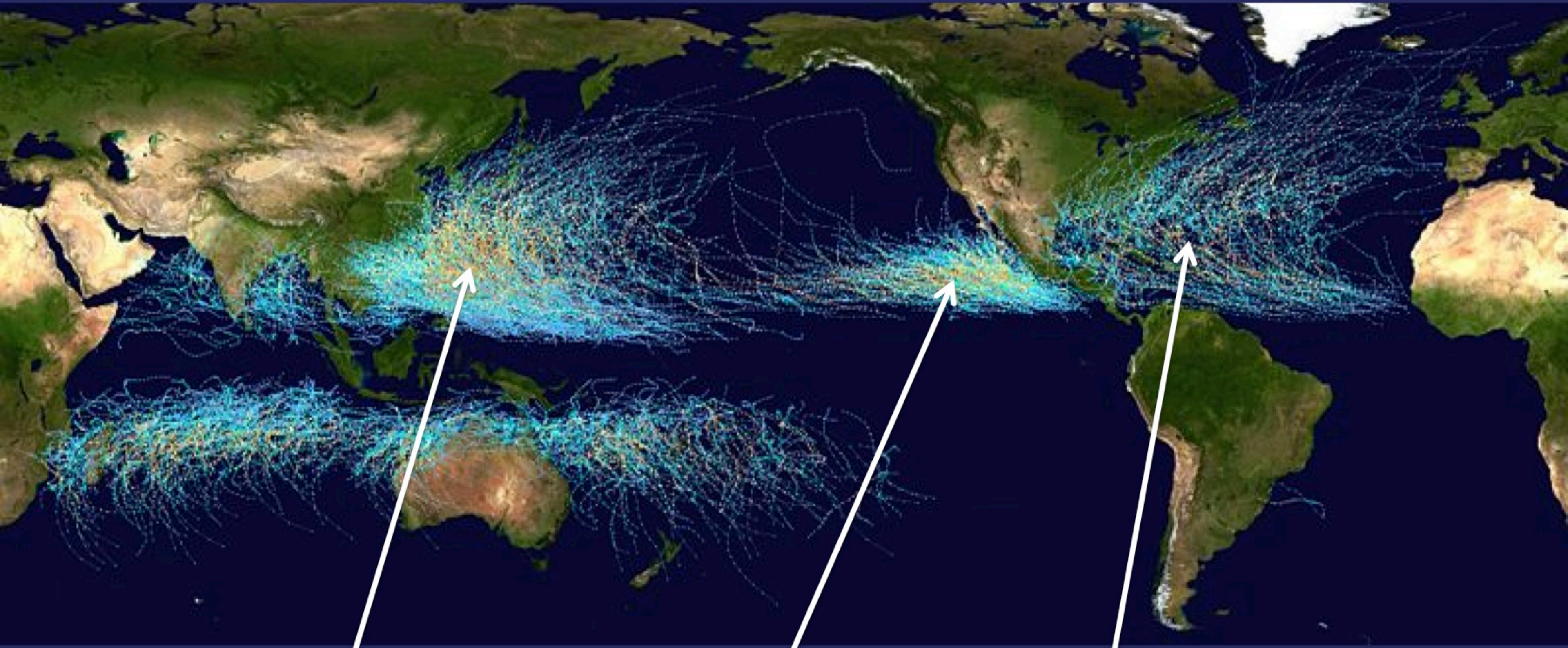
Outline for this talk

❑ **Air-sea interaction in high winds**: *Field campaigns and Unified Wave INterface-Coupled Model (UWIN-CM) & NASA GEOS ESM*

❑ Progress in observing, understanding, and modeling

❑ Grand challenges: rainfall and air-sea fluxes

Tropical Cyclone Field Experiments

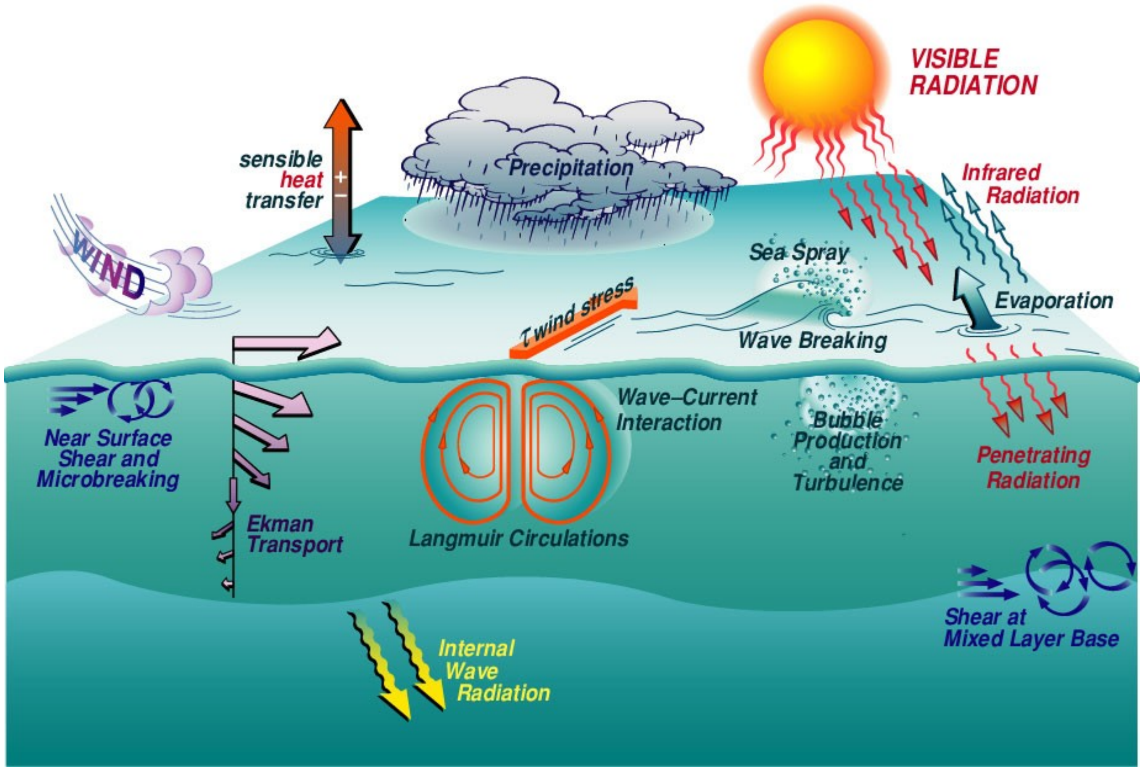


2010: ITOP/TCS10
2008: TCS08/DOTSTAR
1990: TCM90

2005: TCSP
1991: TEXMEX

2010: PREDICT/GRIP/IFEX
2005: RAINEX
2003-04: CBLAST
2001 & 1998: CAMEX
1961-71: STORMFURY
1959: NHRP

Coupled Boundary Layer Air-Sea Transfer (CBLAST) in 2003-2004



Emanuel (1995):

- Axisymmetric hurricane model
- Bulk PBL
- Gradient wind

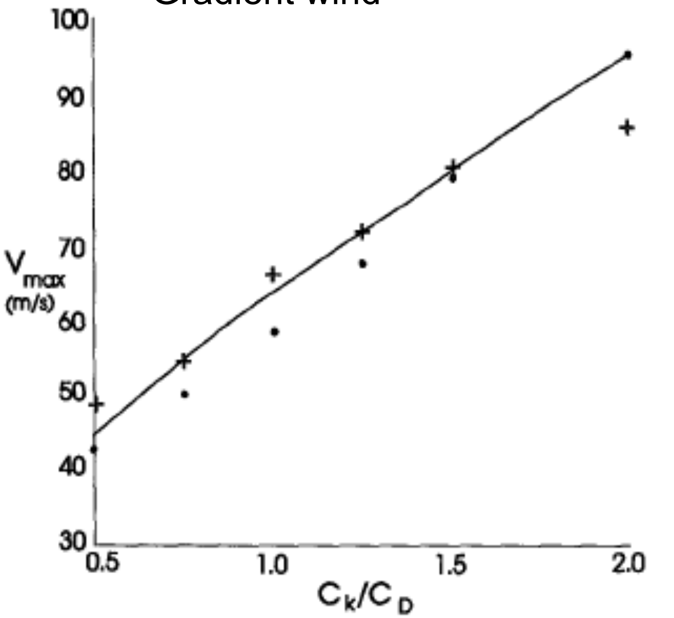
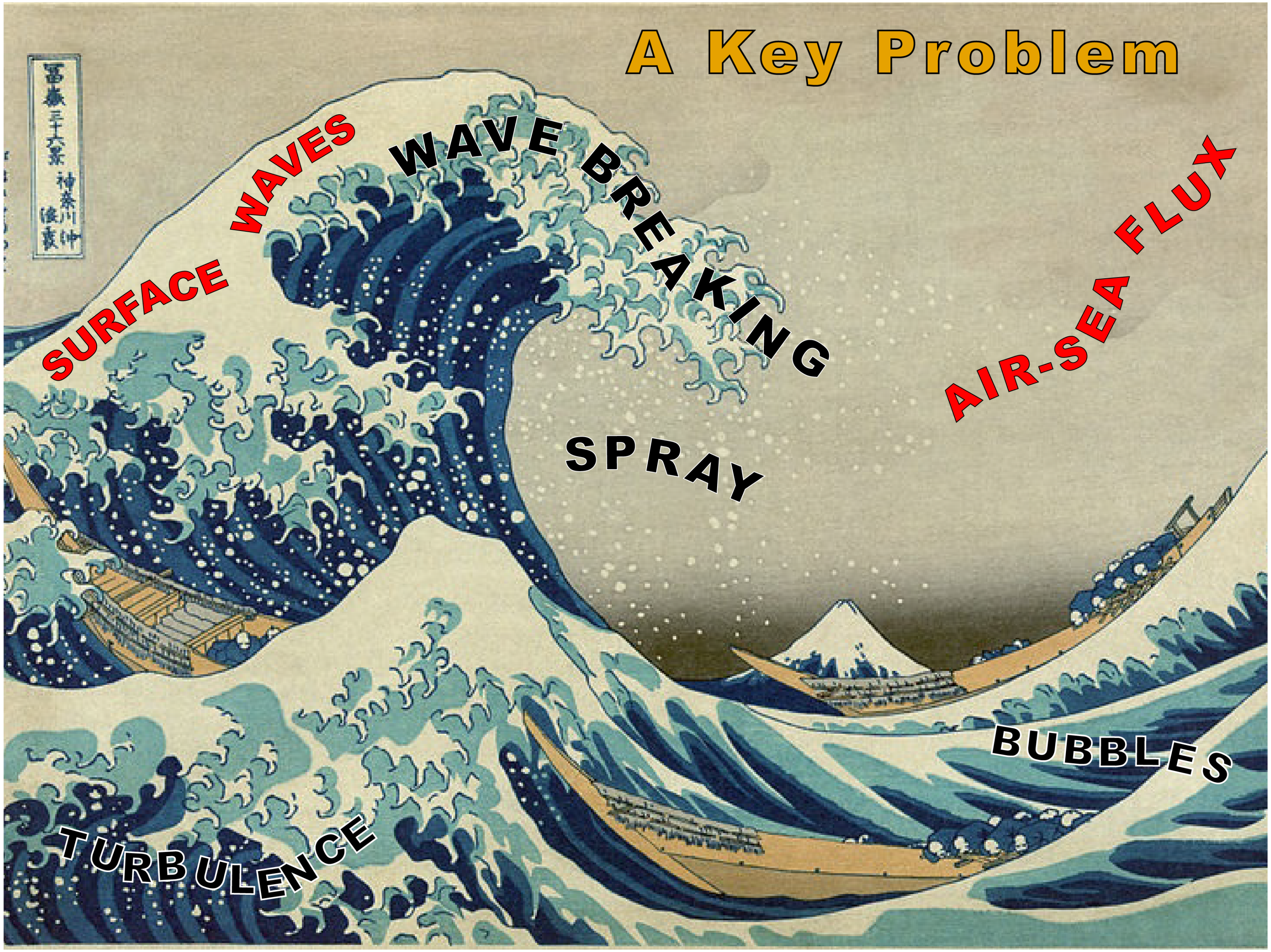


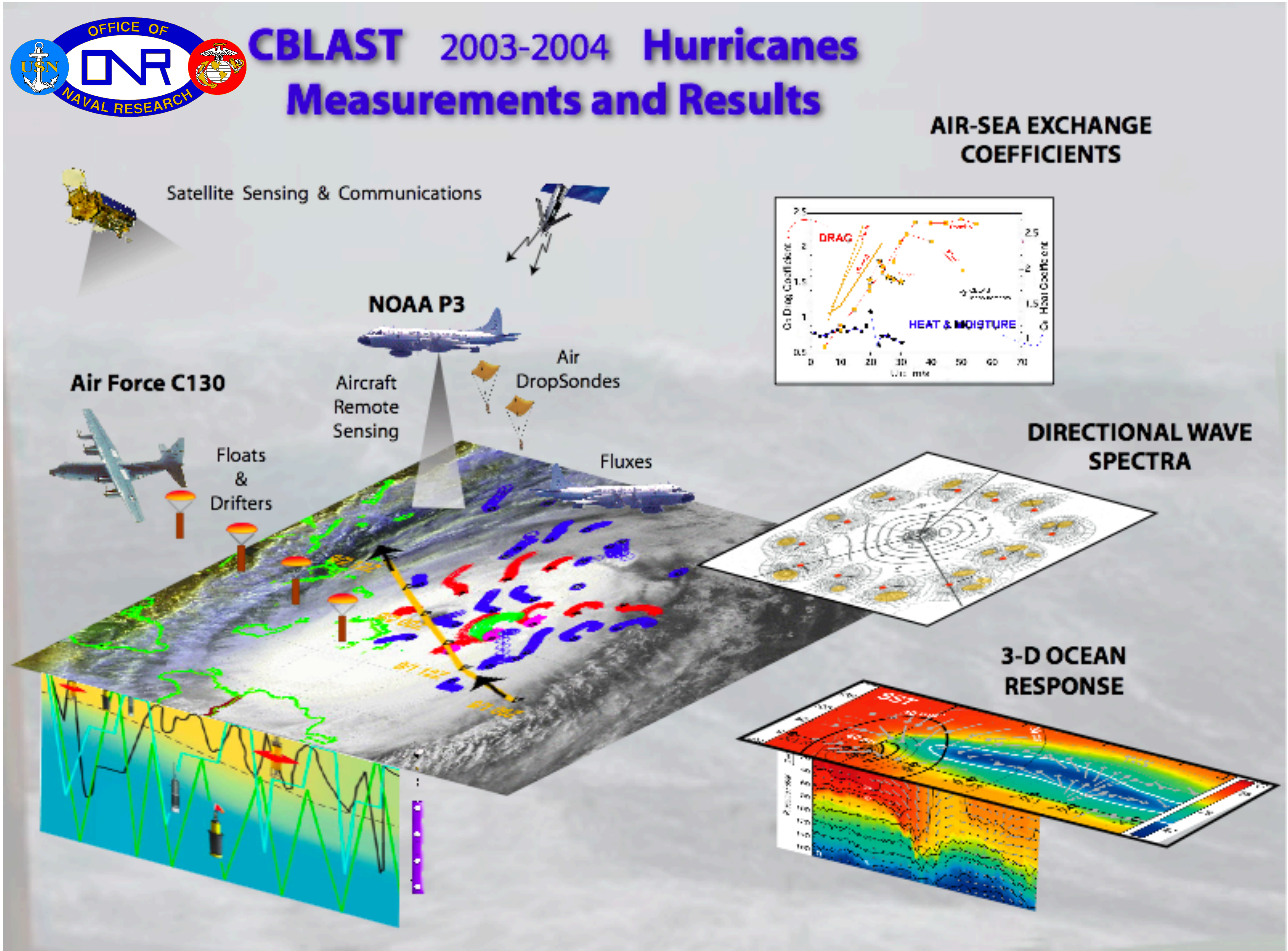
FIG. 1. Maximum azimuthal wind according to (16) (solid curve) and results of running the E95 (dots) and RE87 (+'s) models, as a function of the ratio of enthalpy to momentum surface exchange coefficients.

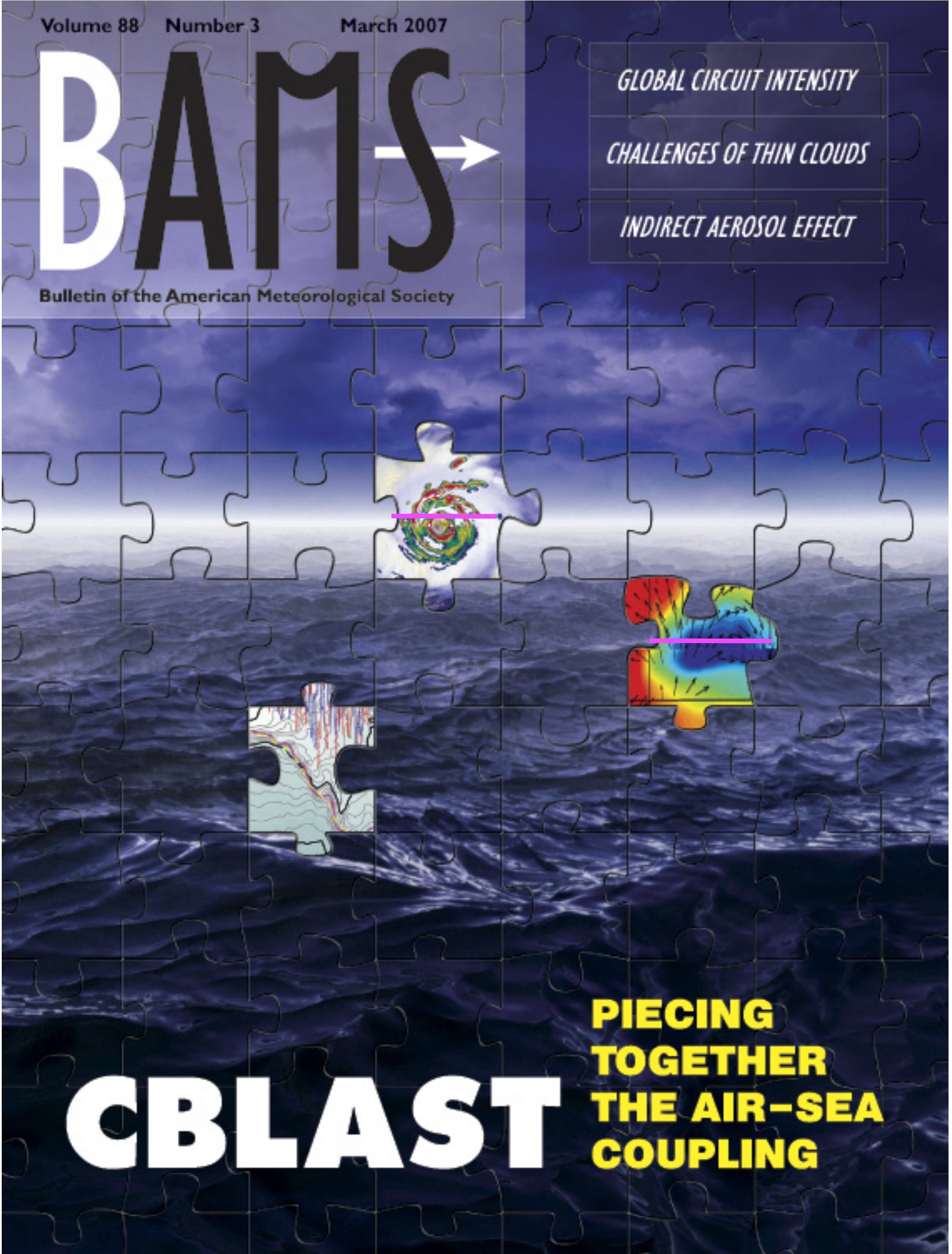
What are C_k (enthalpy) and C_D (momentum) in high winds?



Eric D’Asaro’s “rendition”

How surface waves affect air-sea fluxes in TCs?



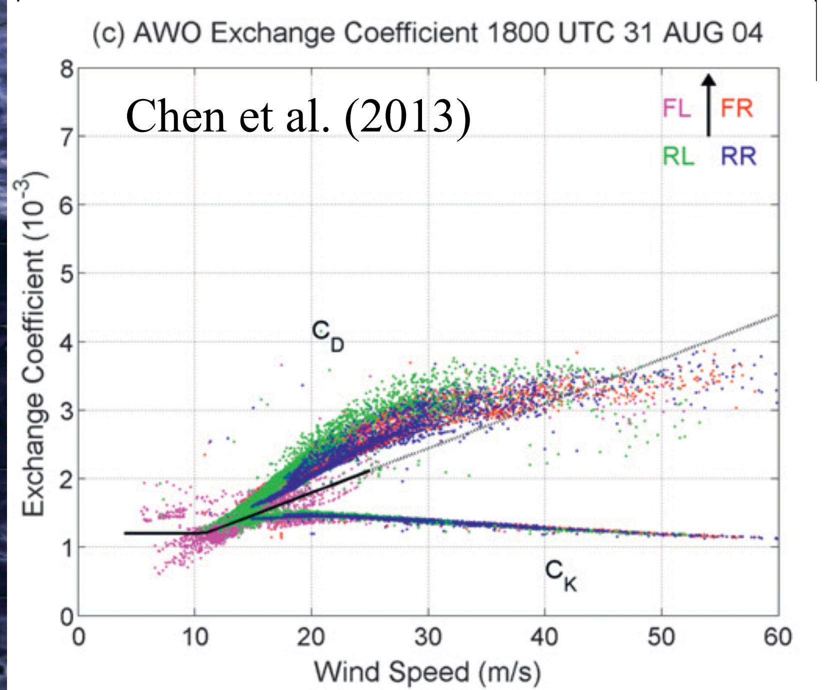


<u>BAMS issue on CBLAST:</u>

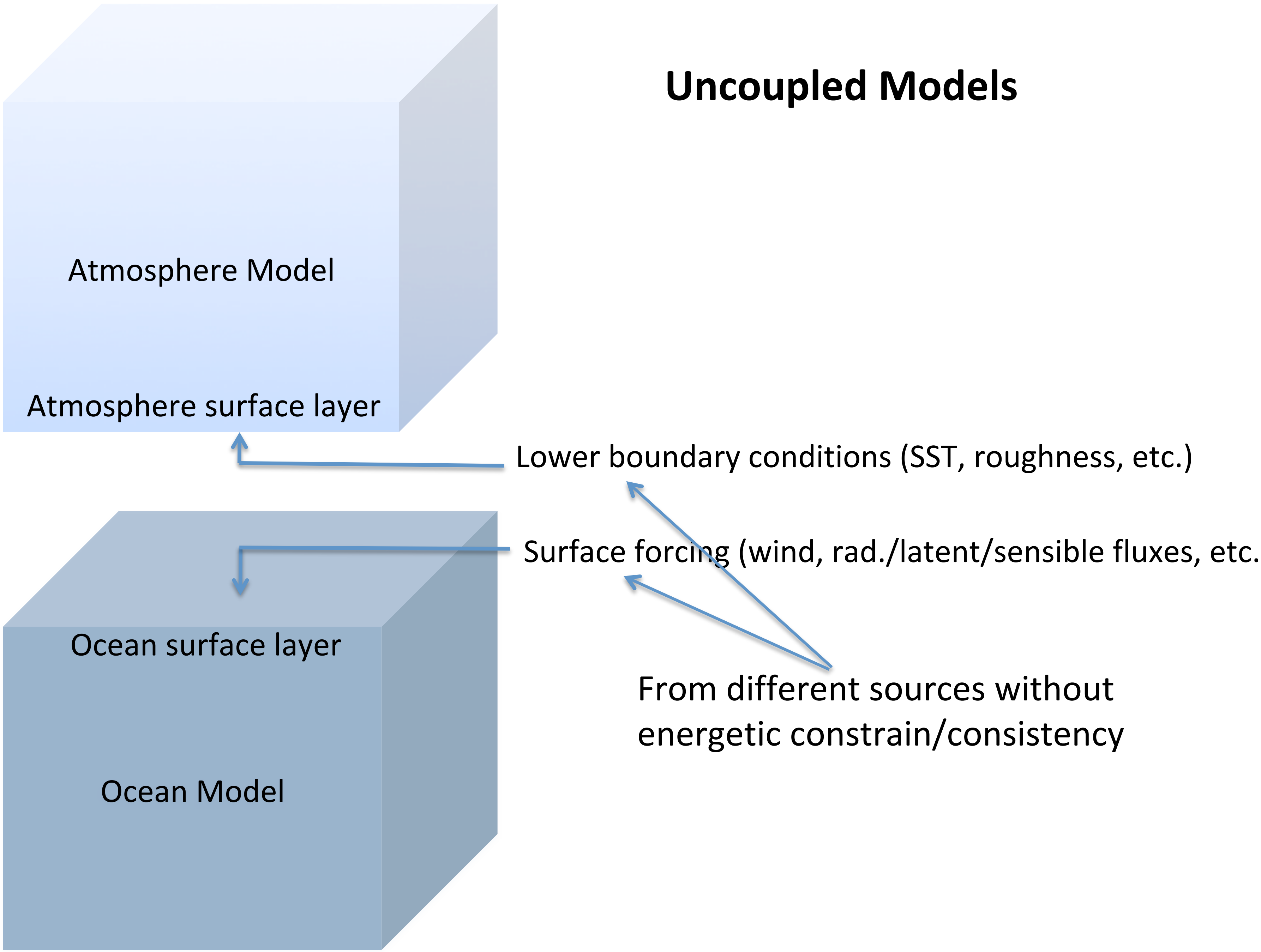
Black et al. 2007**:** Air-Sea Exchange in Hurricanes: Synthesis of Observations from the Coupled Boundary Layer Air-Sea Transfer Experiment, *BAMS*, 357-374.

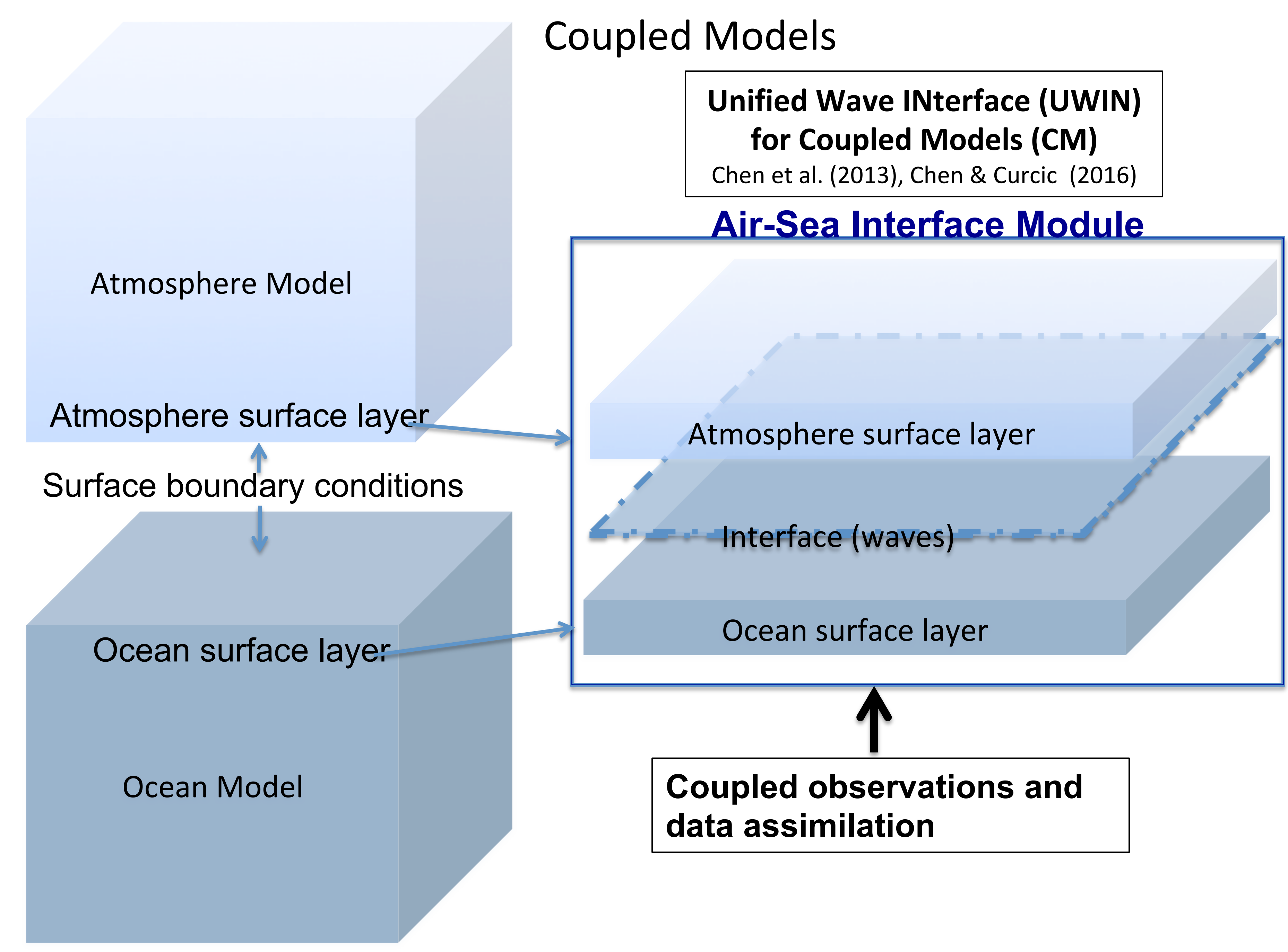
Chen et al. 2007**:** The CBLAST-Hurricane Program and the next-generation fully coupled atmosphere-wave-ocean models for hurricane research and prediction. *BAMS, 311-317*.

Edson et al. 2007**:** The Coupled Boundary Layers and Air-Sea Transfer Experiment in Low Winds (CBLAST-LOW).

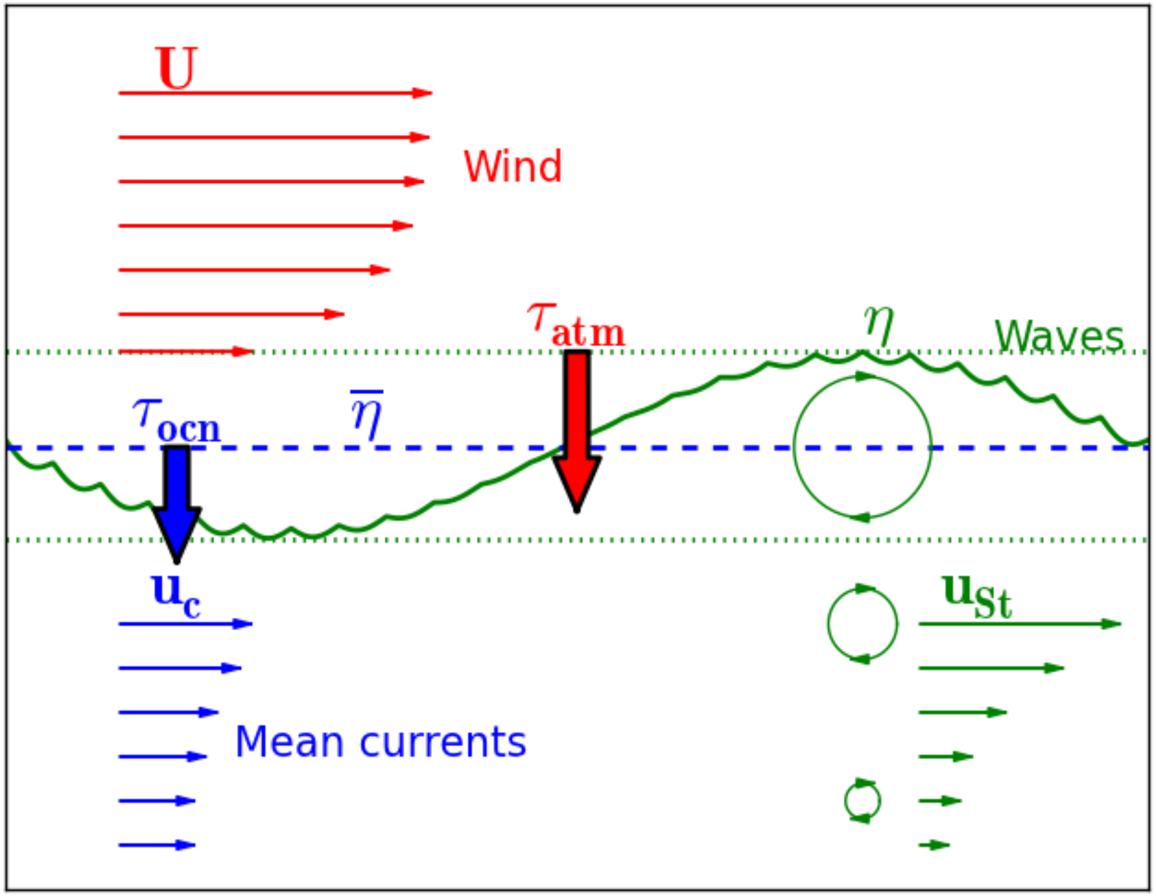


Uncoupled Models




Coupled Models
Unified Wave INterface (UWIN)
for Coupled Models (CM)
Chen et al. (2013), Chen & Curcic (2016)
Air-Sea Interface Module
Atmosphere Model
Atmosphere surface layer
Surface boundary conditions
Ocean surface layer
Ocean Model
Atmosphere surface layer
Interface (waves)
Ocean surface layer
Coupled observations and
data assimilation

Air-Sea Momentum Exchange through Surface Waves



$\tau_{atm} > \tau_{ocn}$, when wave growth is greater than dissipation

Momentum Equations without Waves

Atmosphere:

$$\partial(\rho\boldsymbol{u})_A/\partial t + \nabla(\rho\boldsymbol{u}^2)_A + 2\boldsymbol{\Omega}\times(\rho\boldsymbol{u})_A = -\nabla p + \partial\boldsymbol{\tau}/\partial z + \mu\nabla^2\boldsymbol{u}_A + \boldsymbol{\Phi}_A$$

at z = 0

Ocean:

$$\partial(\rho\boldsymbol{u})_O/\partial t + \nabla(\rho\boldsymbol{u}^2)_O + 2\boldsymbol{\Omega}\times(\rho\boldsymbol{u})_O = -\nabla p + \partial\boldsymbol{\tau}/\partial z + \mu\nabla^2\boldsymbol{u}_O + \boldsymbol{\Phi}_O$$

Unified Wave INterface (UWIN) for Coupled Models (CM)

Chen and Curcic (2016), Curcic et al. (2016)

<u>Atmosphere Momentum:</u>

$$d(\rho \boldsymbol{u})/dt = -2\Omega \times \rho \boldsymbol{u} - \nabla p + \partial \boldsymbol{\tau}/\partial z + \boldsymbol{\Phi}$$

Wind stress from wave growth

<u>Wave energy balance:</u>

$$\partial E/\partial t + \partial(\boldsymbol{c}_g + \boldsymbol{u}_E)E/\partial \boldsymbol{x} + \partial k\, E/\partial k + \partial \theta\, E/\partial \theta = S_{in} + S_{ds} + S_{nl}$$

Stokes Drift

$$\boldsymbol{u}_{St} = \int_{-\pi}^{\pi} \int_0^{\infty} \omega k^2 \cosh[2k(z+d)]/\sinh^2(kd)\, E\, d\boldsymbol{k}\, d\theta$$

Ocean stress from wave dissipation

<u>Ocean Momentum:</u>

$$d(\rho \boldsymbol{u}_E)/dt = -2\Omega \times \rho(\boldsymbol{u}_E + \boldsymbol{u}_{St}) + \rho \boldsymbol{u}_{St} \times \zeta - \nabla p + \partial \boldsymbol{\tau}/\partial z + \boldsymbol{\Phi}$$

<u>Scalar tracer transport:</u>

$$\partial C/\partial t = -(\boldsymbol{u}_E + \boldsymbol{u}_{St}) \cdot \nabla C$$

$\boldsymbol{u}_L$ - Total Lagrangian velocity

Unified Wave INterface-Coupled Model (UWIN-CM) (Chen et al. 2013, 2018)

- Weather Research and Forecasting (WRF):

  12/4/1.3 km horizontal resolution with storm following nests, 36 vertical levels (phys: YSU, Donelan+Garrat sfc., WSM5)

  Initial and boundary conditions from NCEP GFS/FNL

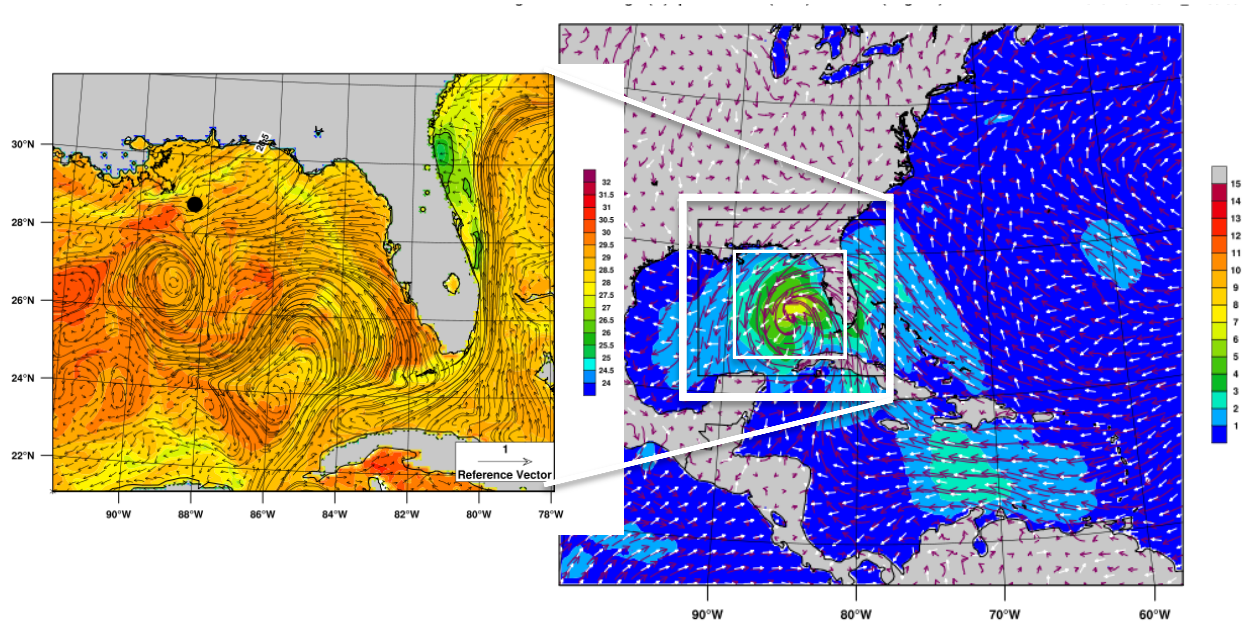
- University of Miami Wave Model (UMWM):

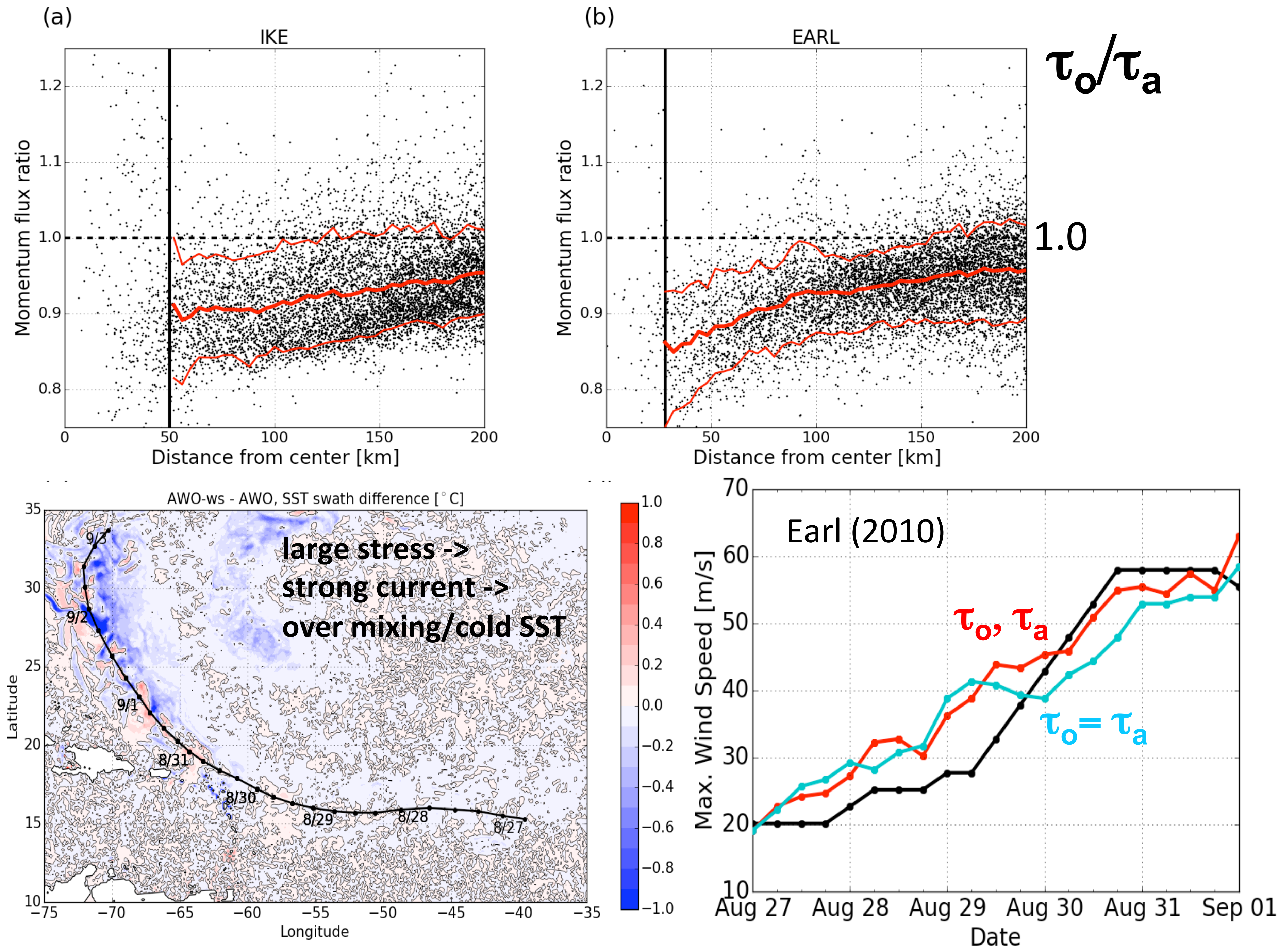
  4 km horizontal resolution, 36 directional bins and 37 frequency bins from 0.0313 - 2 Hz

- HYbrid Coordinate Ocean Model (HYCOM):

  1/25 degree (~4 km) horizontal resolution, 41 vertical levels;

  Initial and boundary conditions from global 1/12 deg. HYCOM

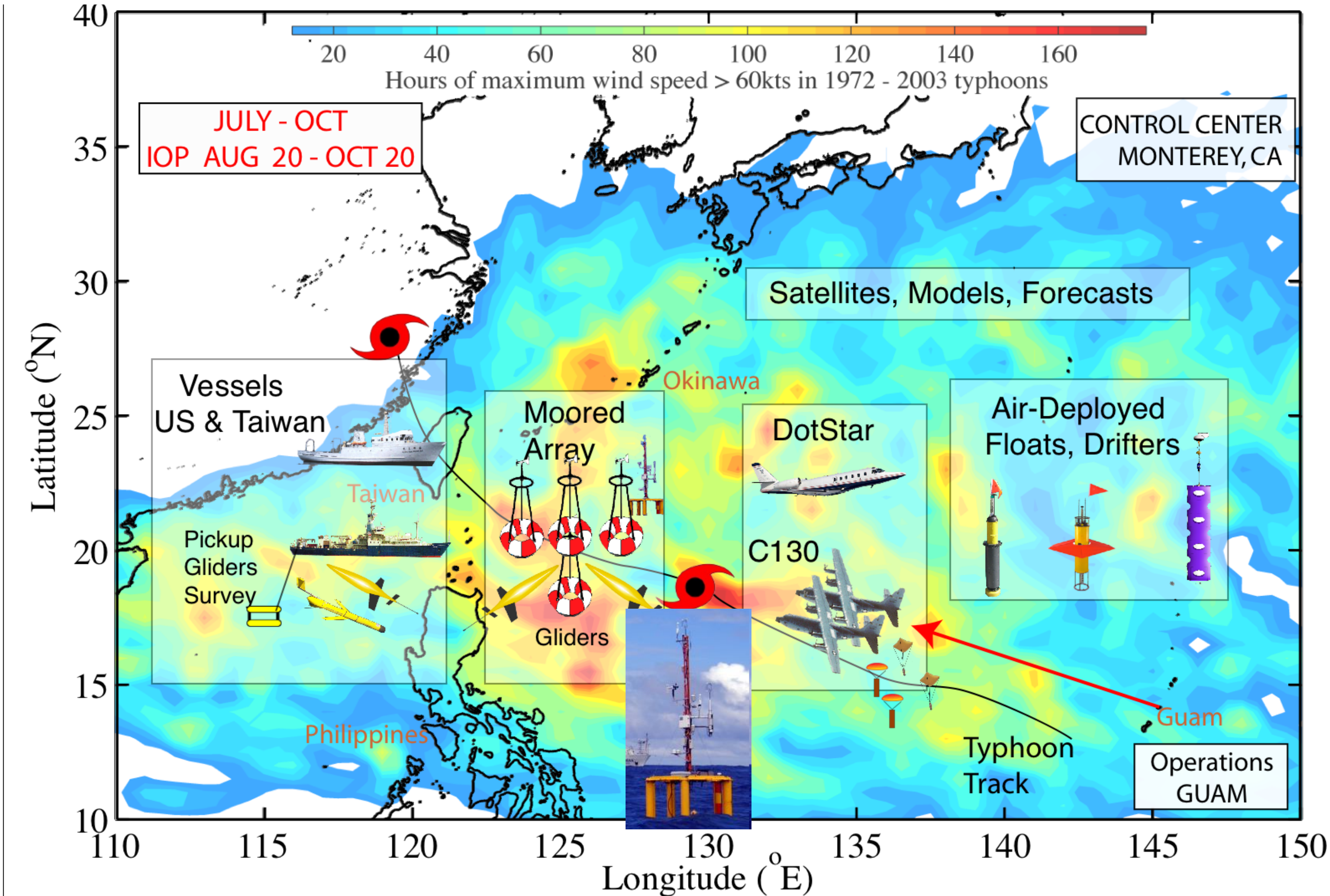




(a)
IKE
Momentum flux ratio
Distance from center [km]
(b)
EARL
Momentum flux ratio
Distance from center [km]
τo/τa
1.0
AWO-ws - AWO, SST swath difference [°C]
Latitude
Longitude
9/3
9/2
9/1
8/31
8/30
8/29
8/28
8/27
large stress ->
strong current ->
over mixing/cold SST
Earl (2010)
Max. Wind Speed [m/s]
Date
Aug 27
Aug 28
Aug 29
Aug 30
Aug 31
Sep 01
τo, τa
τo= τa

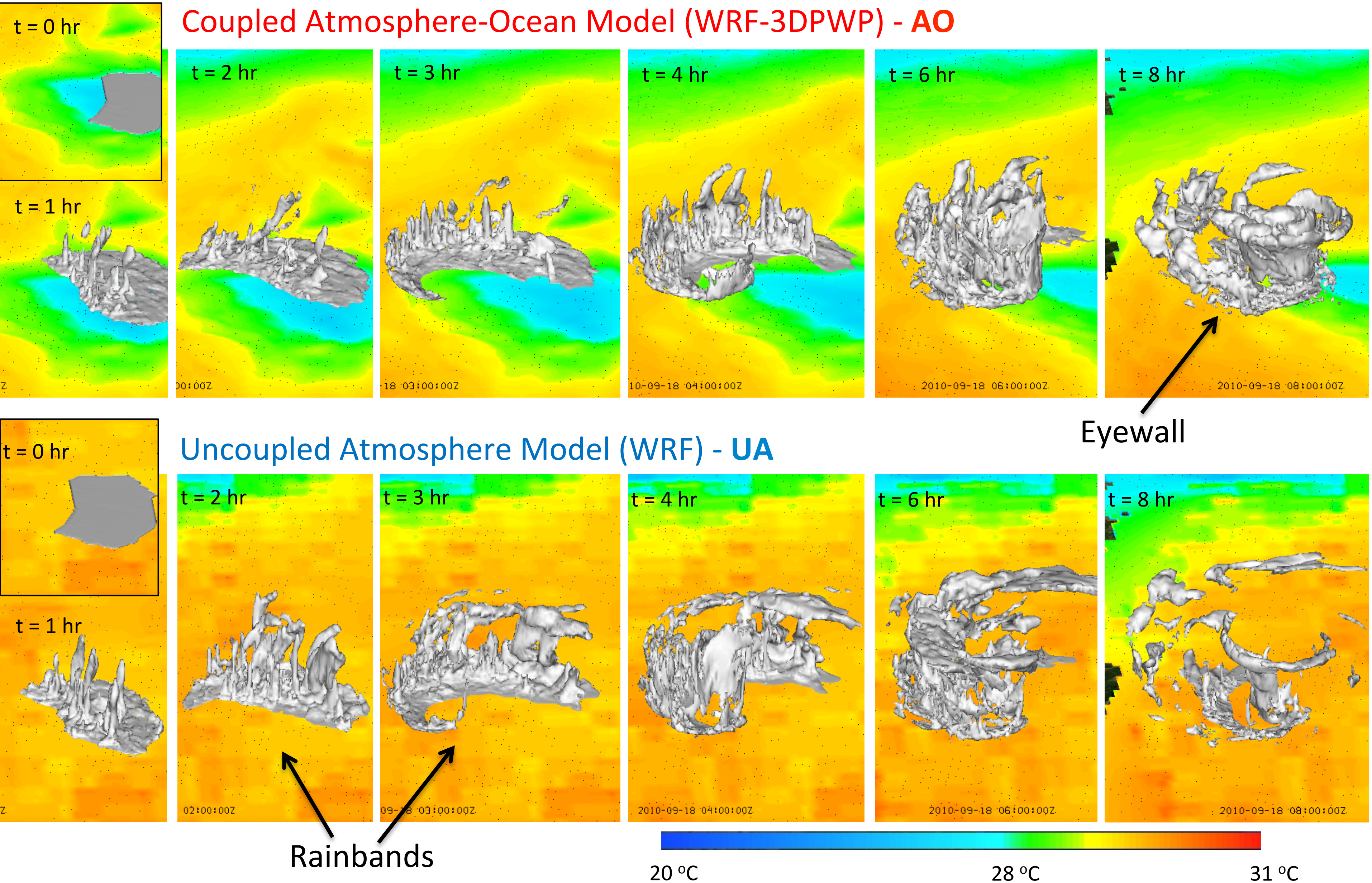
ITOP 2010 (Impact of Typhoons on the Ocean in Pacific) - D'Asaro et al. (2014)

How TC-induced cold wake affect TC structure and intensity?

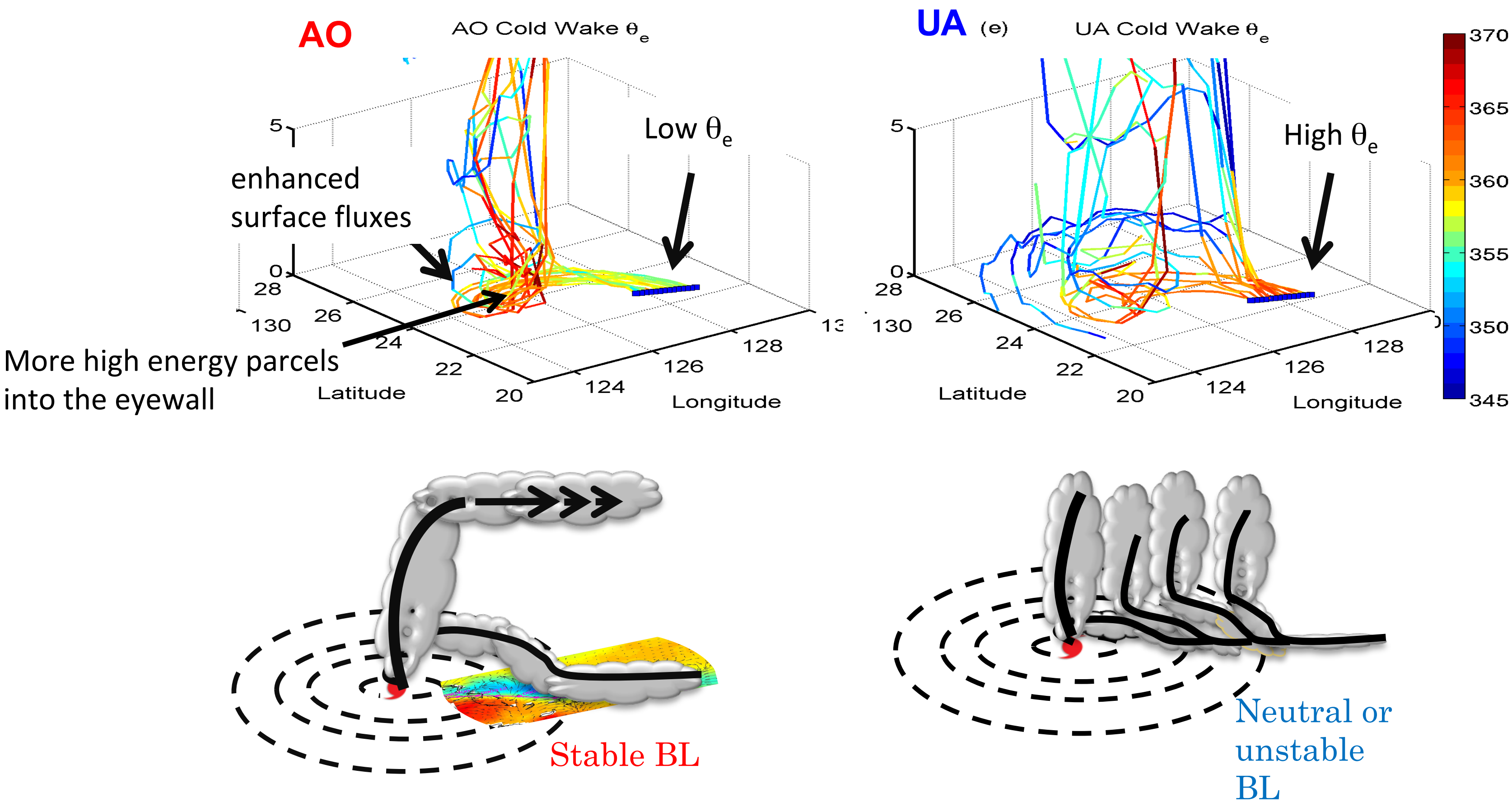


Lee and Chen (2012, 2014); Chen et al. (2019)

Typhoon Fanapi (2010): Stable BL, enhanced inflow from cold wake to eyewall

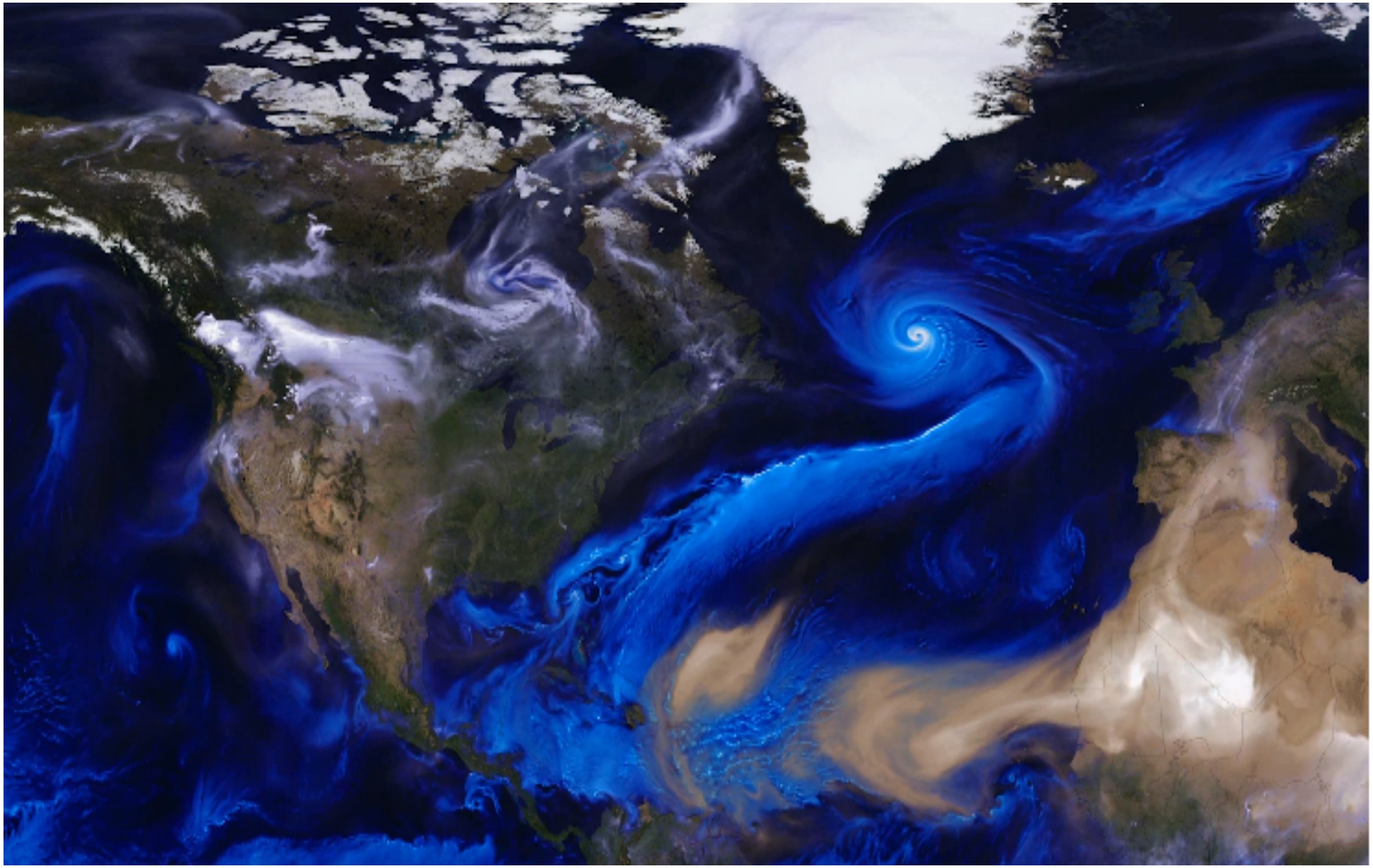


Lee and Chen (2014): Effects of Stable Boundary Layer over Cold Wake on TC Energetics and Structure



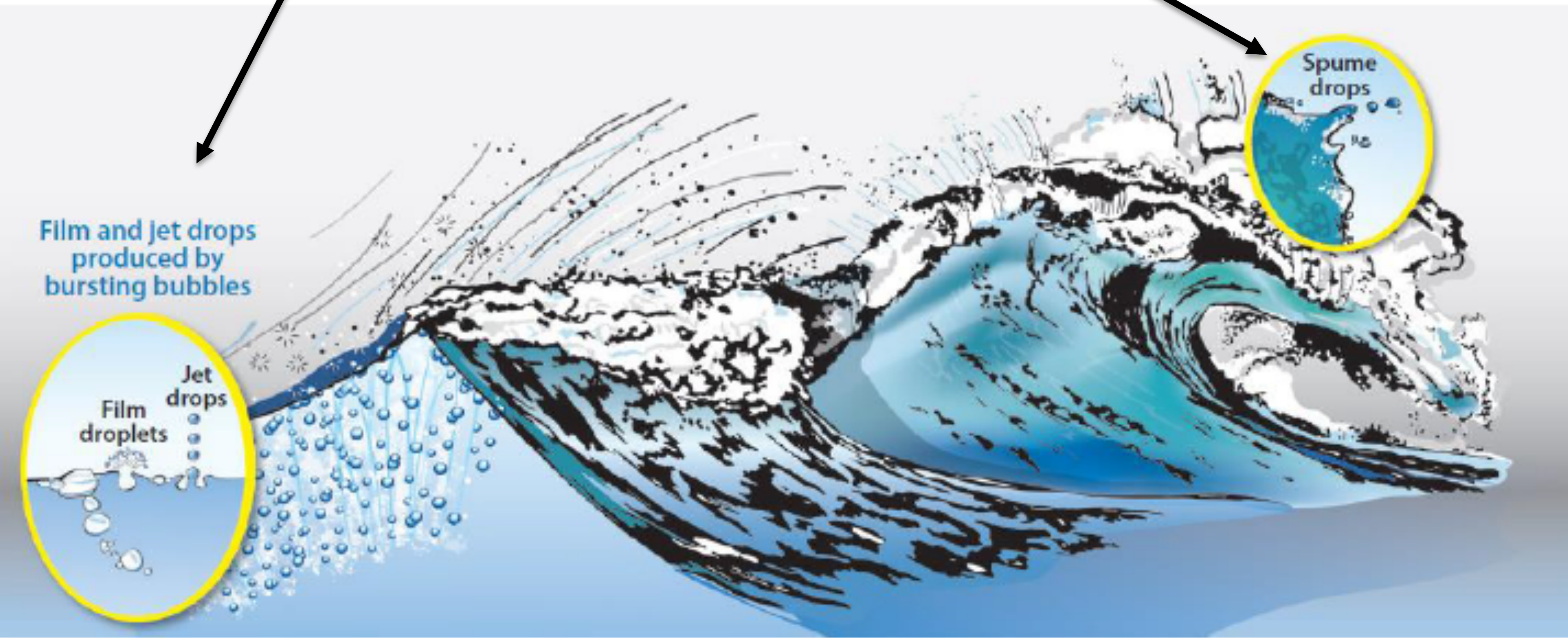
- **SBL leads to less rainband convection, increased inflow angle, enhanced heat fluxes downstream of the cold weak**
- **Although TC-induced ocean cooling reduce TC intensity, SBL over the cold wake can mitigate the negative oceanic feedback and increase the storm efficiency**

NASA GMAO GEOS model simulation of aerosol, dust (brown), sea salt (blue), and smoke (white), production and transport by weather systems on August 1, 2017.

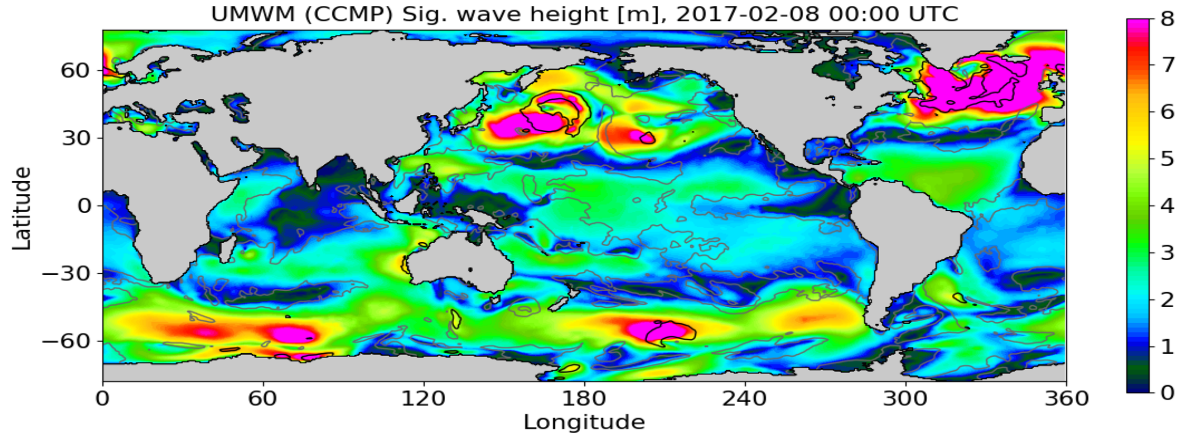


Important for sea salt aerosol production

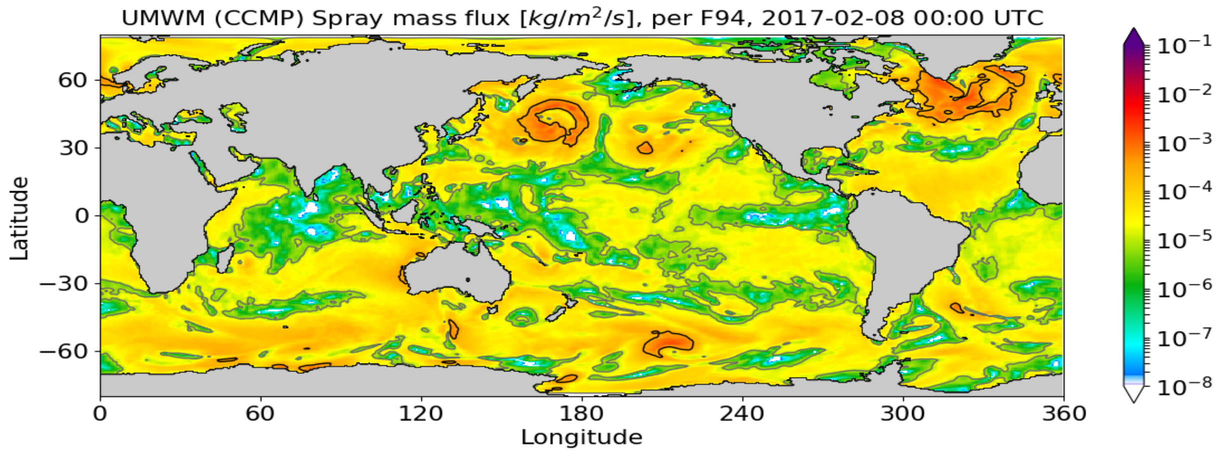
Important for heat (momentum?) fluxes



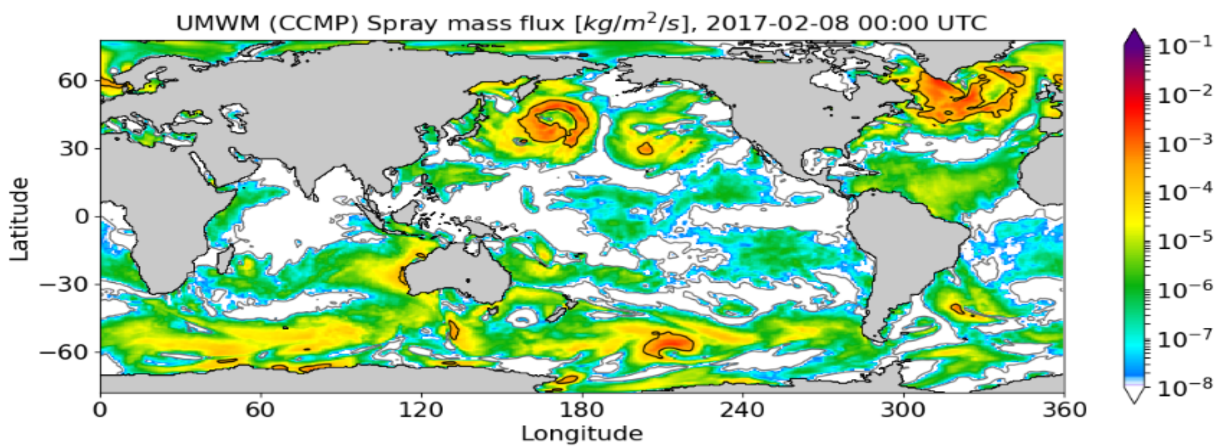
Veron (2015)



Significant wave height



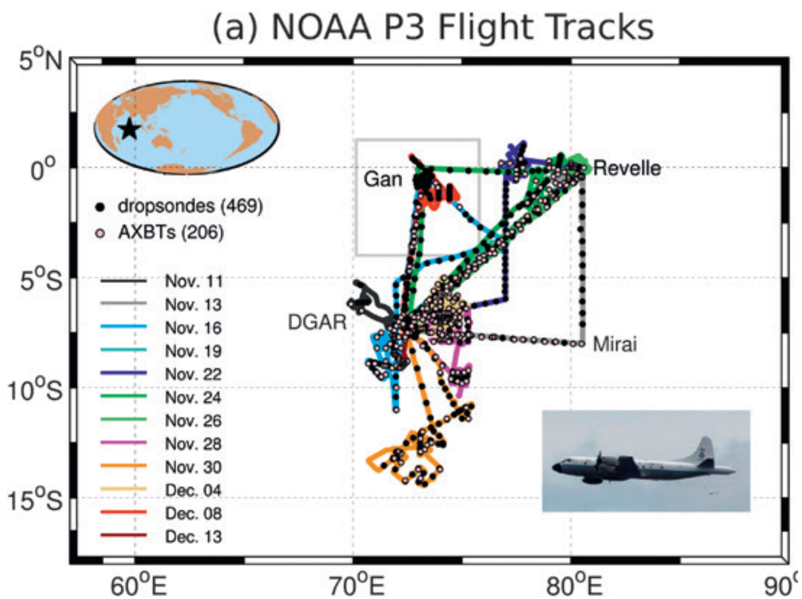
Wind-based spray mass flux (Fairall94)

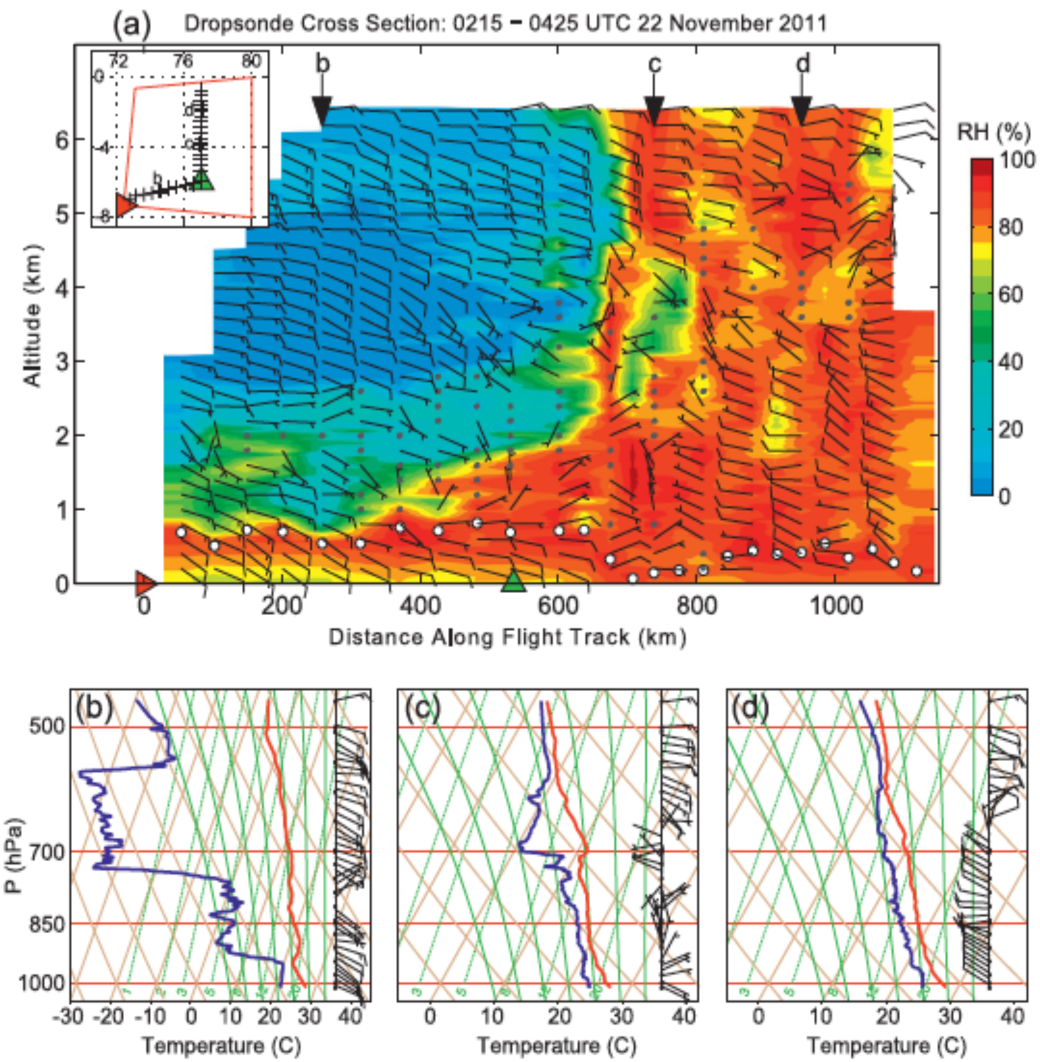


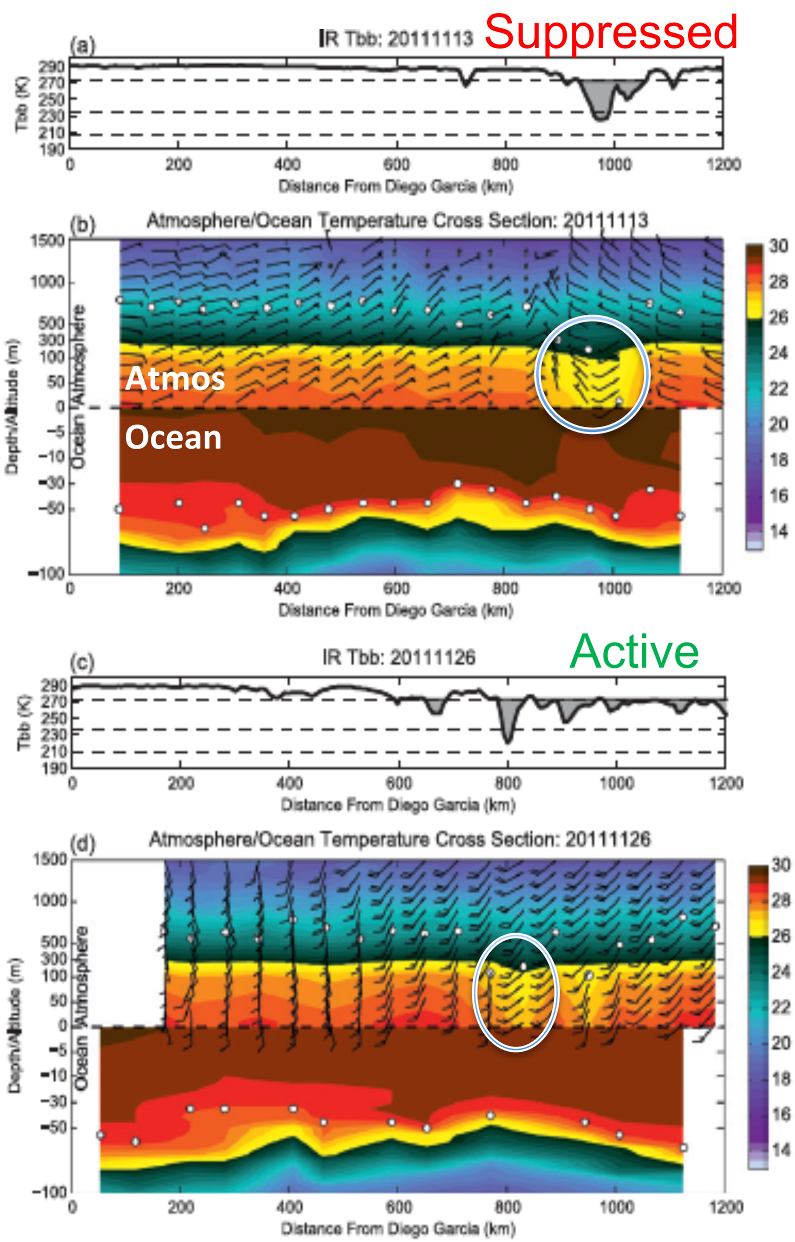
Wave-based spray mass flux (Fairall09)

10-m wind speed contours for 6 m s^{-1} (white cap) and 17 m s^{-1} (Gale force)

Chen et al. (2016, BAMS):
DYNAMO airborne observation of convection, cold pools, water vapor, and air–sea fluxes from the suppressed to active phases of MJO initiation.







Cool pool BL recovery time and air-sea fluxes (MJO suppressed, transition, active phases)

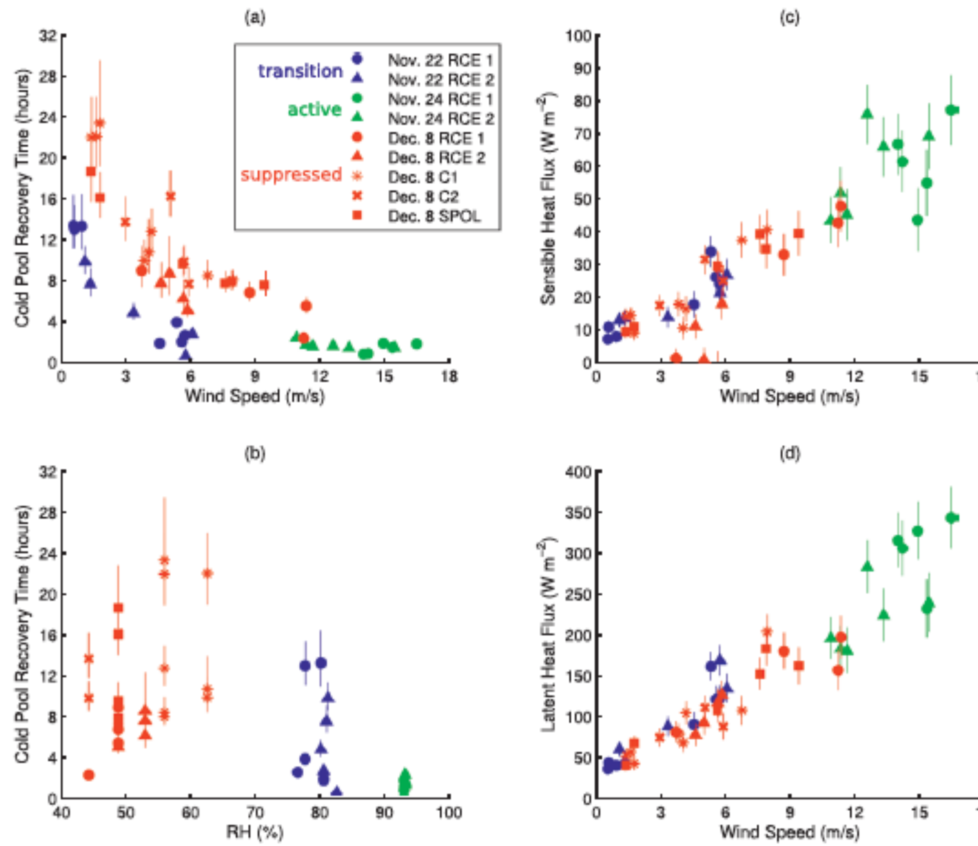
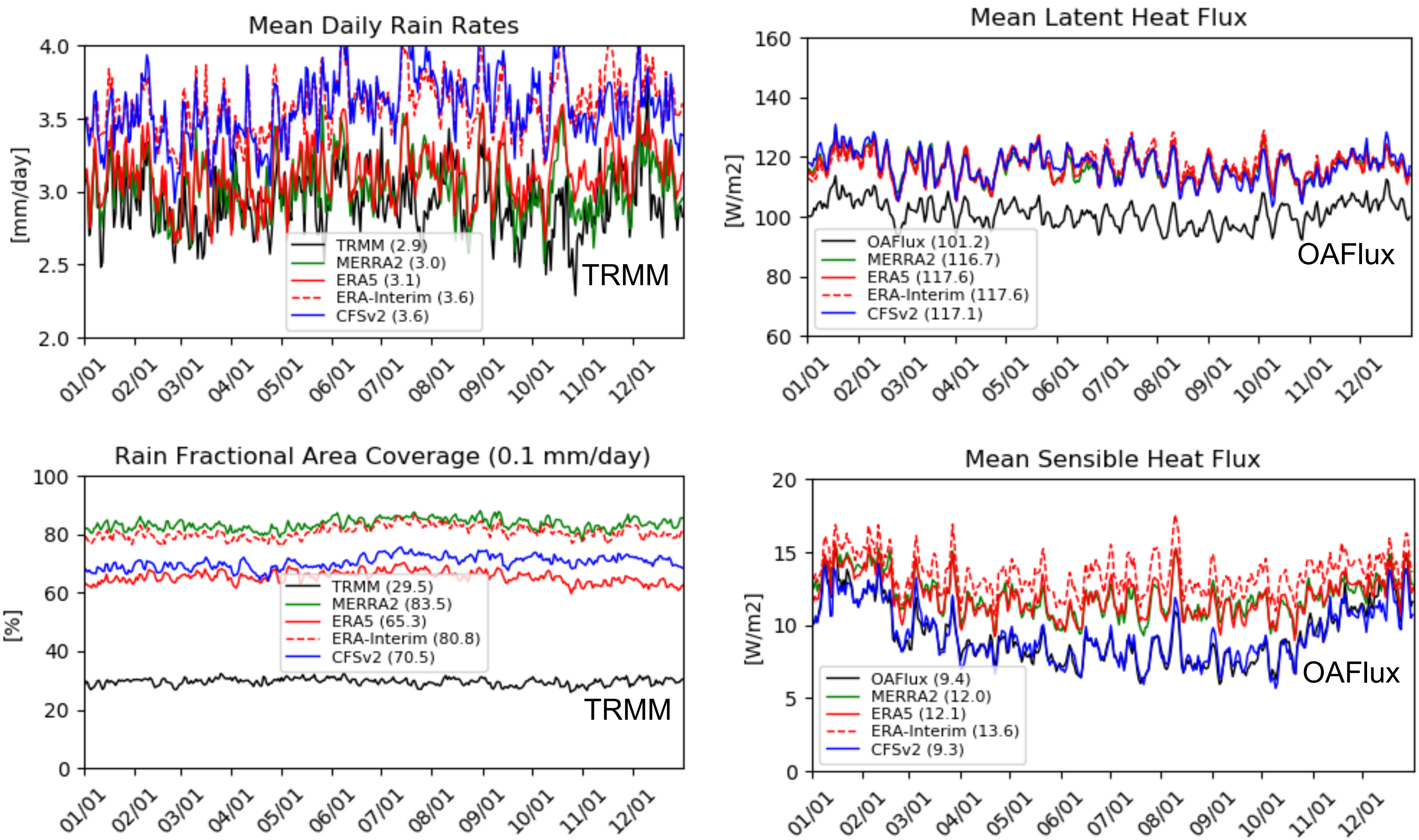


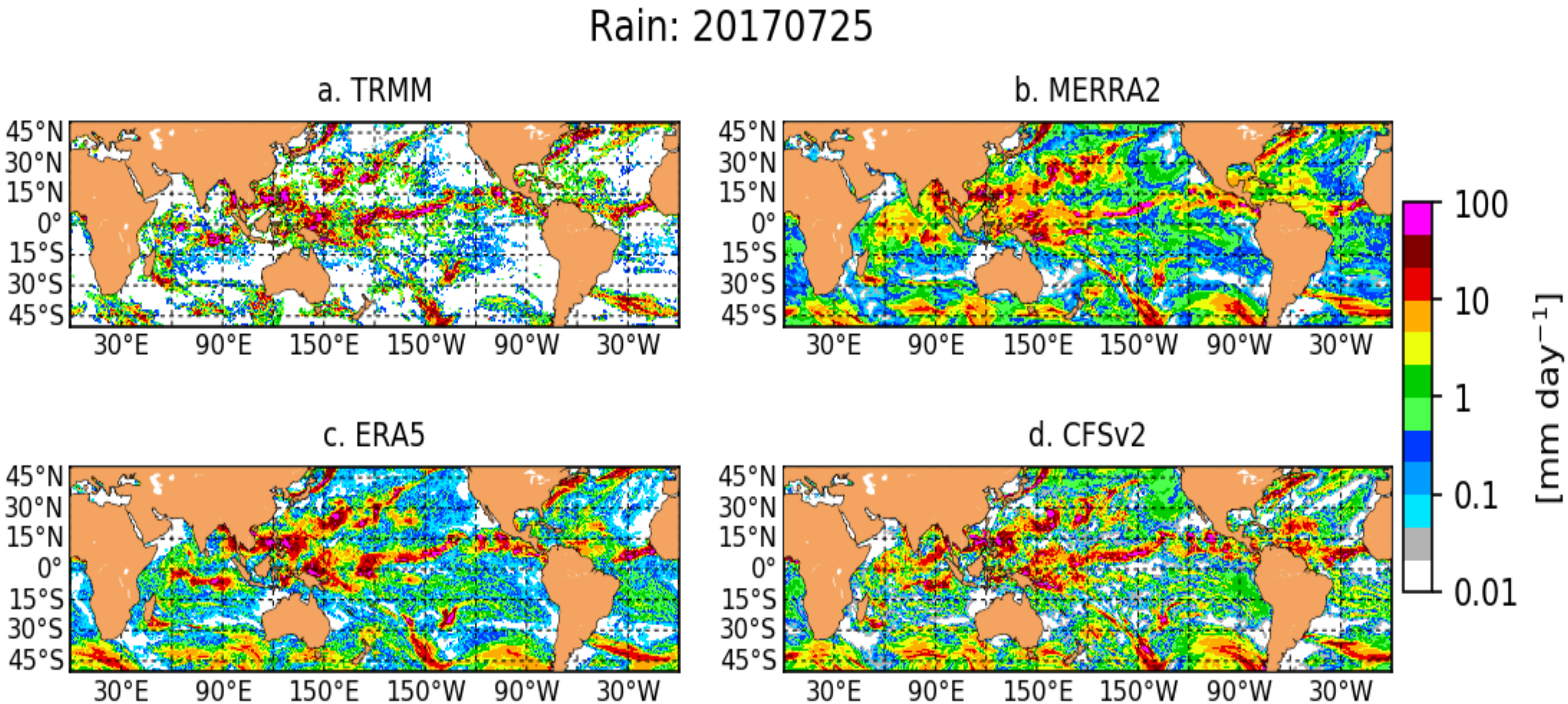
Fig. 14. The WP-3D aircraft observed convective cold pool recovery time varies with (a) wind speed and (b) the 700–500-hPa environment RH averaged over a circular area of 200–500-km radius from each dropsonde. The (c) surface sensible heat and (d) latent heat fluxes varying with wind speed, for individual convective modules from 22 Nov (blue), 24 Nov (green), and 8 Dec 2011 (red), which represent the MJO transition/onset, convectively active, and suppressed phases, respectively. The error bars represent the uncertainty due to SST ±0.5°C and the range of wind speeds within the lowest 50 m.

Chen et al. (2016, BAMS)

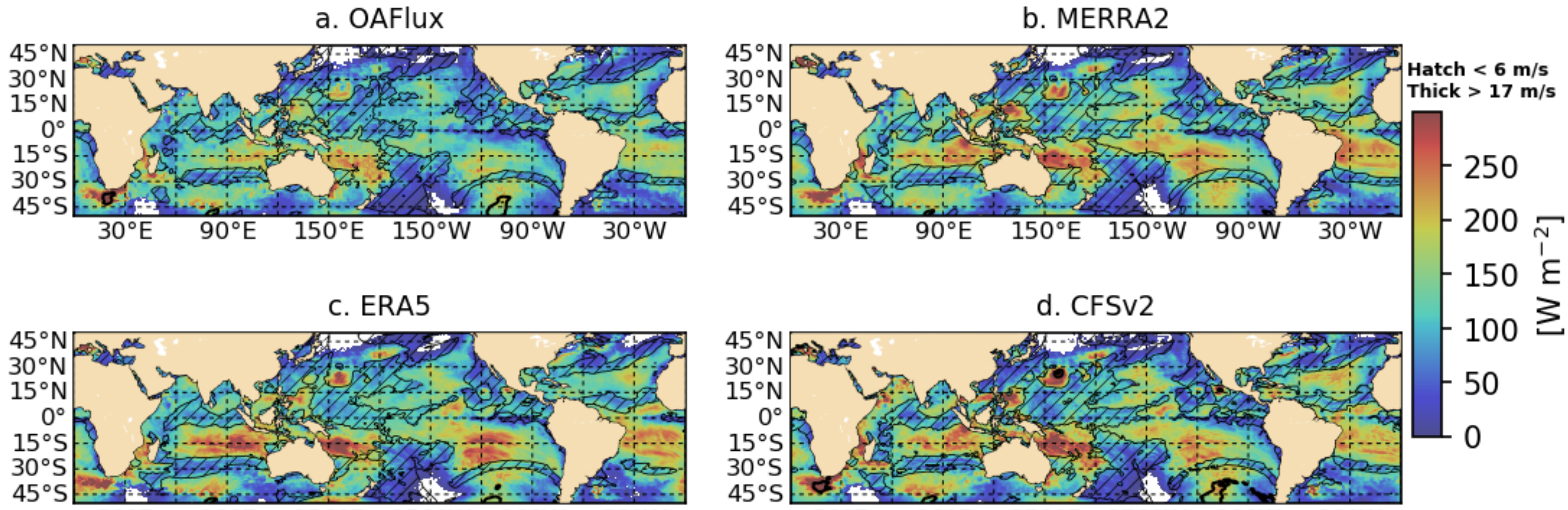
Grand challenges

Global water & energy cycle: rainfall and air-sea fluxes in global reanalysis

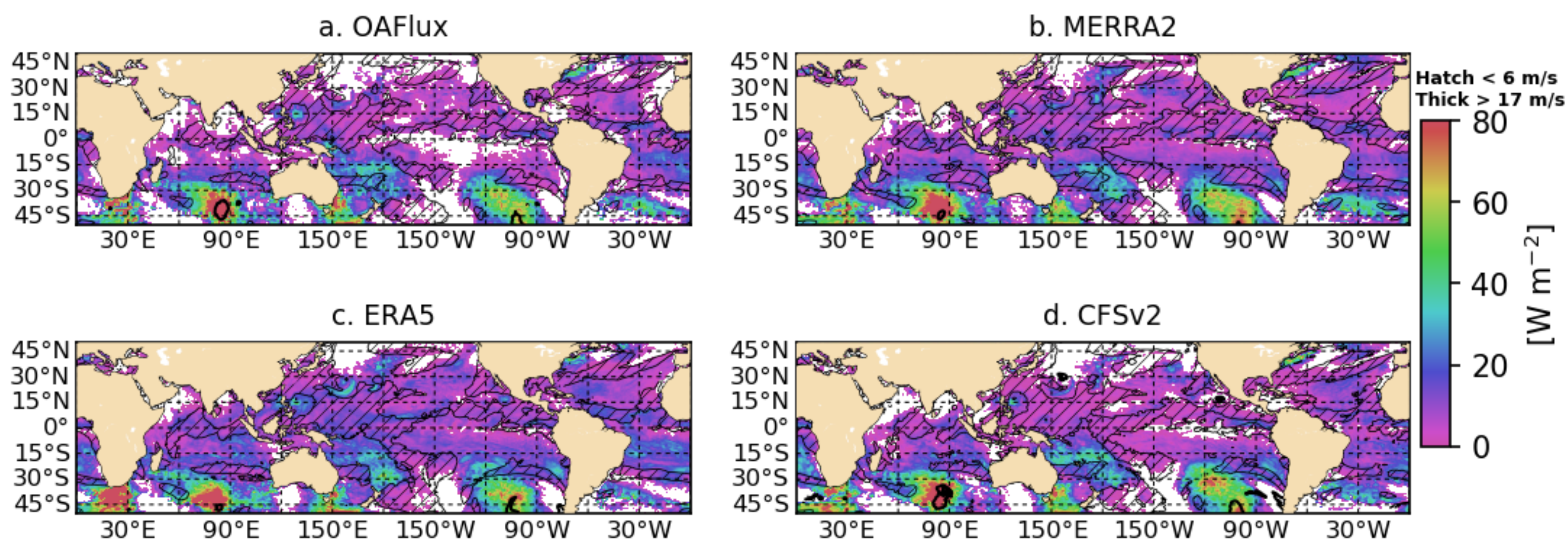



Rain: 20170725
a. TRMM
b. MERRA2
c. ERA5
d. CFSv2
45°N
30°N
15°N
0°
15°S
30°S
45°S
30°E
90°E
150°E
150°W
90°W
30°W
100
10
1
0.1
0.01
[mm day^{-1}]

Latent Heat Flux: 20170725



Sensible Heat Flux: 20170726



Progress, Challenges, and Way Forward

- **Field campaigns and coupled atmosphere-wave-ocean model development**
- **Better understanding of the physical processes in air-sea interaction**
- **Rainfall prediction and air-sea fluxes**
- **Unified physics of PBL for global weather and Climate**
- **Earth System modeling (atmosphere-wave-ocean-land-ice) and prediction, coupled observations and data assimilation**