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

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

Emanuel (1995):
- Axisymmetric hurricane model
- Bulk PBL
- Gradient wind
A Key Problem

Eric D’Asaro’s “rendition”
How surface waves affect air-sea fluxes in TCs?
**BAMS issue on CBLAST:**


**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).

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**Chen et al. (2013)**

![Graph](graph.png)

- Exchange Coefficient vs. Wind Speed
- Legend: FL, FR, RL, RR
Uncoupled Models

Atmosphere Model

Ocean Model

Atmosphere surface layer

Ocean surface layer

Lower boundary conditions (SST, roughness, etc.)

Surface forcing (wind, rad./latent/sensible fluxes, etc.)

From different sources without energetic constrain/consistency
Atmosphere Model

Ocean Model

Surface boundary conditions

Atmosphere surface layer

Ocean surface layer

Air-Sea Interface Module

Unified Wave INterface (UWIN) for Coupled Models (CM)
Chen et al. (2013), Chen & Curcic (2016)

Coupled observations and data assimilation
Air-Sea Momentum Exchange through Surface Waves

\[ \tau_{\text{atm}} > \tau_{\text{ocn}}, \text{ when wave growth is greater than dissipation} \]
Momentum Equations without Waves

Atmosphere:

\[ \partial (\rho u) \downarrow A / \partial t + \nabla (\rho u^2) \downarrow A + 2\Omega \times (\rho u) \downarrow A = - \nabla p + \partial \tau / \partial z + \mu \nabla^2 u \downarrow A + \Phi \downarrow A \]

Ocean:

\[ \partial (\rho u) \downarrow O / \partial t + \nabla (\rho u^2) \downarrow O + 2\Omega \times (\rho u) \downarrow O = - \nabla p + \partial \tau / \partial z + \mu \nabla^2 u \downarrow O + \Phi \downarrow O \]
Unified Wave INterface (UWIN) for Coupled Models (CM)
Chen and Curcic (2016), Curcic et al. (2016)

Atmosphere Momentum:
\[ \frac{d(\rho \mathbf{u})}{dt} = -2\Omega \times \rho \mathbf{u} - \nabla p + \partial \mathbf{r} / \partial z + \Phi \]

Wave energy balance:
\[ \frac{\partial E}{\partial t} + \partial (\mathbf{c} \downarrow g + \mathbf{u} \downarrow E) E / \partial x + \partial k E / \partial k + \partial \theta E / \partial \theta = S \downarrow \text{in} + S \downarrow ds + S \downarrow \text{nl} \]

Stokes Drift
\[ \mathbf{u} \downarrow \text{St} = \int -\pi \uparrow \pi \int 0 \uparrow \infty \omega k \uparrow 2 \cosh[2k(z+d)] / \sinh \uparrow 2 (kd) F d k d \theta \]

Ocean Momentum:
\[ \frac{d(\rho \mathbf{u} \downarrow E)}{dt} = -2\Omega \times \rho (\mathbf{u} \downarrow E + \mathbf{u} \downarrow \text{St}) + \rho \mathbf{u} \downarrow \text{St} \times \zeta - \nabla p + \partial \mathbf{r} / \partial z + \Phi \]

Scalar tracer transport:
\[ \frac{\partial C}{\partial t} = - (\mathbf{u} \downarrow E + \mathbf{u} \downarrow \text{St}) \cdot \nabla C \]

\[ \mathbf{u} \downarrow L \] - 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
\( \frac{\tau_o}{\tau_a} \)

Earl (2010)

large stress -> strong current -> over mixing/cold SST

\( \tau_o = \tau_a \)
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

**Coupled Atmosphere-Ocean Model (WRF-3DPWP) - AO**

**Uncoupled Atmosphere Model (WRF) - UA**
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

More high energy parcels into the eyewall

- Enhanced surface fluxes
- Neutral or unstable BL
- 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)

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
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