HAROKOPIO UNIVERSITY OF ATHENS
DEPARTMENT OF GEOGRAPHY

ATMOSPHERE AND CLIMATE DYNAMICS GROUP (ACDG)
http://meteoclima.gr

Coastal Hydrology and Surface Processes linked to Air/Sea Modeling:
1st community of users workshop
Madeira Island 26-27 September 2017

The impact of rain on ocean wave evolution and its feedback to the atmosphere

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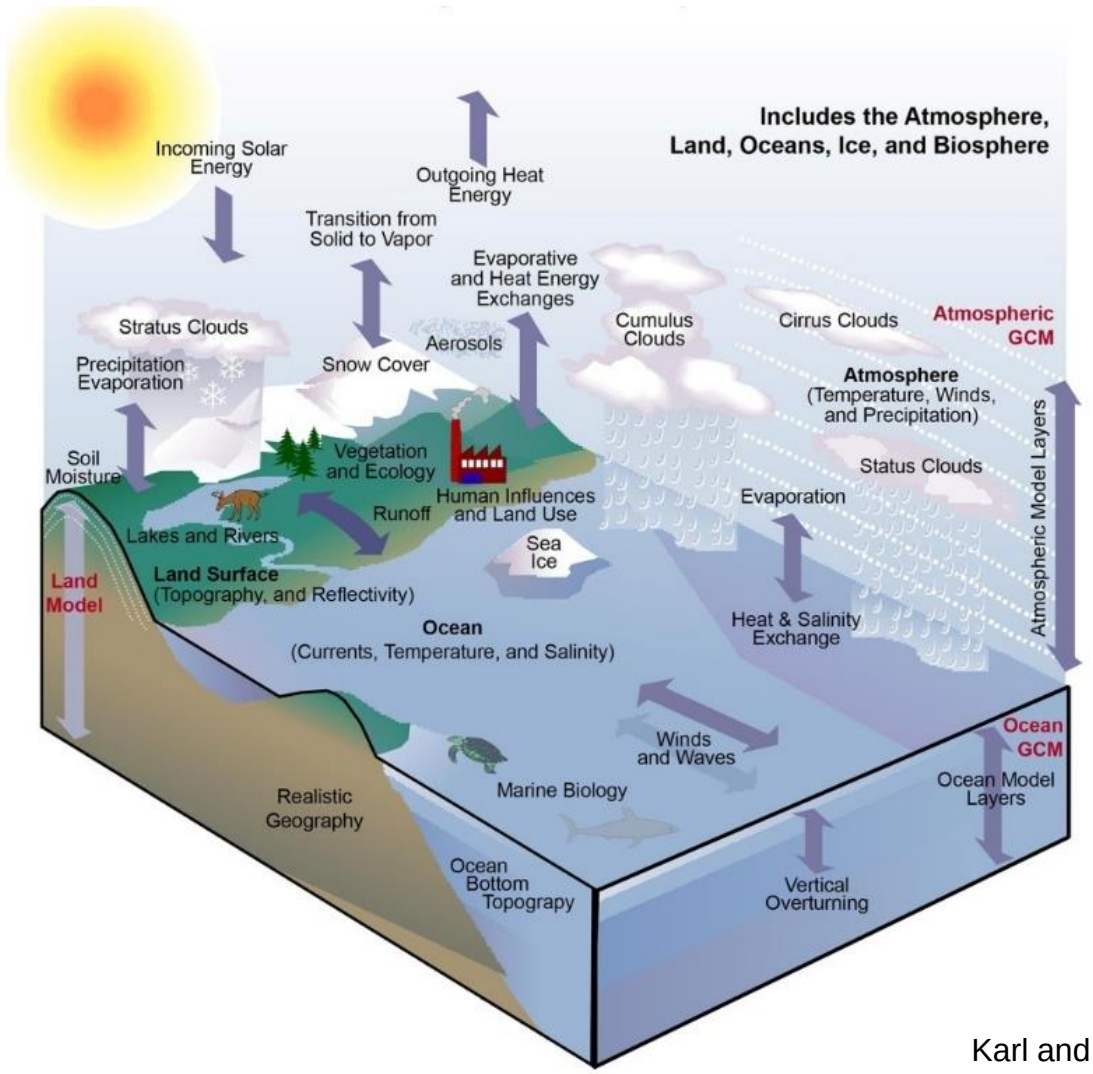
Air-sea interaction processes



Karl and Trenberth, 2003

Why coupling?

- ✓ On the basis of air-ocean wave dynamics, medium to high-frequency waves increase sea surface roughness and extract energy and momentum from the atmosphere
- ✓ The modification of momentum, enthalpy and moisture exchanges by sea surface roughness affects the characteristics of the marine atmospheric boundary layer (MABL)
- ✓ Atmosphere-wave interaction determines wave breaking and the production of sea spray as well as its impact on the dynamical and thermodynamic processes of the atmosphere (Andreas and Decosmo, 2002; Bao et al., 2011; Wu et al., 2015)
- ✓ Multi-model, multi-scale advanced prediction systems simulate the environmental processes in a cross-talking way among Earth's biosphere components (Katsafados et al., 2016)
- ✓ Coupling systems do not always demonstrate a massive improvement on the forecast skill but they do simulate the physical processes in a more realistic content

Atmosphere-ocean wave coupling

- The total roughness length consists of wave-induced (z_w), and viscous (z_v) terms

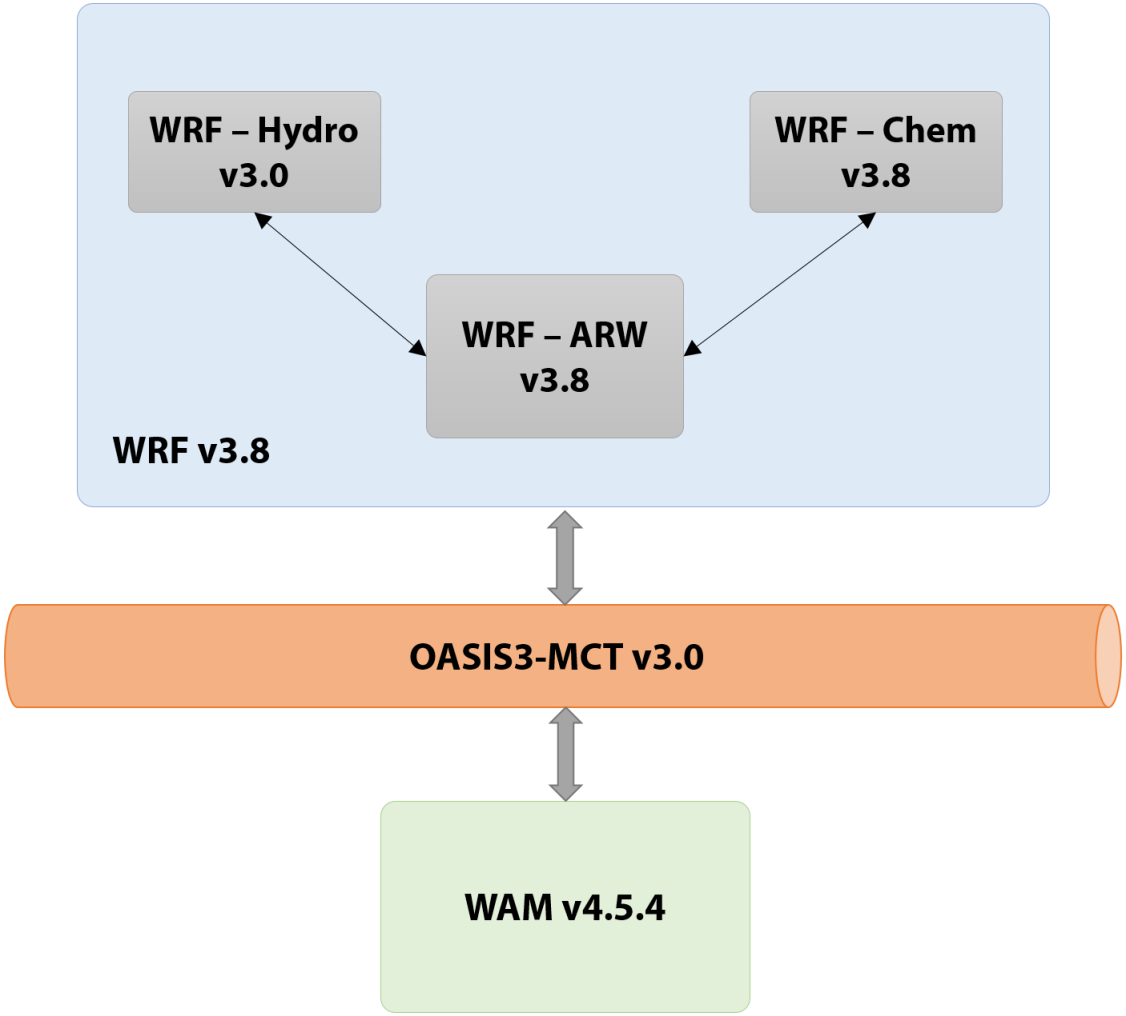
$$z_0 = z_w + z_v = \frac{a_w u_*^2}{g} + \frac{0.11 v_a}{u_*}$$

- The wave-induced term consists of the Charnock equation. Charnock parameter (a_w) is calculated by Janssen's (1991) formulation

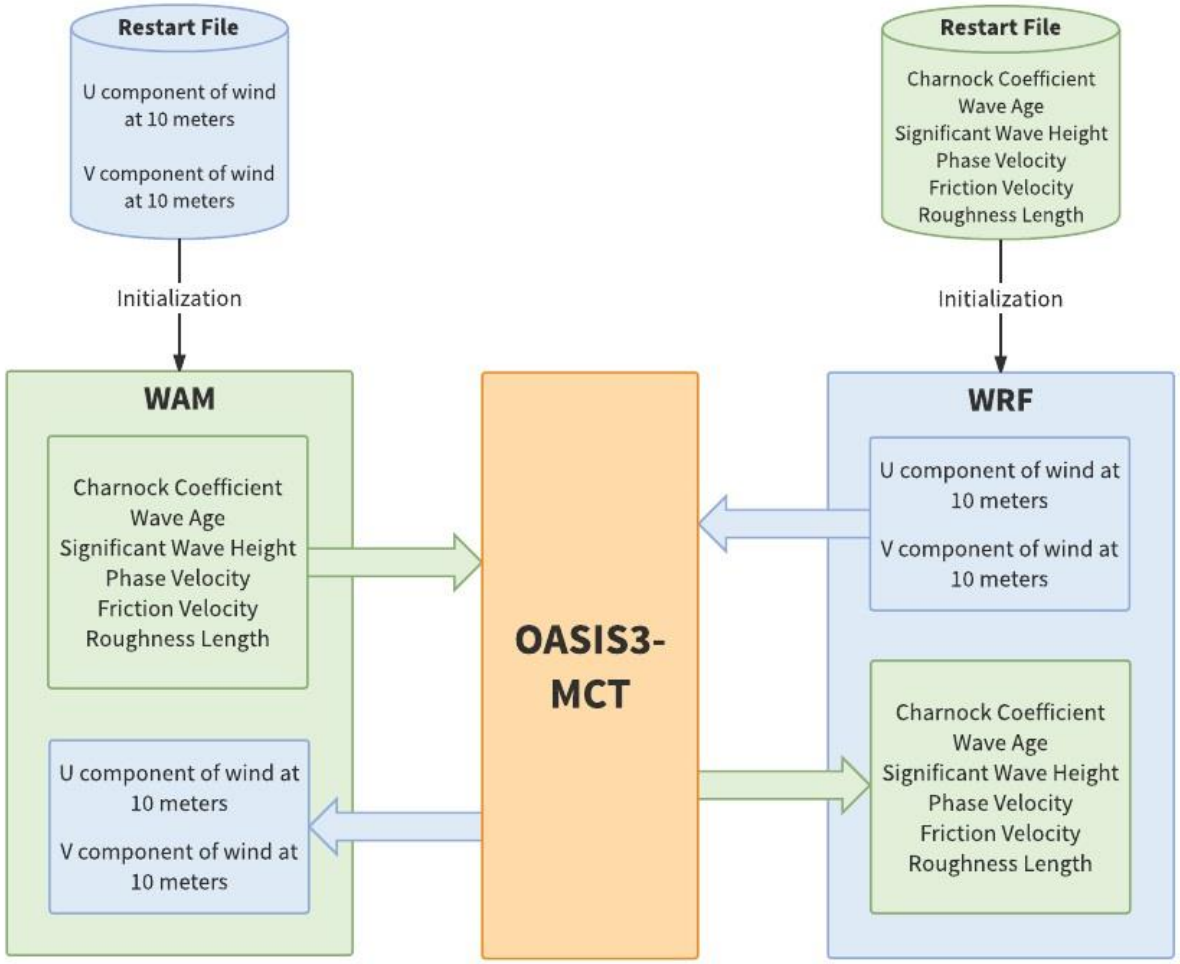
$$a_w = \frac{0.01}{\sqrt{1 - \frac{\tau_w}{\tau}}}$$

- The viscous term is significant for smooth surface in order to represent the molecular motions along the air-sea interface (v_a is the dynamical viscosity of air)

Chemical Hydrological Atmosphere Ocean Wave System (CHAOS)



CHAOS exchanging fields



Surface layer parameterizations

WRF

$$a_L = \begin{cases} \left(0.085 z_a^{3/2}\right)^{1-(1/b)} \left[0.03 z_a \exp(-0.14 z_a)\right]^{1/b}, & \sim 0.35 < z_a < 35 \\ 17.60^{1-(1/b)}\, 0.008^{1/b}, & z_a \geq 35 \end{cases}$$

$$a_S = \frac{0.48}{z_a}$$

$$Z_r = \frac{1.5 \times 10^{-4} I V_r^2 D}{g v_w}$$

$$Z_r = 0$$

$$z_0 = \frac{a u_*^2}{g} + \frac{0.11 v_a}{u_*} + Z_r$$

$$a = a_L$$

$$a = a_C = 0.0185$$

$$a = a_J$$

$$a = a_S$$

$$u_{10m} = u_a \frac{\ln\left(\frac{10+z_0}{z_0}\right) - \psi_m\left(\frac{10+z_0}{L}\right) + \psi_m\left(\frac{z_0}{L}\right)}{\ln\left(\frac{z+z_0}{z_0}\right) - \psi_m\left(\frac{z+z_0}{L}\right) + \psi_m\left(\frac{z_0}{L}\right)}$$

OASIS

WAM

$$z_a = \frac{c_p}{u_*}$$

$$c_p = \sqrt{\frac{g \lambda_p}{2\pi} \tanh\left(\frac{2\pi h}{\lambda_p}\right)}$$

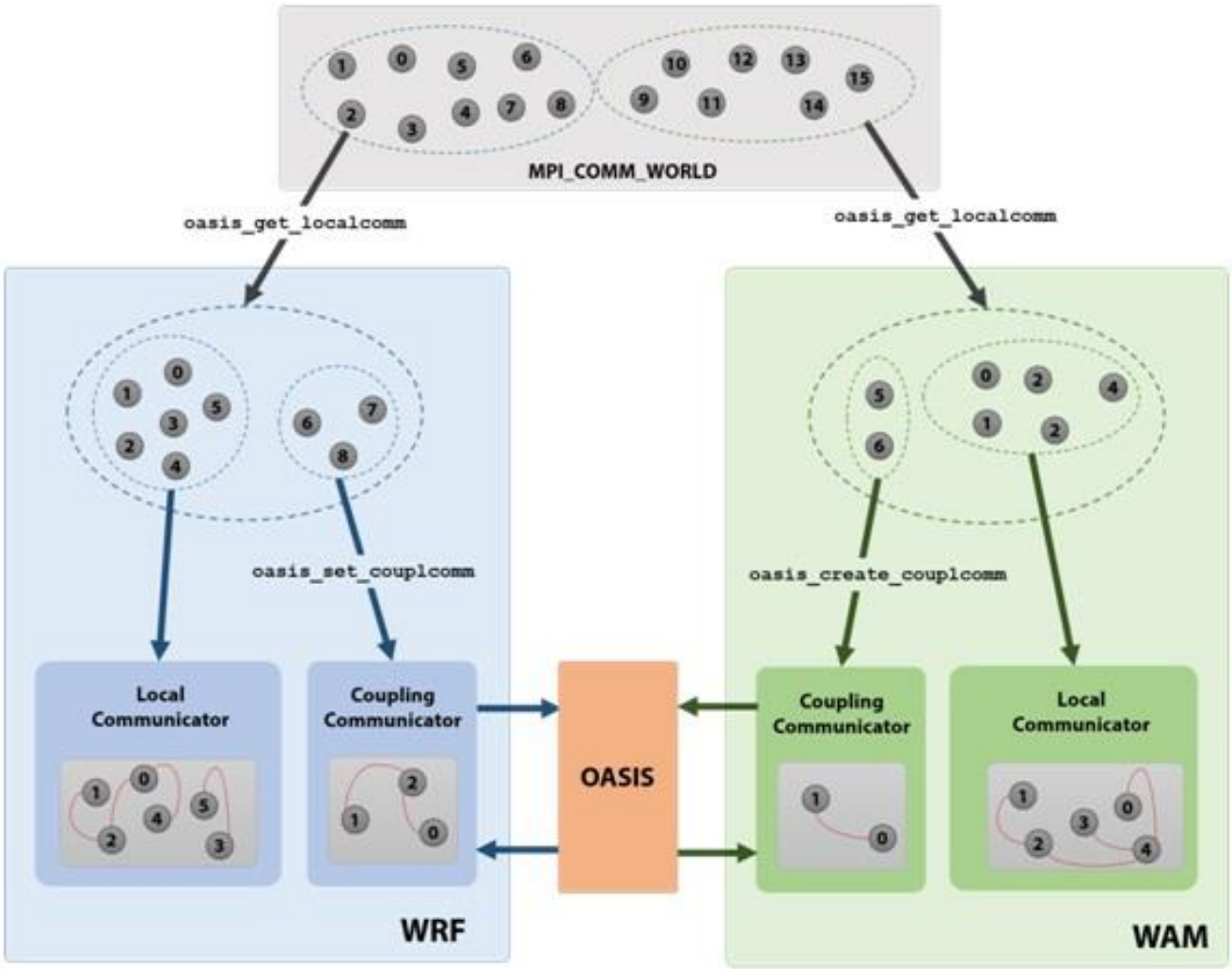
$$u_* = \frac{\kappa\, U\, z_{obs}}{\ln \frac{z_{obs}}{z_0}}$$

$$a_J = \frac{0.01}{\sqrt{1 - \frac{\tau_w}{\tau}}}$$

$$\tau = u_*^2$$

$$\tau_w = \frac{g}{\epsilon} \int S_{in} k \, d\omega \, d\theta$$

WRF-WAM technical integration through OASIS



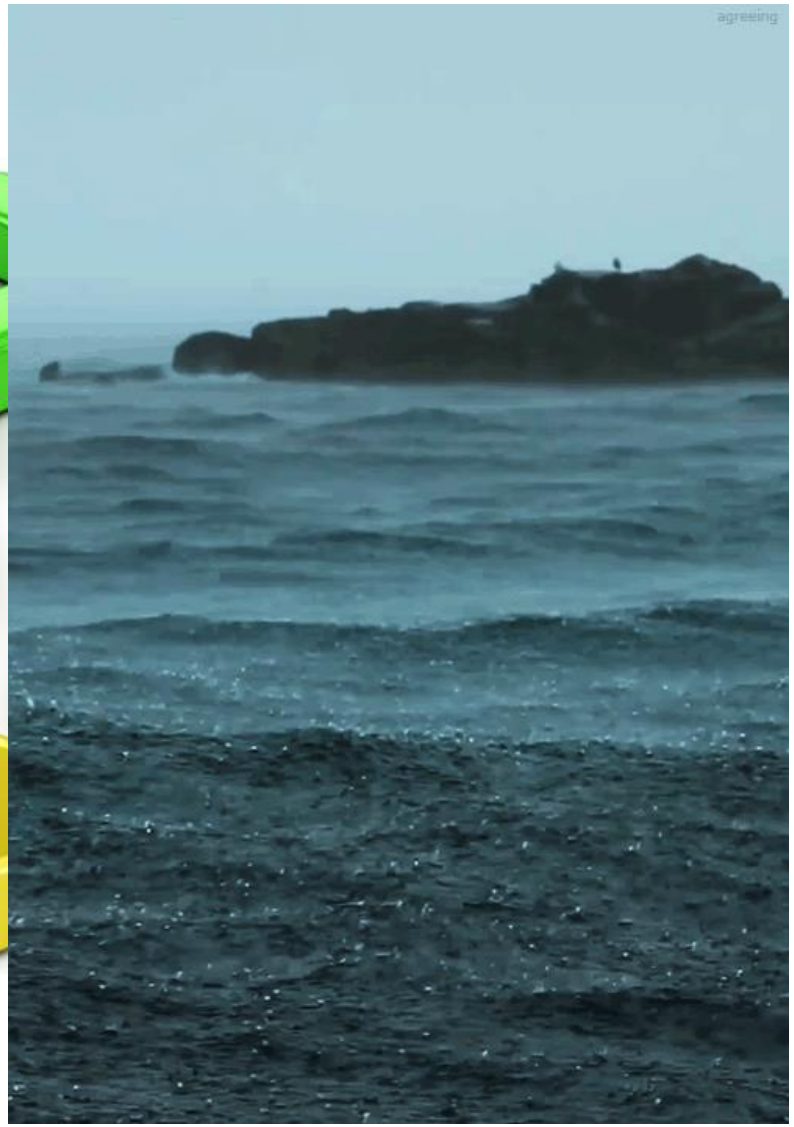
Discussion on two-way coupling

- ✓ CHAOS offer a more realistic representation of the aerodynamic roughness especially over rough sea surfaces
- ✓ Space-time Charnock variability decreases the medium to high-frequency gravity waves as the roughness length and the friction velocity are also increased
- ✓ The roughness is progressively decreased with the increase of the wave frequencies forming a more slip sea surface under swell conditions
- ✓ The improvements are more prominent for wave over open sea because the intensity of the wave spectrum is dependent to wind-generated waves and, consequently, to near surface wind speed and fetch

Discussion on two-way coupling

- ✓ Two-way coupling changes the equilibrium of air-sea enthalpy and momentum
- ✓ CHAOS simulates a more turbulent and deeper MABL having a weakening effect on the cyclonic systems as well. The energy imbalance delays the cyclone evolution and produces an average increase of the minimum MSLP
- ✓ The troposphere also responds on the perturbations come from the sea surface fluxes. Differences in water vapor mixing ratio and relative humidity are detectable up to 7 km alongside with the wind speed, the vertical velocity and the temperature up to the tropopause
- ✓ In extreme weather events, CHAOS offers robust statistical improvements up to 24% and 5% over the sea and the land, respectively

Is wind the only factor affecting the sea state?



Rain on ocean wave: The physical mechanism

- ✓ Rainfall affects the wave generation and determines the sea surface roughness by enhancing both vertical and horizontal stresses when raindrops strike the moving water surface
- ✓ **Wavy sea state** Collision between raindrops and sea surface waves → Decrease the white capping and the wave height
- ✓ **Calm sea state** Momentum flux from raindrops to sea surface → Generation of capillary waves (ripples)

Rain on ocean wave: Literature review

- For vertical or near vertical rainfall, the fluctuating sea surface forces are responsible for a non-negligible wave amplitude decay, particularly in the high frequency range (Le Mehaute and Khangaonkar, 1990)
- Kumar et al. (2009) observed that damping at low wind speed occurs when horizontal momentum produced by rain is negligible compared with the vertical momentum
- Cavaleri et al. (2015) proposed that rain attenuates high-frequency waves decreasing sea surface roughness and white-capping as well as increasing the wind speed. Young waves are very sensitive to change in external force such as the raindrop striking. On the other hand, mature waves are not much affected by rain of low intensity and short duration irrespective of wind speed magnitudes which exist over the sea-surface

The parameterization scheme

- Kumar et al. (2009), following Kitaigorodskii (1973) and Houk& Green (1976), added a rain-induced roughness length to the roughness length produced by wind blowing over sea-surface

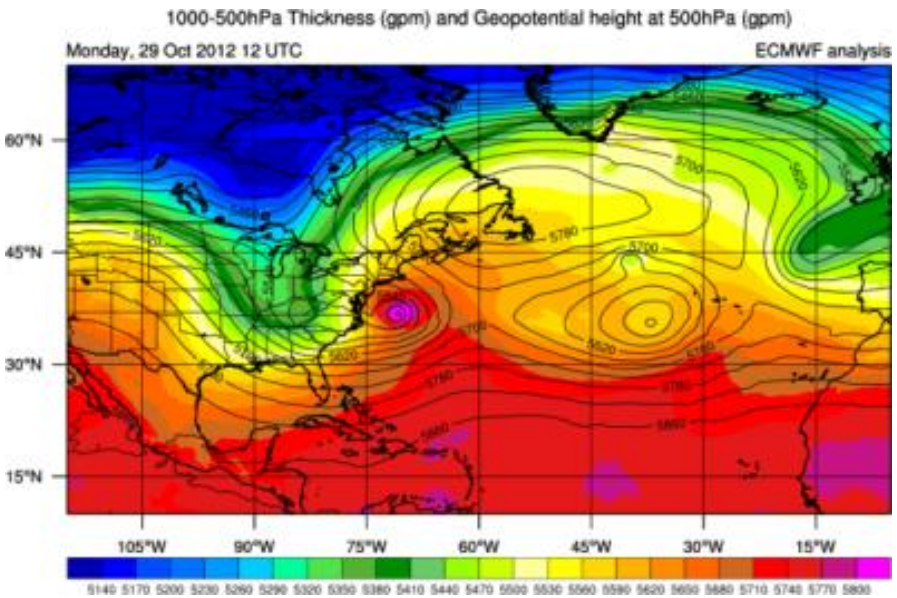
$$z_0 = z_w + z_v + z_r = \frac{a_w u_*^2}{g} + \frac{0.11 v_a}{u_*} + \frac{1.5\times10^{-4} I V_r^2 D}{g v_w}$$

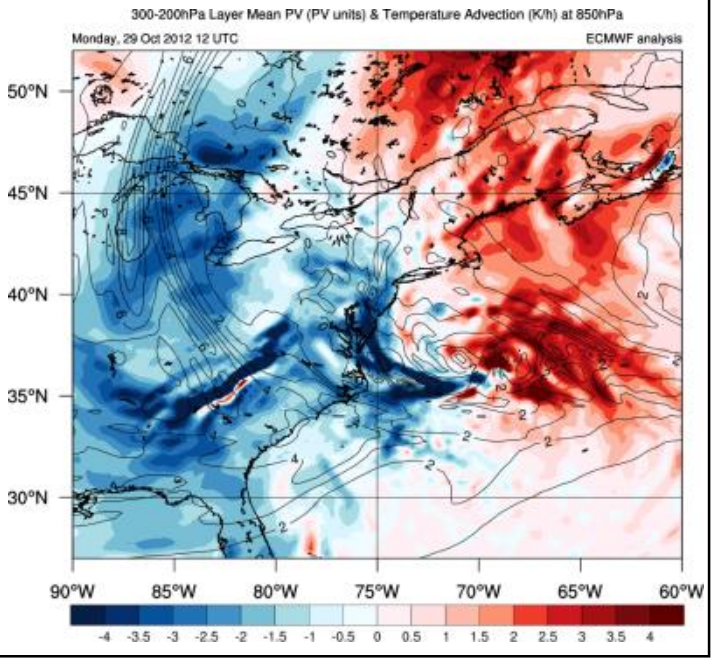
the impact of surface waves	the impact of smooth surface	the impact of rain

- In the last term, D the drop diameter, v_w is the kinematic viscosity of water, I is the rain intensity and V_r terminal velocity of the rain drop
- K is the rain kinetic energy flux $K = \frac{I V_r^2}{2}$

Case study: Hurricane Sandy (late Oct 2012)

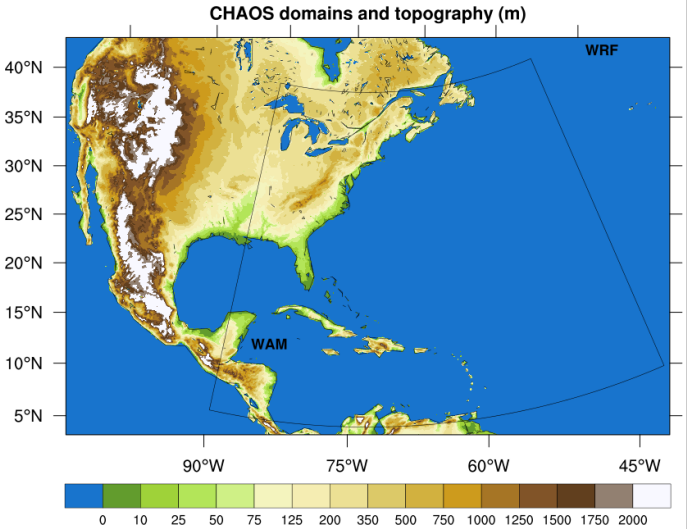
- ✓ 233 fatalities and total economic losses of up to $68 billion had been attributed to Sandy
- ✓ The relative position of a polar jet streak and a subtropical jet streak at 200hPa, caused a scale-transformation
- ✓ Combination of warm seclusion and the upper air trough at NW
- ✓ Blocking anticyclone over North Atlantic Ocean

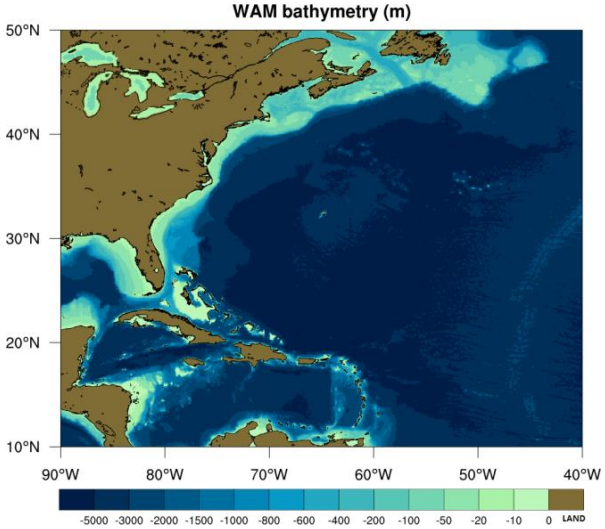




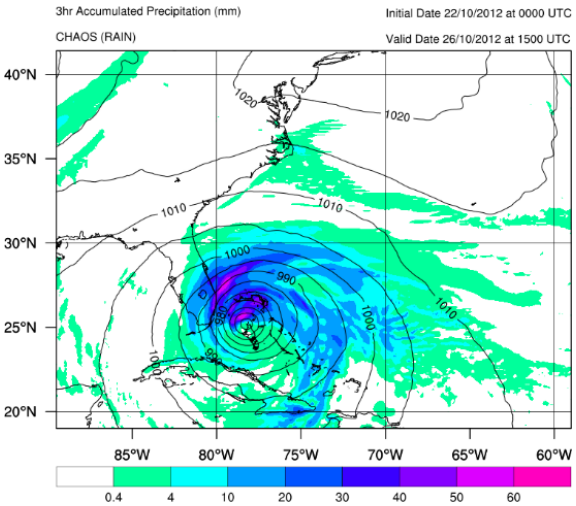
CHAOS configuration

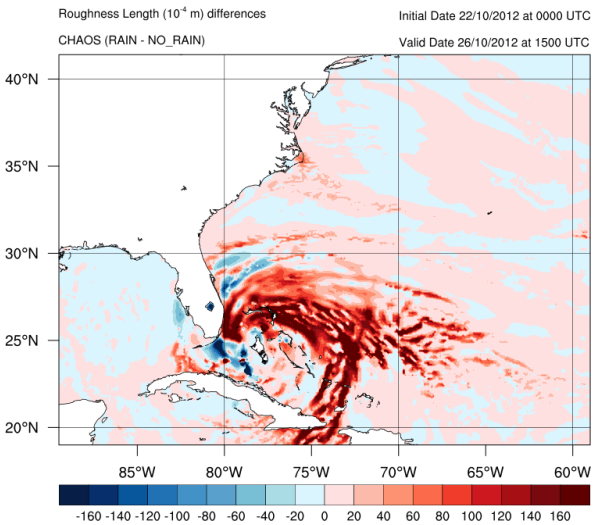
CHAOS	Atmospheric Component	Ocean Wave Component
Model	WRF-ARW, WRF-Chem V3.8 and WRF-Hydro V3.0	WAM Version 4.5.4
Coupler	OASIS3-MCT Version 3.0	
Integration Domain	Western Atlantic Ocean, Caribbean Sea, United States	
Grid	Arakawa semi-staggered C-grid	Spherical latitude-longitude grid
Horizontal grid Increment	10km x 10km	0.1^ox0.1^o
Spectral resolution	–	24 directional bins (15° directional resolution), 25 frequency bins (with first frequency = 0.04177248 Hz)
Vertical coordinate	Terrain-following hydrostatic pressure η coordinate	–
Vertical levels	38	–
Time steps	30 s	Propagation time step: 75 s Source time step: 600 s
Initial & boundary Conditions	ECMWF, 0.5^ox0.5^o 17 isobaric levels 6h update of boundary conditions	Hot start
SST	ECMWF SST update every 6 hours	–
Exchange rate	600 s	
Surface layer	Revised Monin-Obukhov	–
PBL	YSU	–
Microphysics	Thompson	–
Cumulus	Kain-Fritsch	–
Land surface	Unified NOAH	–
Radiation	RRTM	–
Chemistry options	Disabled	–
Coupled to WRF-Hydro	Disabled	–
Topography	30-arc-second USGS GMTED2010	–
Vegetation	MODIS FPAR	–
Land-use	21-class IGBP MODIS	–
Bathymetry	–	ETOPO1
Water approximation	–	Shallow water approximation with depth refraction and wave breaking due to depth change near shore

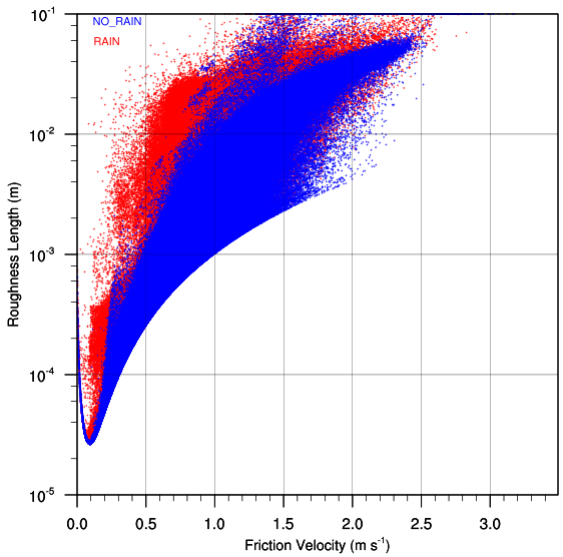


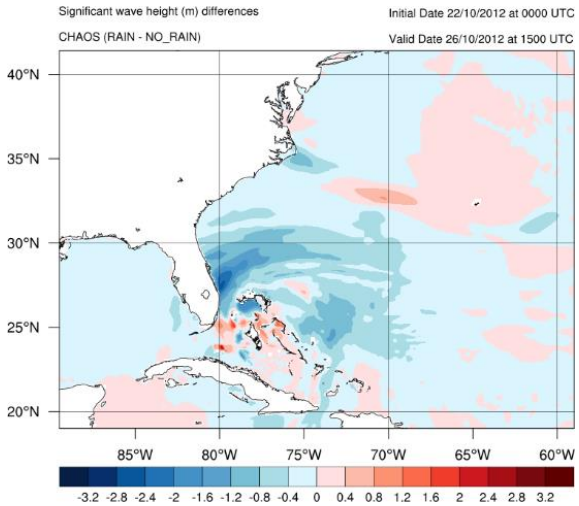


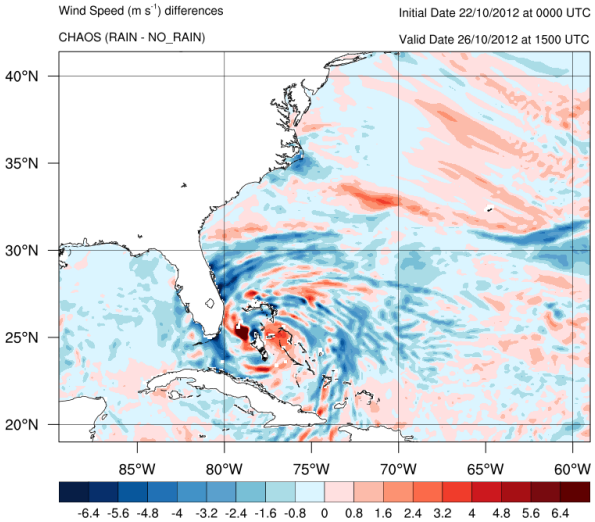
CHAOS RAIN-NO_RAIN EXPs

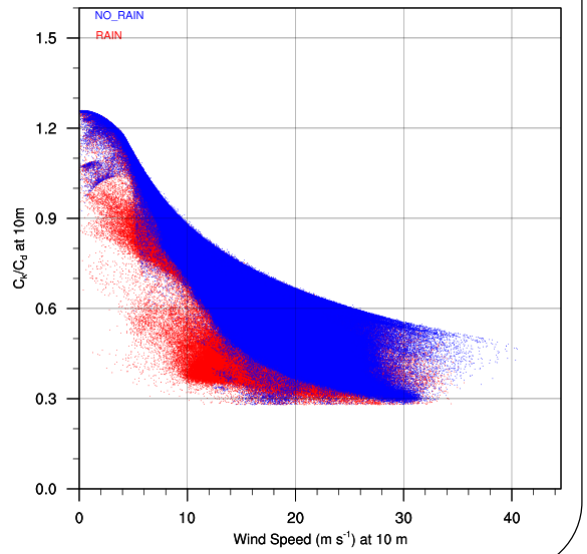






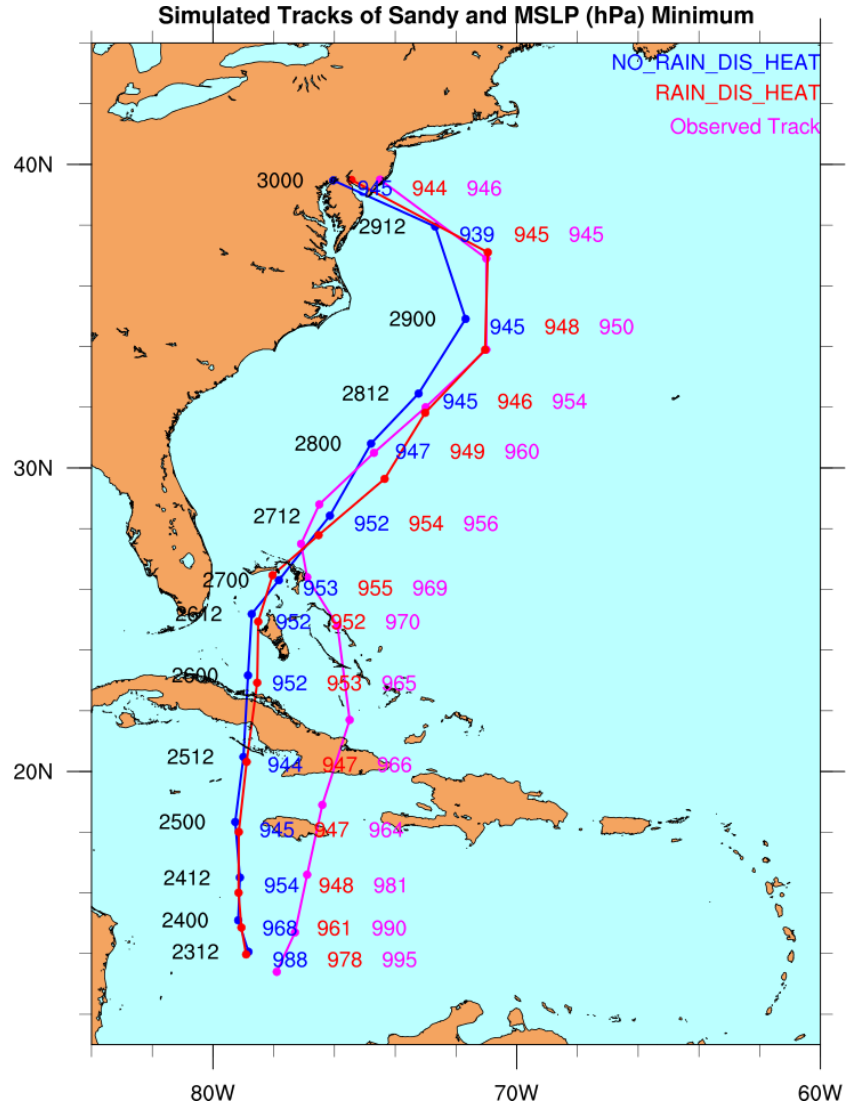






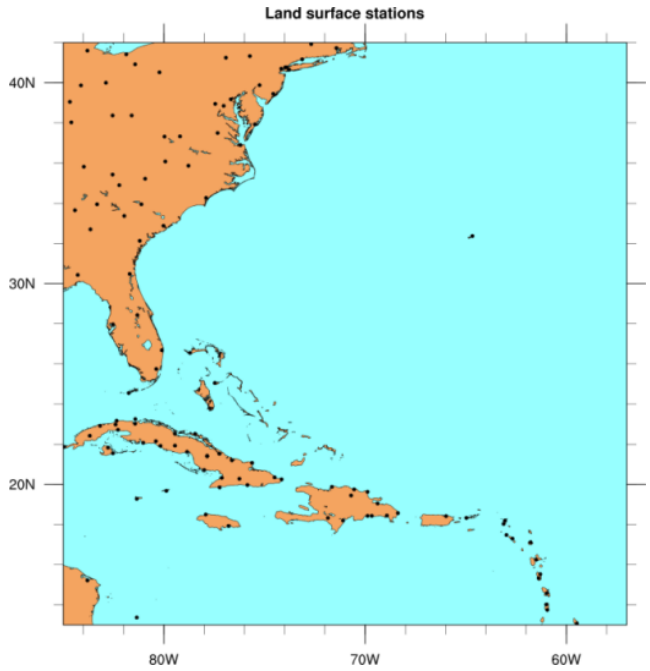
Sandy's track and lowest MSLP

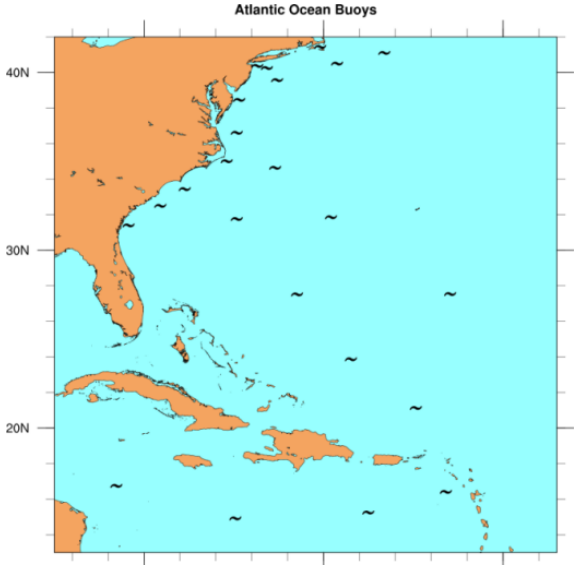
- ✓ CHAOS_RAIN simulates slighter deeper Sandy at the time of landfall and its track closer to the observed one
- ✓ The incorporation of rain in the roughness length modifies Sandy's asymmetry and finally affects its minimum MSLP

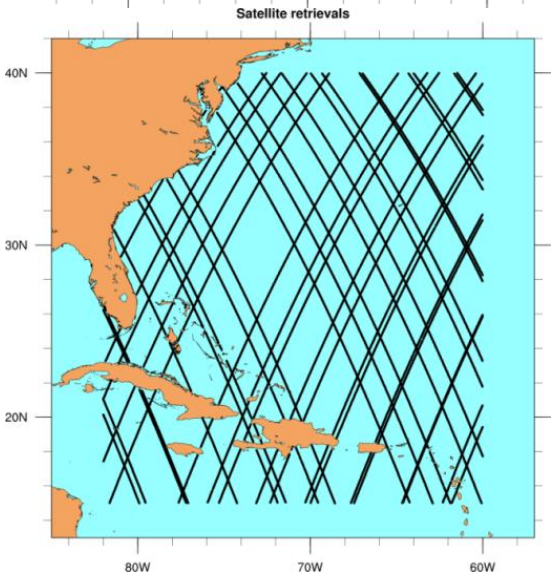


Statistical evaluation

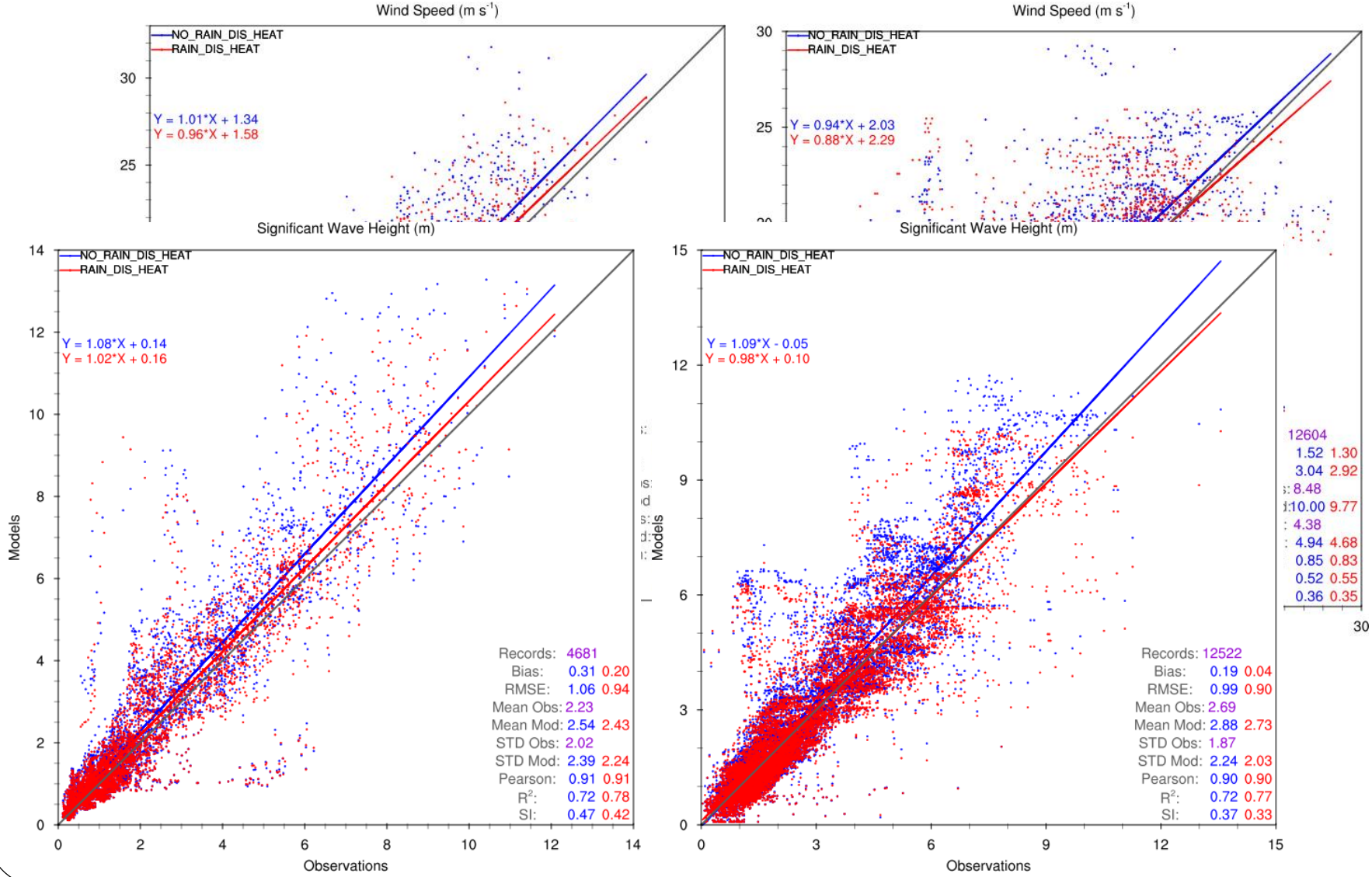
- ✓ 23 buoys at the Atlantic Ocean
- ✓ Jason1-2 satellite retrievals
- ✓ 113 surface weather stations







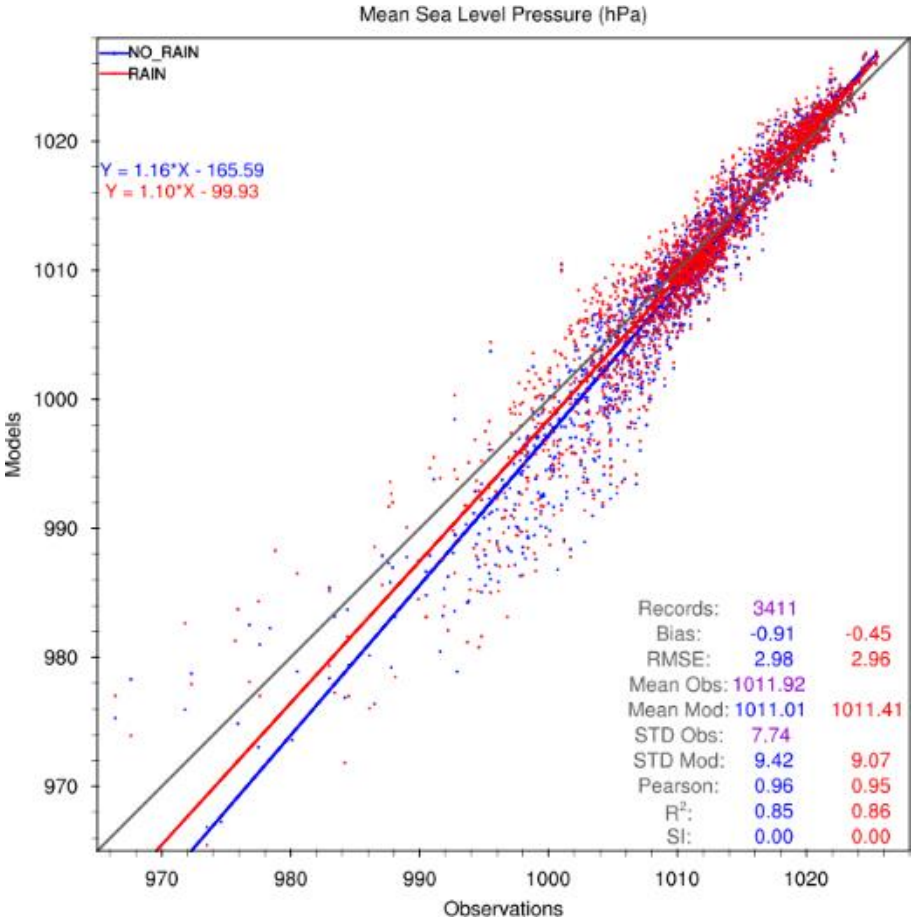
Evaluation against buoys and Jason1/2

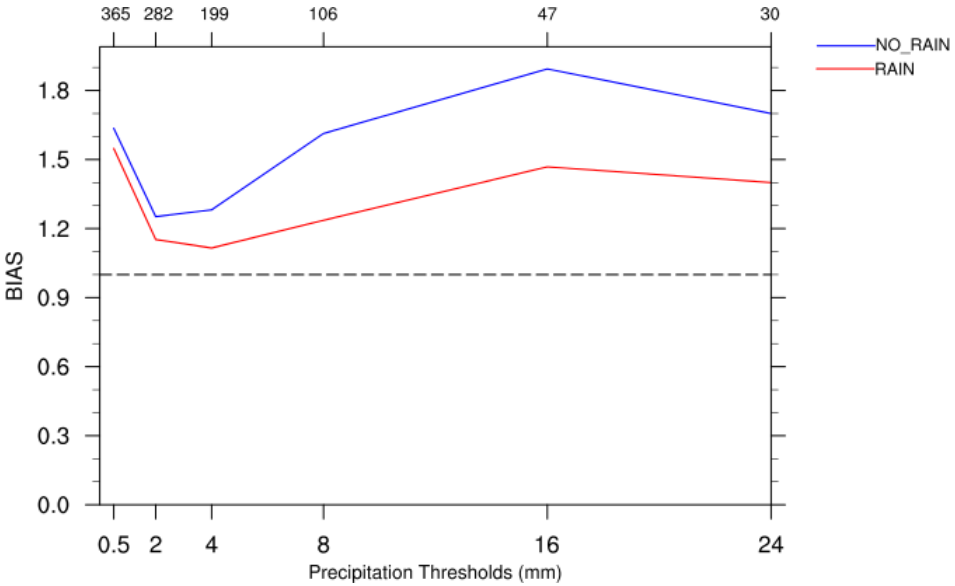


Reduced RMSE for the wave by 11%

	Wind Buoys			Wave Buoys			Wind SAT			Wave SAT		
	NO RAIN	RAIN	%	NO RAIN	RAIN	%	NO RAIN	RAIN	%	NO RAIN	RAIN	%
Bias	1.45	**1.24**	-	0.31	**0.2**	-	1.52	**1.3**	-	0.19	**0.04**	-
RMSE	2.87	**2.65**	**7.7**	1.06	**0.94**	**11.3**	3.04	**2.92**	**3.9**	0.99	**0.9**	**9**
R^2	0.64	**0.69**	**7.8**	0.72	**0.78**	**8.3**	0.52	**0.55**	**5.8**	0.72	**0.77**	**6.9**
SI	0.34	**0.32**	**5.9**	0.47	**0.42**	**10.6**	0.36	**0.35**	**2.8**	0.37	**0.33**	**10.8**

Responses on the forecast skill over land





Thank you for organizing this important workshop