# Impacts of Wave-Dependent Surface Fluxes on CESM2 Historical Simulations

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## Abstract

Traditional climate models estimate these air-sea exchanges based on a simplified ocean surface roughness, solely determined by wind and atmospheric stability, essentially assuming ocean waves are in equilibrium. However, this equilibrium state rarely occurs in reality. The integration of Wave Watch III (WW3) with the CESM2 now allows for the incorporation of ocean wave impacts on momentum and energy exchanges at the air-sea interface. This study presents our efforts in incorporating a wave-state-dependent surface flux scheme into CESM2, which accounts for wave effects on ocean surface roughness and sea spray's influence on sensible and latent heat exchange. Our findings indicate that this new scheme significantly improves the model's representation of atmospheric circulation and ocean upper levels. It reduces errors in mean circulation and surface temperature patterns, decreases the speed of the eddy-driven jet, weakens the Hadley circulation, and mitigates the sea surface temperature (SST) warm bias. Notably, the scheme introduces a slight cooling trend in the eastern Pacific's historical simulation over recent decades, addressing the existing SST trend bias in CESM2.

## Data and Methods

- Roughness is decomposed to a smooth flow component $Z_0^s$ due to viscocity and rough flow component $Z_0^r$ that is driven by surface gravity waves,

$$Z_0 = Z_0^s + Z_0^r$$

$$Z_0^s = 0.11\nu/u_* \qquad Z_0^r = \begin{cases} 4.54 h_s (c_p/u_*)^{-3.90}, & c_p/u_* < 12 \\ 5.61\times 10^{-3} h_s (c_p/u_*)^{-1.20}, & 12 \le c_p/u_* < 30 \\ 1.57\times 10^{-5} h_s (c_p/u_*)^{0.50}, & c_p/u_* \ge 30 \end{cases}$$

where $u_*$ is friection velocity, $h_s$ is significant wave heights, and $c_p/u_*$ is wave age, with $c_p$ being the peak phase speed of waves (Lin et al., 2021).

- Sea spray-induced sensible and latent heat fluxes are added to the flux from bulk formulas.

$$E_{sp} = \rho_w \left\{ 1 - \left[ \frac{r(\tau_{f,50})}{50\mu\text{m}} \right]^3 \right\} V_E(u_*)$$

$$H_{sp} = \rho_w C_w (T_s - T_{eq,100}) V_S(u_*)$$

where $\tau_{f,50}$ is the residence time of droplets with 50 µm initial radius, and $T_{eq,100}$ is the equilibrium temperature of droplets with 100 µm initial radius, $V_E$ and $V_S$ are wind function that depends on the friction velocity. These expressions assume that the microphysical behavior of droplets at those radii might be good indicators of sea spray-induced fluxes (Andreas et al., 2015).

- Three historical simulations are conducted,

1) **REF**: using the original CESM2 code without any changes;
2) **MOM**: including the formulation of wave-dependent roughness length calculation, but not the sea spray effects;
3) **FLX**: including both the new roughness length and sea spray-induced fluxes.

## Results

- Drag coefficient is increased at all latitudes due to the new scheme.
- Sensible heat flux decreases and latent heat flux increases due to the new scheme.

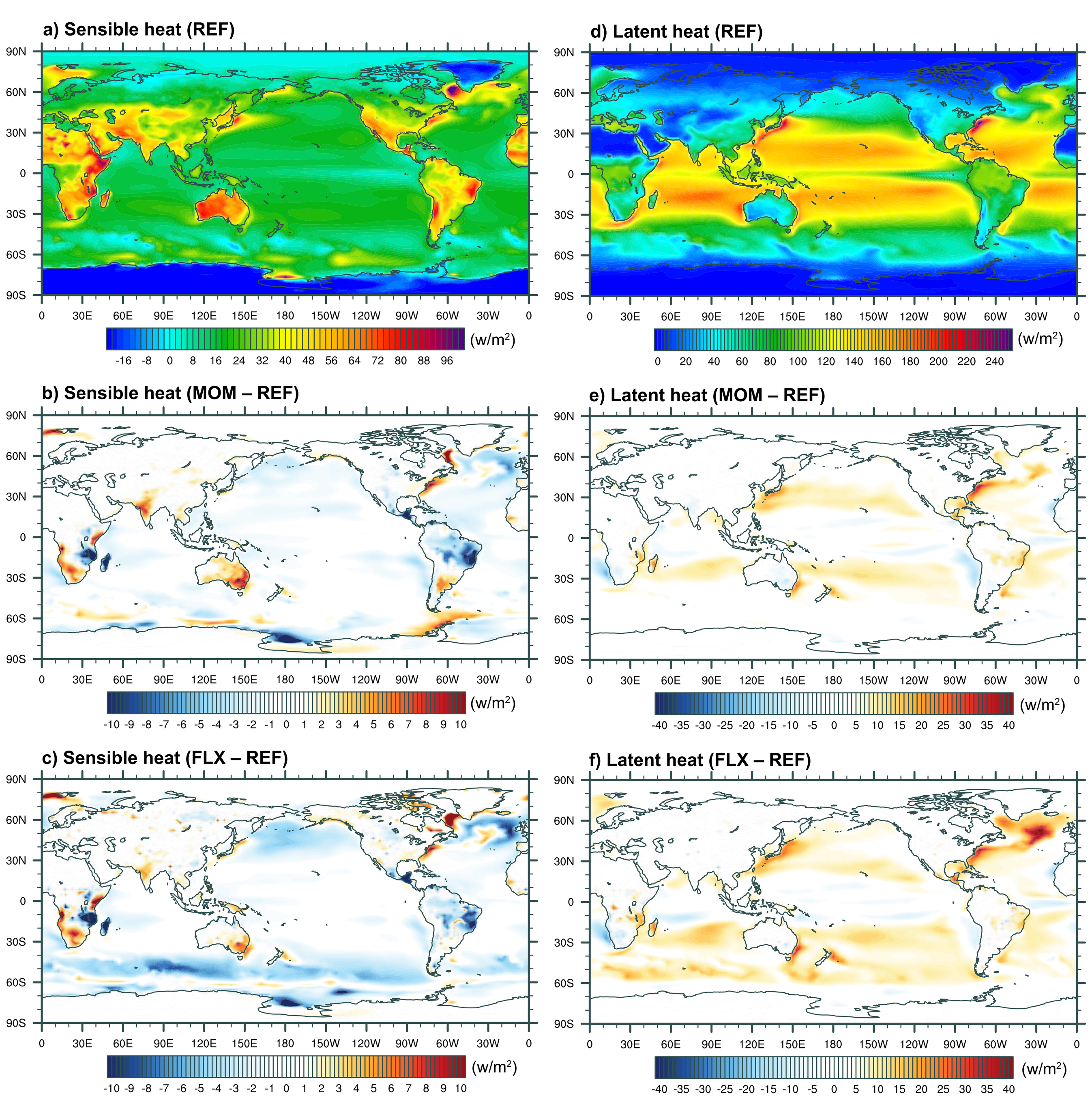


**Figure 1:** Total sensible (a,b,c) and latent (d,e,f) heat flux into the atmosphere in the simulations (1975-2014).

- The wave-dependent flux parameterization changes the surface temperature over both ocean and land.
  - Subtropical Pacific ocean surface becomes warmer due to increased cloudiness.
  - Southern Ocean surface temperature exhibit significant decrease especially in the FLX run, possibly due to flux-temperature-sea ice feedback.
  - Asia continent temperature increases significantly in response to the wave-dependent scheme, due to weakened extratropical stationary waves.

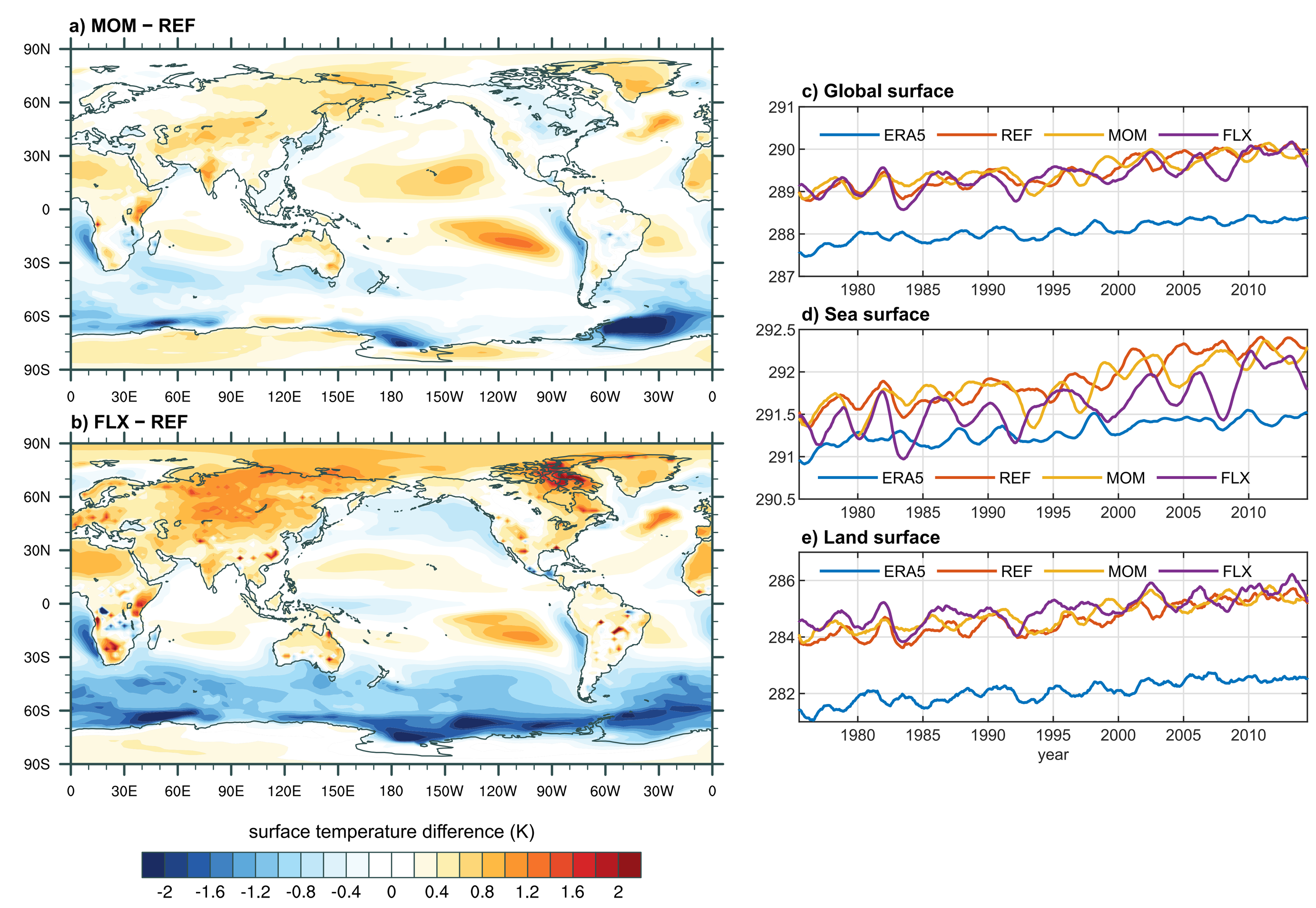


**Figure 2:** Time mean surface temperature difference between MOM and REF (a) and between FLX and REF simulations (b). (c-e) are the time series of the area mean surface temperature for c) global, d) sea surface, and e) land surface average.

- The AMOC is significantly strengthened in the FLX simulation due to enhanced latent flux in North Atlantic and the subsequent increase in sea water salinity.

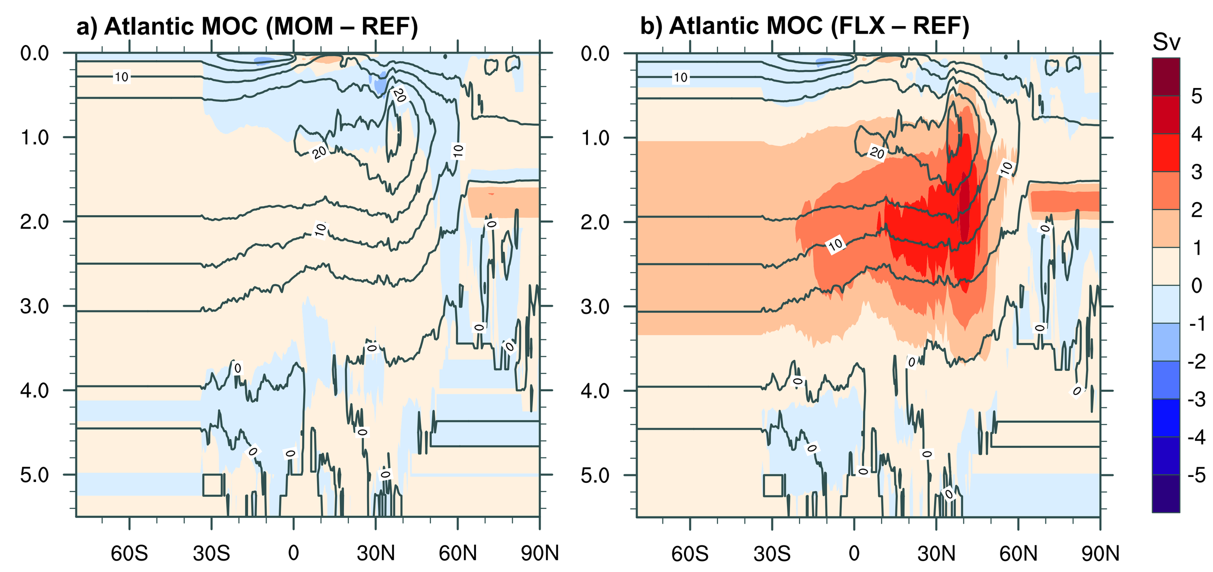


**Figure 3:** Ocean meridional overturning circulation (MOC) for the Atlantic. Contours show the streamfunction of the REF simulation, and color shading is the difference between MOR or FLX and the REF.

- The wave-dependent fluxes changes the surface temperature change pattern under global warming. Notably, the slight cooling in Eastern Pacific appears in the FLX run.

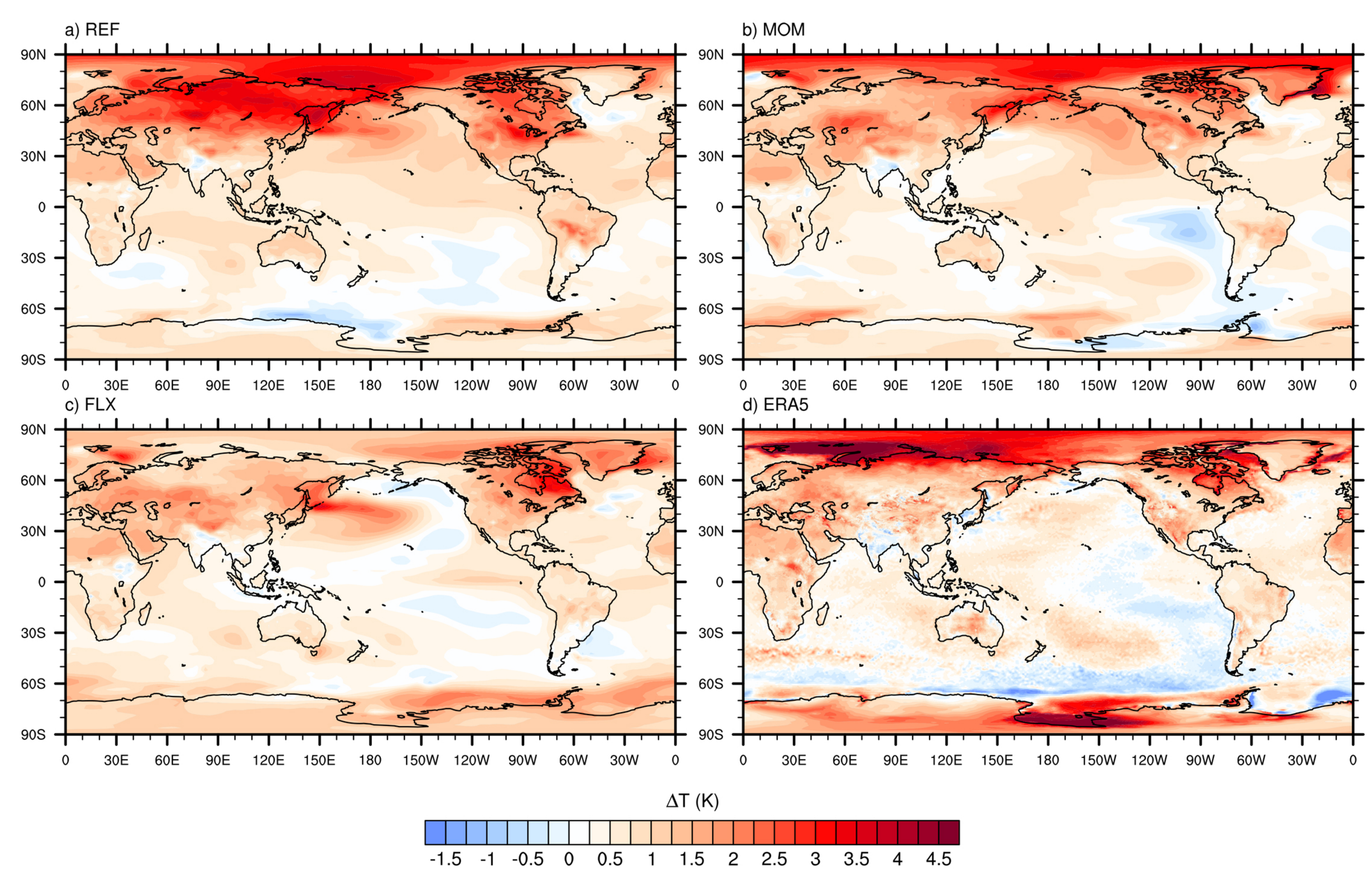


**Figure 4:** Temperature difference between the time average of the last ten years (2005–2014) and first ten years (1975-1984) of the three simulations and the ERA5 reanalysis.

## Summary

- Wave state-dependent surface flux schemes significantly change the dynamic and thermodynamic structures of the atmosphere and ocean circulations.
- The current simulations used coarse resolutions (e.g., WW3 uses 3.2°×4.0° grid mesh). Finer resoultions and longer simulations are needed to tune the new parameterization scheme and evaluate its full impacts.

## References

Lin, S. et al., (2021). Wave-current interactions during hurricanes Earl and Igor in the northwest atlantic. *Journal of Geophysical Research: Oceans*, 126(12), e2021JC017609.

Andreas, et al., (2015). An improved bulk air-sea surface flux algorithm including spray-mediated transfer. *Quarterly Journal of the Royal Meteorological Society*, 141(687), 642-654.