A diurnal cycle in the mechanical efficiency of tropical cyclones

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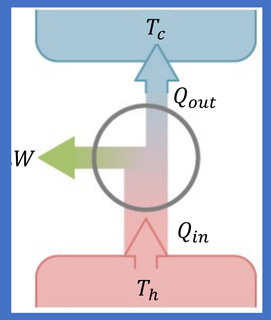
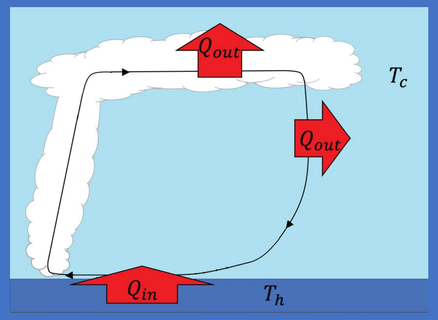
Tropical cyclone wind strength is generated at a "mechanical efficiency", which may experience a diurnal cycle. Analysis of a hurricane nature run and two idealized simulated tropical cyclones shows evidence of a diurnal cycle in the mechanical efficiency and related tropical cyclone energetics. We additionally find a lack of evidence for rectification of the daily-mean mechanical efficiency and energetics by the diurnal cycle.

Tropical Cyclones can be viewed as Heat Engines [1]

The Classical Heat Engine



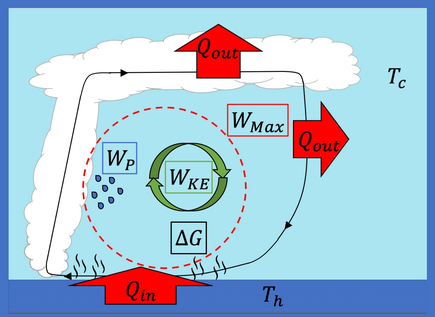
The Tropical Cyclone Heat Engine



Left: Heat transfer and generation of useful work, W, in the Carnot heat engine [2] compared to (right) similar heat transfer in the Tropical Cyclone.

Wind field strength is related to "mechanical efficiency", η_{mech} [3, 4]

- $W_{Max} = W_{KE} + W_{Moist}$
- $W_{Moist} = W_P + \Delta G$
- $\eta_{mech} = \frac{W_{KE}}{Q_{in}}$
- The efficiency is affected by:
  - The portion of the net heating that powers the winds
  - The total heat input
- Variables are calculated using MAFALDA. Assumes closed circulation in an open system.



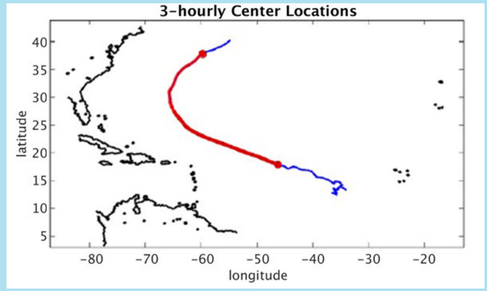
The tropical cyclone heat engine uses the net heating, W_{Max}, either as wind kinetic energy (W_{KE}) or to power moist processes (precipitation, W_P, and phase transitions, ΔG)

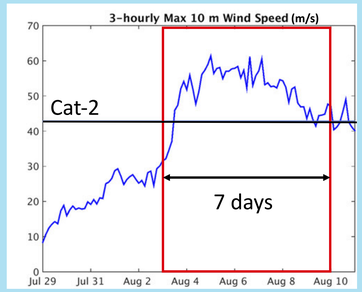
The mechanical efficiency may experience a diurnal cycle

- Diurnal cycles in:
  - Precipitation [e.g., 3-10]
  - Boundary layer relative humidity [10, 11]
  - Azimuthal and radial wind fields [10, 12-15]
  - Integrated Kinetic Energy [16]

[1]: Emanuel (1986, JAS)
[2]: OpenStax University Physics (2019)
[3]: Pauluis (2016, JAS)
[4]: Pauluis and Zhang (2017, JAS)
[5]: Jiang et al. (2011, JAMC)
[6]: Shu et al. (2013, Atmos. Oceanic Sci. Lett.)
[7]: Bowman and Fowler (2015 , JCLI)
[8]: Wu and Ruan (2016 , JGR Atmos.)
[9]: Leppert and Cecil (2016 , MWR)
[10]: Dunion et al. (2019 , MWR)
[11]: Zhang and Xu (2021 , JCLI)
[12]: Williams (2022, Meteor. Atmos. Phys.)
[13]: Zhang et al. (2020 , GRL)
[14]: Navarro and Hakim (2016 , JAS)
[15]: Evans and Nolan (2022 , JAS)
[16]: Duran et al. (2021 , AMS 34th Conference on Hurricanes and Tropical Meteorology)
[17]: Nolan et al. (2013 , JAMES)
[18]: Bryan and Fritsch (2002 , MWR)

We analyze a hurricane nature run [17]

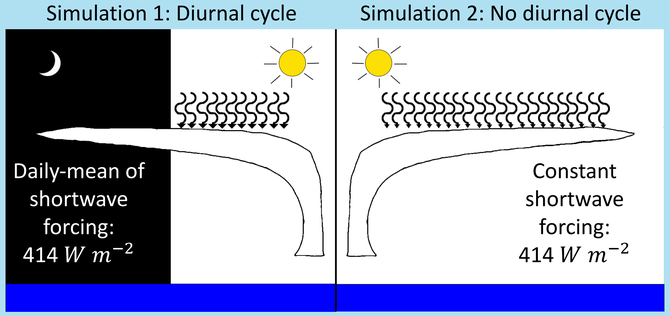




Plots of track and intensity modified from [9]

- 13-day simulation in WRF version 3.2.1
- Analyze output data from 1080 km x 1080 km nested grid with 9km spacing
- Compute mechanical efficiency and energetics for all separate 3-hour periods (Output is every 30 minutes)
- Analyze 7-day subset of the 13-day period where TC is intense
- 7 days of data becomes less than 7 days when converted to local solar time (LST). We study the last 6 full days of the LST time series.

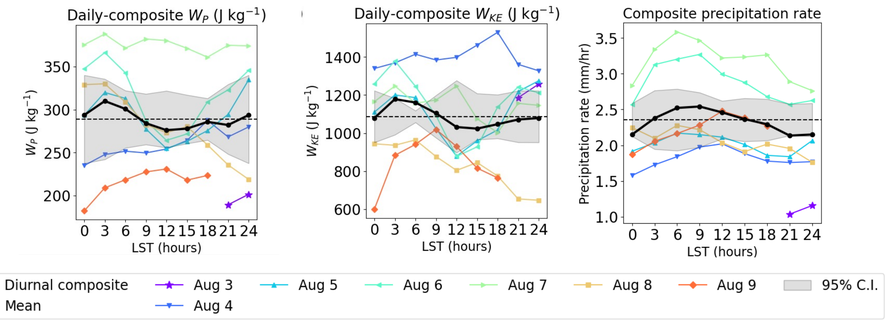
Idealized simulations of a Tropical Cyclone with and without diurnal radiative forcing



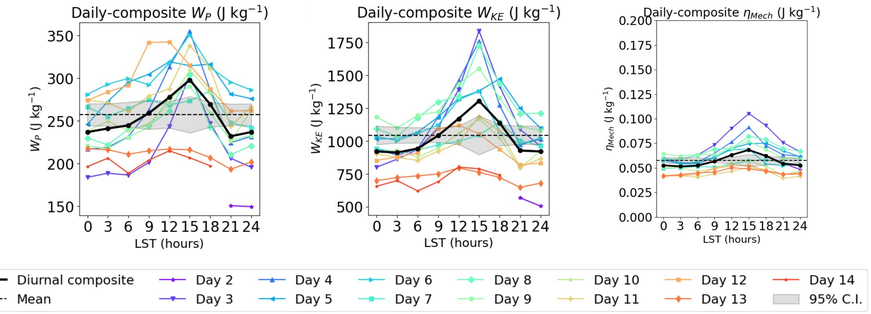
- 20-day simulations in the Bryan Cloud Model 1 [18]
- 3000 km x 3000 km domain
- Simulation 1 (CM1-DC): Shortwave radiation has no seasonal cycle and has a diurnal cycle
- Simulation 2 (CM1-noDC): Perpetual-afternoon shortwave radiation. Same daily-mean shortwave forcing as simulation 1. Serves as a control.
- Compute mechanical efficiency and energetics for all separate 3-hour periods (Output is every 30 minutes) in the 12-day timespan where the TCs are intense and of a realistic size

Results

Hurricane nature run-derived diurnal composite plots show indications of diurnal variability, but largely lack statistical significance



Results from the longer CM1-DC simulation show diurnal oscillations in many variables with statistically significant departures from the long-term mean



Comparison to CM1-noDC confirms the presence of diurnal cycles in CM1-DC. There is no strong difference between the diurnal-mean values of any variable in the two CM1 simulations. This could indicate a lack of rectification.