Modeling the Response of Coastal Stratocumulus Clouds to Sudden and Gradual Variations of Surface Heat Fluxes

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Abstract

Coastal stratocumulus clouds (Sc) have unique modeling challenges due to their development over coastal land, one of them being the accurate representation of surface fluxes. Unlike marine Sc, where the ocean can store significant heat and release relatively constant surface heat fluxes over the day, there are strong diurnal variations of both sensible and latent heat fluxes over land. Moreover, land surface fluxes have a strong feedback with cloud cover. Many modeling efforts have been directed to improve the representation of surface fluxes through developing more accurate land surface models with increasing complexity. Regarding the boundary layer turbulence, for marine Sc, greater sensible fluxes are known to intensify updrafts and increase entrainment, while greater latent heat fluxes have been linked to decoupling. An example of surface flux variations for Marine Sc is the transition of Sc to shallow Cumulus along the trade winds, which occurs over a number of days. For coastal land, changes of surface fluxes occur in a much shorter timescale (hours), and the sensitivity of their dynamical response has not been explored. In this work, we study the response of coastal Sc to controlled variations of surface fluxes using Large Eddy Simulations. Representative scenarios of diurnal profiles are generated using 12 years of surface flux measurements for cloudy days over southern California, and then simulated under several configurations that describe sudden and gradual changes of surface fluxes with varied timing and magnitude. Sudden changes result in increased cloud thinning and earlier dissipation times, although the timing of the sudden increase is also important, in relation to the original dissipation time. The response time to sudden changes of surface fluxes is evident in the evolution of maximum vertical velocity and vertically integrated Turbulent Kinetic Energy, with timescales of 1 and 2 eddy turnover times, respectively.

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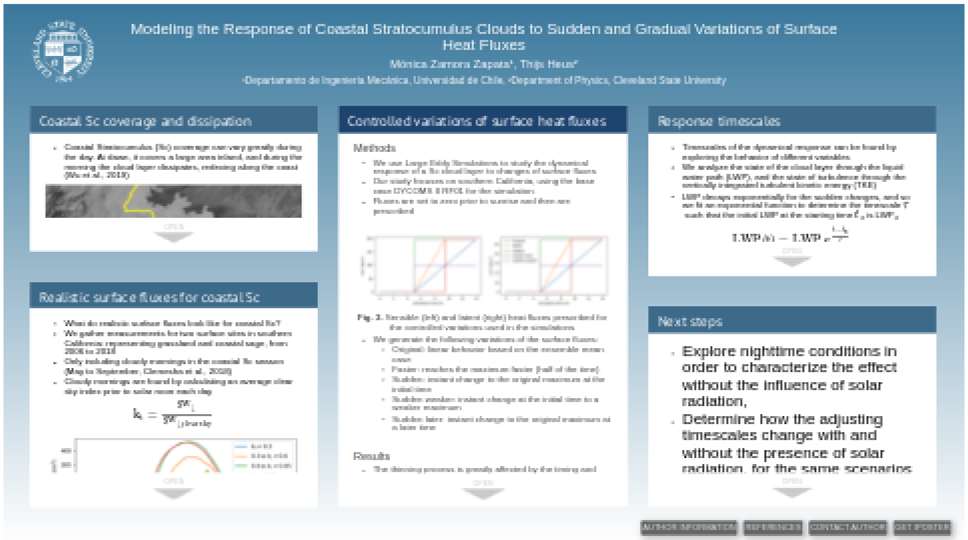

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PRESENTED AT:

COASTAL SC COVERAGE AND DISSIPATION

- Coastal Stratocumulus (Sc) coverage can vary greatly during the day. At dawn, it covers a large area inland, and during the morning the cloud layer dissipates, redecing along the coast (Wu et al., 2019)

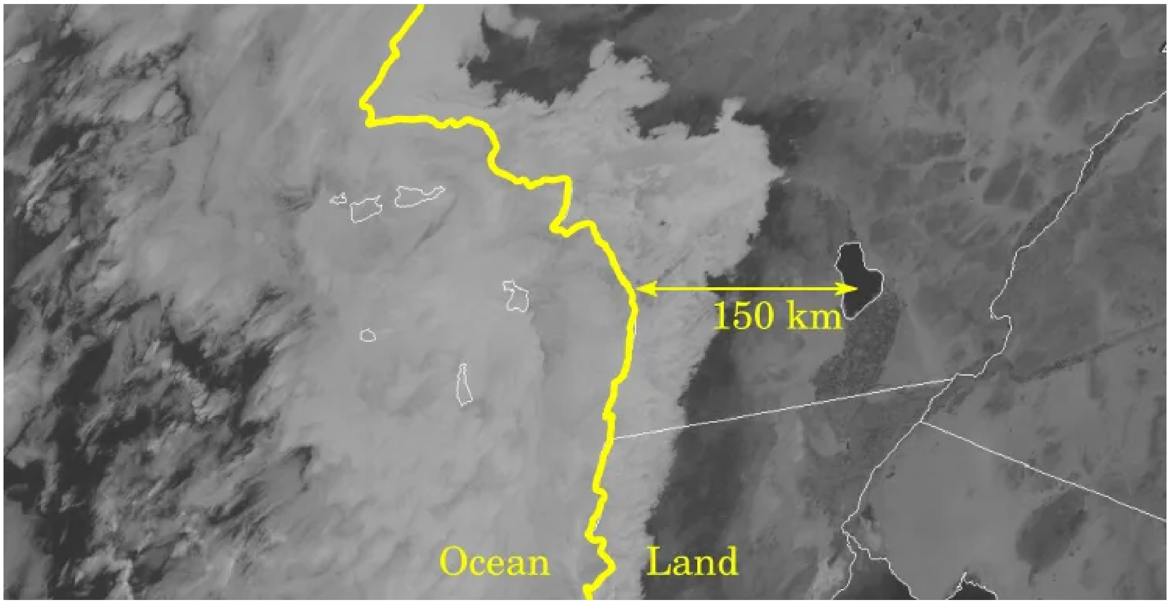

Fig. 1. GOES satellite image over southern California, May 24, 2018, showing a vast coverage inland

- Dissipation is enhanced over land by the strong surface fluxes (Ghonima et al., 2016), which are driven by the diurnal cycle of incoming solar radiation
- Studying the effects of surface fluxes in detail is key to understand the Sc dissipation process
- Coastal Sc clouds affects many human productive activities: solar energy, air traffic, tourism, agriculture

REALISTIC SURFACE FLUXES FOR COASTAL SC

- What do realistic surface fluxes look like for coastal Sc?
- We gather measurements for two surface sites in southern California: representing grassland and coastal sage, from 2006 to 2018
- Only including cloudy mornings in the coastal Sc season (May to September, Clemesha et al., 2018)
- Cloudy mornings are found by calculating an average clear sky index prior to solar noon each day

$$\mathrm{k_t} = \frac{\mathrm{SW}_{\downarrow}}{\mathrm{SW}_{\downarrow,\text{clear sky}}}$$

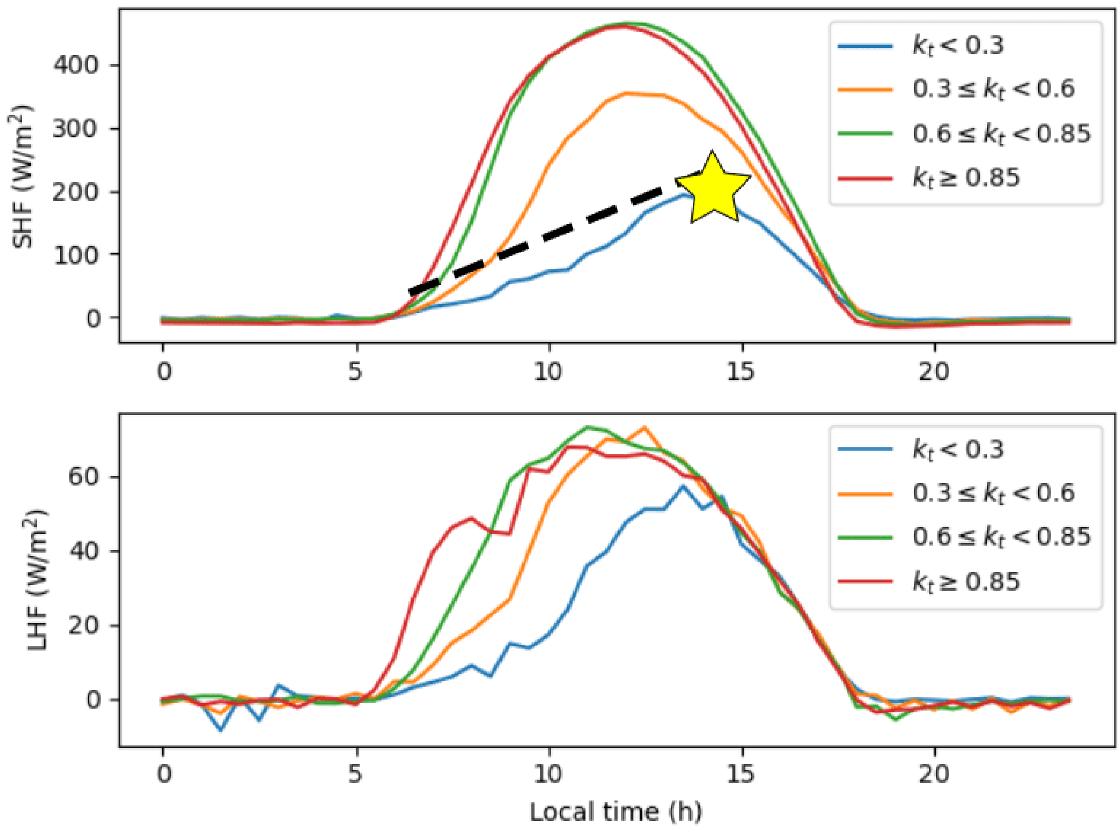

Fig. 2. Ensemble mean sensible (top) and latent (bottom) heat fluxes for the coastal sage site, for 4 ranges of kt representing different levels of cloudiness

- Realistic fluxes can be calculated from energy balances at the surface using Land Surface Models (LSM) but it is hard to disentangle their effects because of the existing complex feedbacks
- We opt for a sensitivity approach with controlled variations of surface fluxes in order to learn the dynamical response of the coastal cloud layer

CONTROLLED VARIATIONS OF SURFACE HEAT FLUXES

Methods

- We use Large Eddy Simulations to study the dynamical response of a Sc cloud layer to changes of surface fluxes
- Our study focuses on southern California, using the base case DYCOMS II RF01 for the simulation
- Fluxes are set to zero prior to sunrise and then are prescribed

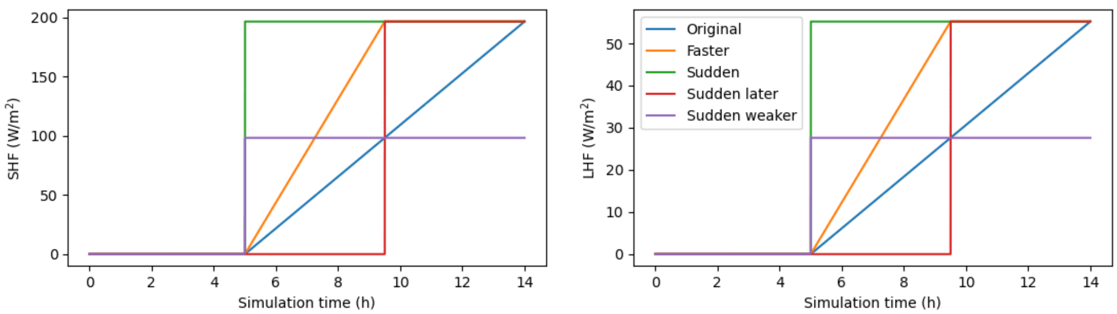

Fig. 3. Sensible (left) and latent (right) heat fluxes prescribed for the controlled variations used in the simulations

- We generate the following variations of the surface fluxes:
  - Original: linear behavior based on the ensemble mean case
  - Faster: reaches the maximum faster (half of the time)
  - Sudden: instant change to the original maximum at the initial time
  - Sudden weaker: instant change at the initial time to a weaker maximum
  - Sudden later: instant change to the original maximum at a later time

Results

- The thinning process is greatly affected by the timing and strength of the surface fluxes
- In terms of cloud cover, the decay has a quasi linear behavior. The sudden, sudden later, and faster configurations lead to a similar and faster decay than the original case, which is closer to the sudden weaker configuration
- In terms of LWP, the decay is non linear, following an exponential form for the sudden cases

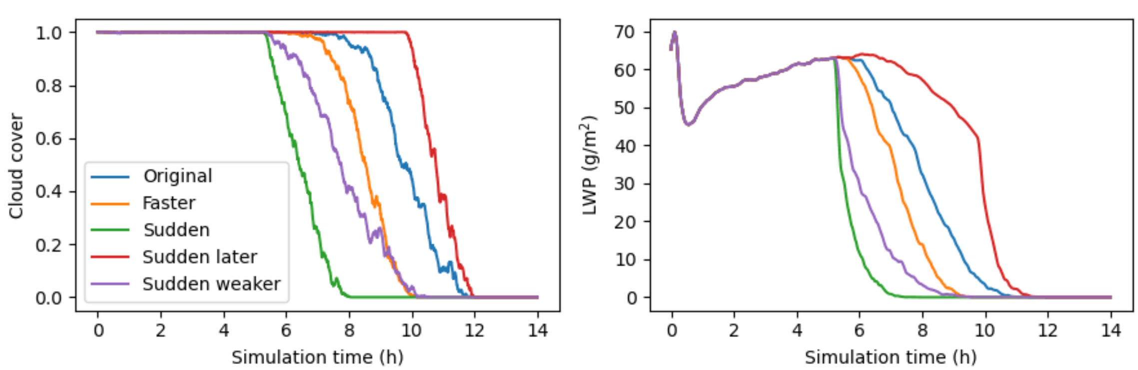

Fig. 4. Time evolution of cloud cover (left) and liquid water path (right) for the configurations studied

RESPONSE TIMESCALES

- Timescales of the dynamical response can be found by exploring the behavior of different variables
- We analyze the state of the cloud layer through the liquid water path (LWP), and the state of turbulence through the vertically integrated turbulent kinetic energy (TKE)
- LWP decays exponentially for the sudden changes, and so we fit an exponential function to determine the timescale τ such that the initial LWP at the starting time t_s is LWP_s

$$\mathrm{LWP(t) = LWP_s e^{\frac{t-t_s}{\tau}}}$$

- Meanwhile, LWP decays like a sigmoid for the linear changes (original and mid), so we fit a sigmoid function to determine the adjusting timescale

$$\frac{\mathrm{LWP(t)}}{\mathrm{LWP_s}} = 1 - \frac{1}{1+e^{-(t-t_s)/\tau}}$$

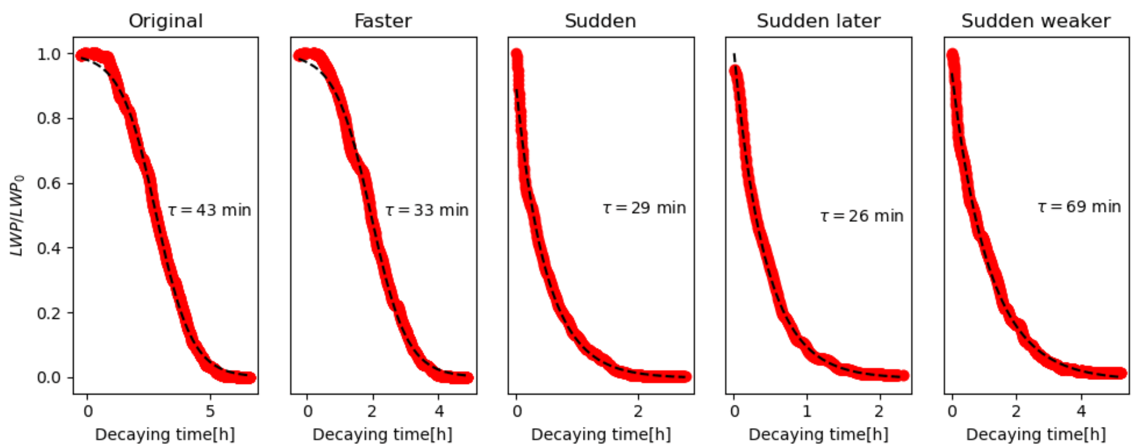

Fig. 5. Adjusting exponential and sigmoid decay functions for LWP timeseries

- Decay is quicker for the strong sudden cases and the faster case, and the longest time is obtained for the sudden weaker case
- On the other hand, TKE increases by the input of surface fluxes. In this case, the sudden changes results in a response similar to a harmonic oscillator with underdampening, meaning that the input of surface fluxes is very strong. TKE adjusts in approximately 2 turnover eddy times for these cases. A more precise timescale detection method needs to be developed.

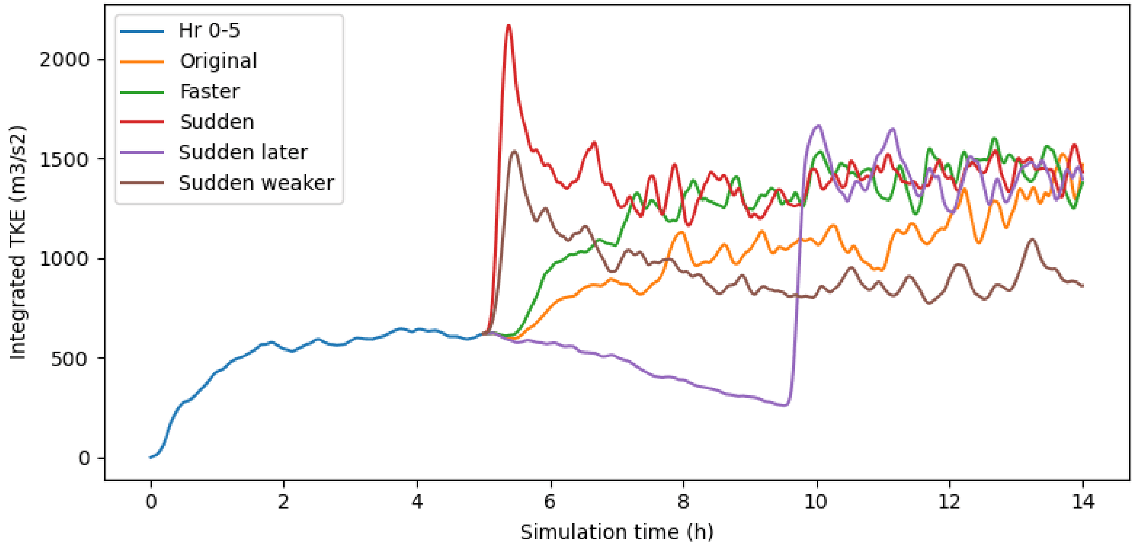

Fig. 6. Time evolution of vertically integrated TKE for the configurations studied

CONCLUSIONS AND NEXT STEPS

- Sudden and gradual variations of surface heat fluxes have different effects on coastal Sc: sudden can lead to faster decays, although both timing and strength matter
- We will explore nighttime conditions in order to characterize the effect without the influence of solar radiation to determine how the adjusting timescales are affected
- We will analyze the spatial behavior of the cloud dissipation process, in order to improve our understanding of the coastal Sc breakup process
- Exploring the time response to idealized shorter or weaker perturbations can help us understand if and how dissipation is determined by past changes of surface fluxes

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