Impacts of South African Wildfire Aerosols on Stratocumulus over Southeast Atlantic Ocean

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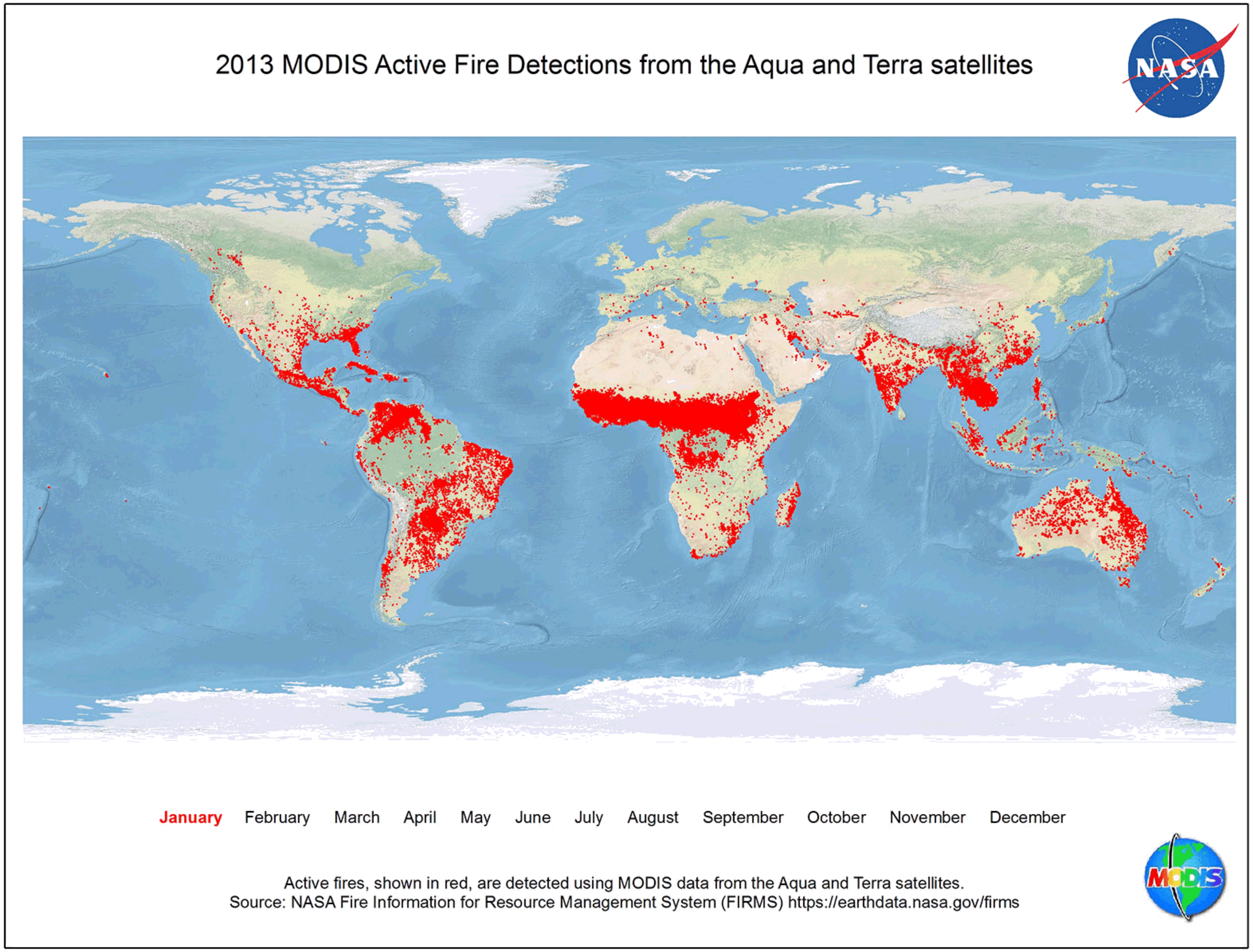
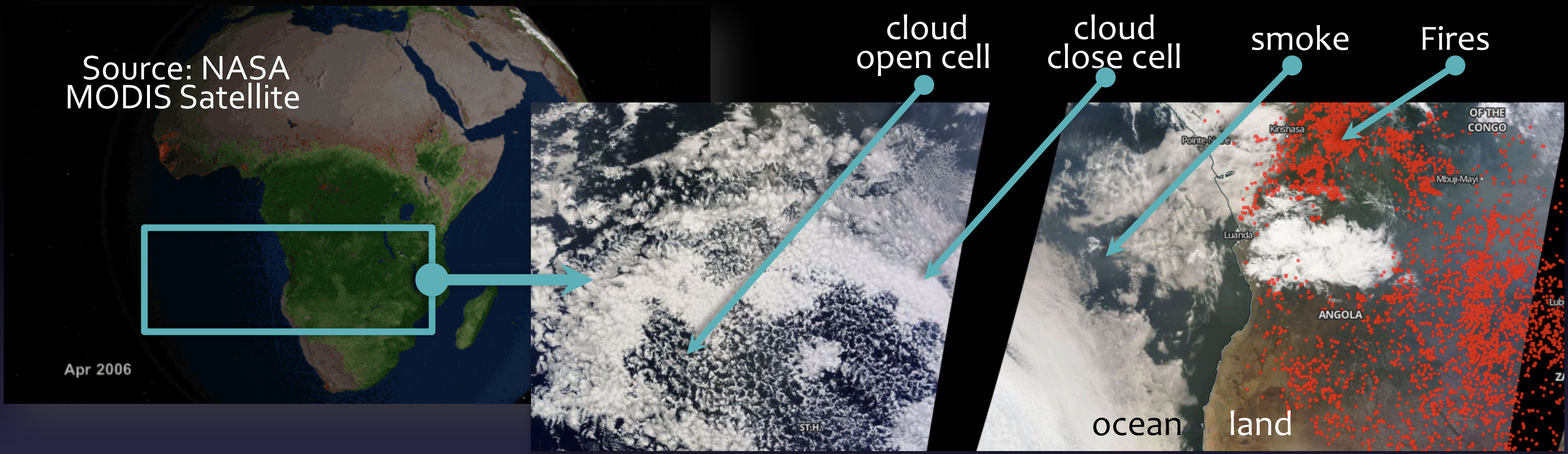
Outline

- ✧ Motivation
- ✧ Model and observation data
- ✧ Evaluation of modeled wildfire aerosols and clouds
- ✧ Effects of wildfire aerosols on stratocumulus clouds
- ✧ Summary

2013 monthly active fire detections



Motivation



- Wildfires in Southern Africa contribute ~27% of global wildfire aerosol emissions[1]
- Wildfire season (July-August-September) in Southern Africa[2] in coincidence with maximum *stratocumulus* season (August-September-October)[3]

1. Van der Werf et al., 2010; 2. Randerson et al., 2012; 3. Wood, 2012

Motivation

- Smoke as SW absorber in S. Africa
  - Direct effect: smoke layer above clouds: negative RF ➔ positive RF depending on cloud fraction (Chand et al. 2009)
  - Semi-direct effect: smoke strengthens cloud-capping temperature inversion ➔ thicken stratocumulus clouds (Sakaeda, Wood, and Rasch 2011; Wilcox 2012)

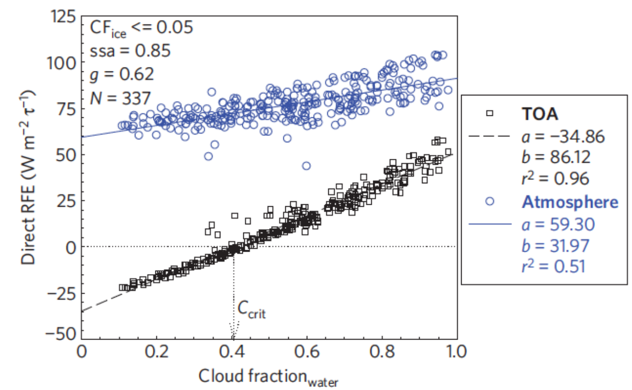
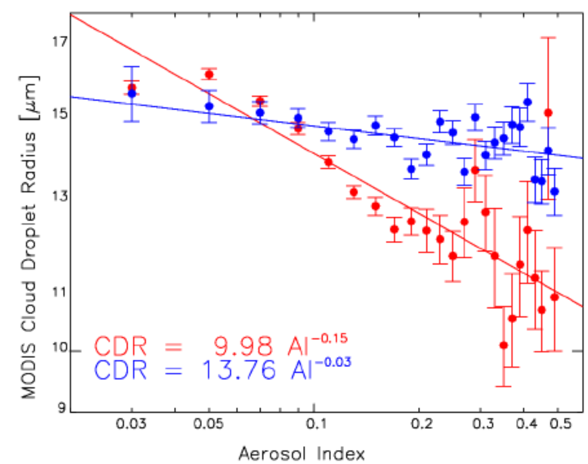


Figure 3 | Correlation of aerosol direct RFE with cloud fraction for July–October 2006–2007. RFE at the top of the atmosphere (squares) and within the atmosphere (circles) as a function of cloud fraction. C_{crit} is the cloud fraction when the top-of-atmosphere (TOA) RFE changes sign.

Chand et al. 2009

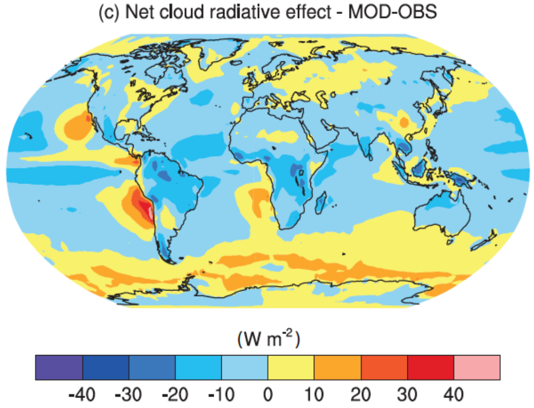
- Smoke as CCN in S. Africa
  - Indirect effect: Less studied, especially for the nighttime period
  - During daytime, 56% of smoke layers elevated above clouds; 44% touching clouds based on Calipso observations (Constantino and Bréon 2013)



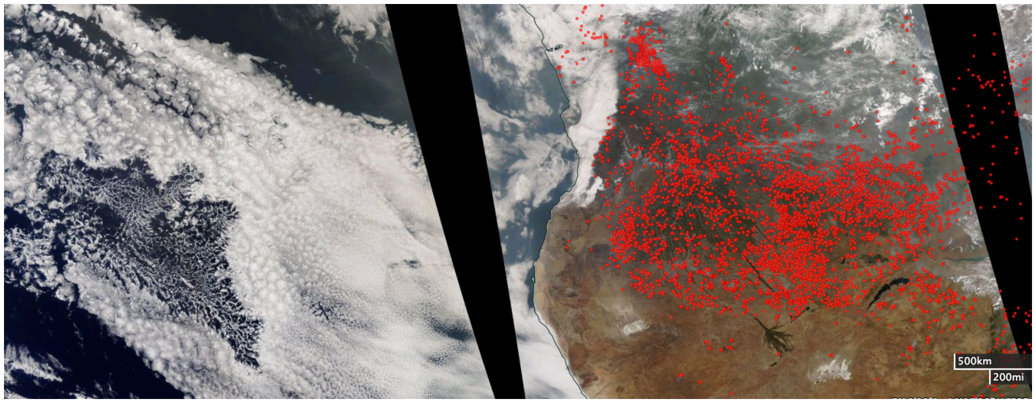
Constantino and Bréon, 2013

Motivation

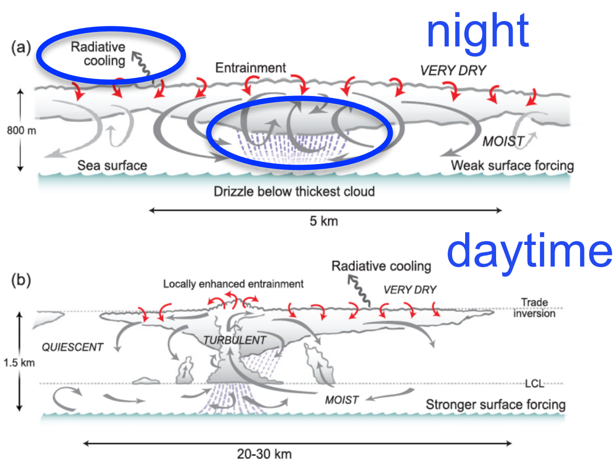
- Modeling stratocumulus
  - Cloud radiative forcing underestimated by GCMs (IPCC AR5)
  - Organizational complexity: open/close cell
  - Coupling-decoupling cycle: shallow well-mixed STBL (night) ➔ a deep and decoupled STBL ➔ a cumulus-dominated boundary layer (daytime)



IPCC AR5



earthdata
NASA



Coupling-decoupling of stratocumulus
Wood, 2013

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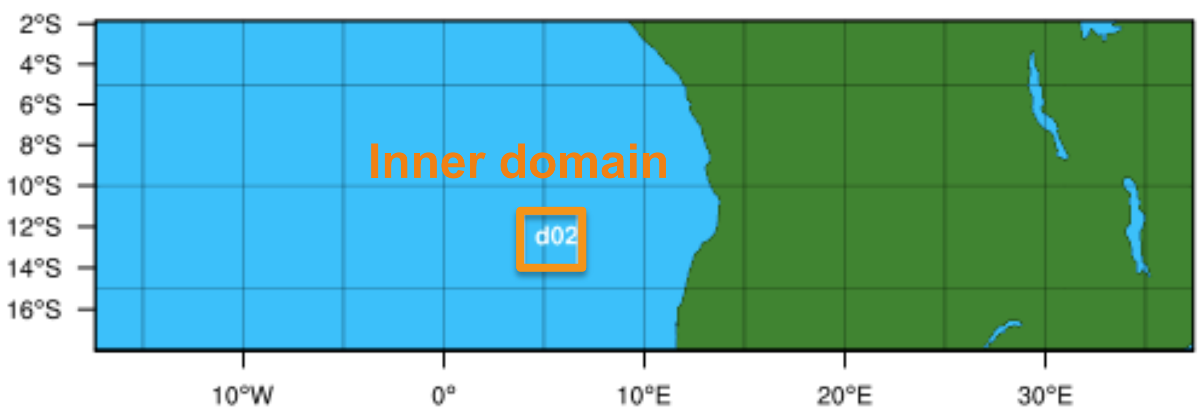
Model and Data

- **WRF-Chem** model V3.6.1
- Domain and spatial resolution: 6000 km (Δx=3 km, E-W) × 1800 km (Δy=3 km, S-N) × 42 (v)
- Period: August 1 – October 31, 2014; 3-h output frequency
- Three cases: **SMOKE**, **CLEAN** (only sea salt and DMS-generated aerosols), and **NO_RAD** (radiative effect of smoke not considered)
- Aerosol-cloud-radiation interactions in WRF-Chem
  - MOSAIC aerosol scheme; Abdul-Razzak and Ghan cloud droplet activation parameterization
  - Cloud microphysics: Morrison two-moment scheme
  - Radiation: Goddard SW + RRTM LW schemes
- **Inner domain** simulation by **WRF** model: Domain size: 300km (Δx=300m, E-W) × 300km (Δy=300m, S-N) × 97 (v); Δz=16 m in 0~1 km, Δz=32 m in 1~2 km



Model and Data

- Hourly **smoke emissions**
  - The fire radiative power (FRP) technique[1]
  - Smoke emission rate = FRP × Ce (Ce=0.021 kg/MW)
  - FRP values from SERVRI satellite (resolution: 15 min + 3 km)
  - OC, BC mass ratios: Vegetation-dependent[2]; MODIS Land Cover Type (16 types)

LCT Classification	Generic Vegetation Type	CO_2	CO	CH_4	H_2	NO_x (as NO)	NO	NO_2	NMOC	NMHC	SO_2	NH_3	$PM_{2.5}$	TPM	TPC	OC	BC
Evergreen Needleleaf Forest	BOR	1514	118	6	2.3	1.8	1.5	3	28	5.7	1	3.5	13	18	8.3	7.8	0.2
Evergreen Broadleaf Forest	TROP	1643	92	5.1	3.2	2.6	0.91	3.6	24	1.7	0.45	0.76	9.7	13	5.2	4.7	0.52
Deciduous Needleleaf Forest	BOR	1514	118	6	2.3	3	1.5	3	28	5.7	1	3.5	13	18	8.3	7.8	0.2
Deciduous Broadleaf Forest	TEMP	1630	102	5	1.8	1.3	0.34	2.7	11	5.7	1	1.5	13	18	9.7	9.2	0.56
Mixed Forests	TEMP	1630	102	5	1.8	1.3	0.34	2.7	14	5.7	1	1.5	13	18	9.7	9.2	0.56
Closed Shrublands	WS	1716	68	2.6	0.97	3.9	1.4	1.4	4.8	3.4	0.68	1.2	9.3	15.4	7.1	6.6	0.5
Open Shrublands	WS	1716	68	2.6	0.97	3.9	1.4	1.4	4.8	3.4	0.68	1.2	9.3	15.4	7.1	6.6	0.5
Woody Savannas	WS	1716	68	2.6	0.97	3.9	1.4	1.4	4.8	3.4	0.68	1.2	9.3	15.4	7.1	6.6	0.5
Savannas	SG	1692	59	1.5	0.97	2.8	0.74	3.2	9.3	3.4	0.48	0.49	5.4	8.3	3	2.6	0.37
Grasslands	SG	1692	59	1.5	0.97	2.8	0.74	3.2	9.3	3.4	0.48	0.49	5.4	8.3	3	2.6	0.37
Permanent Wetlands	SG	1692	59	1.5	0.97	2.8	0.74	3.2	9.3	3.4	0.48	0.49	5.4	8.3	3	2.6	0.37
Croplands	CROP	1537	111	6	2.4	3.5	1.7	3.9	57	7	0.4	2.3	5.8	13	4	3.3	0.69
Cropland/Natural Vegetation Mosaic	SG	1692	59	1.5	0.97	2.8	0.74	3.2	9.3	3.4	0.48	0.49	5.4	8.3	3	2.6	0.37
Barren or Sparsely Vegetated	SG	1692	59	1.5	0.97	2.8	0.74	3.2	9.3	3.4	0.48	0.49	5.4	8.3	3	2.6	0.37

1. Ichoku and Kaufmann, 2005; 2. Wiedinmyer et al. 2011

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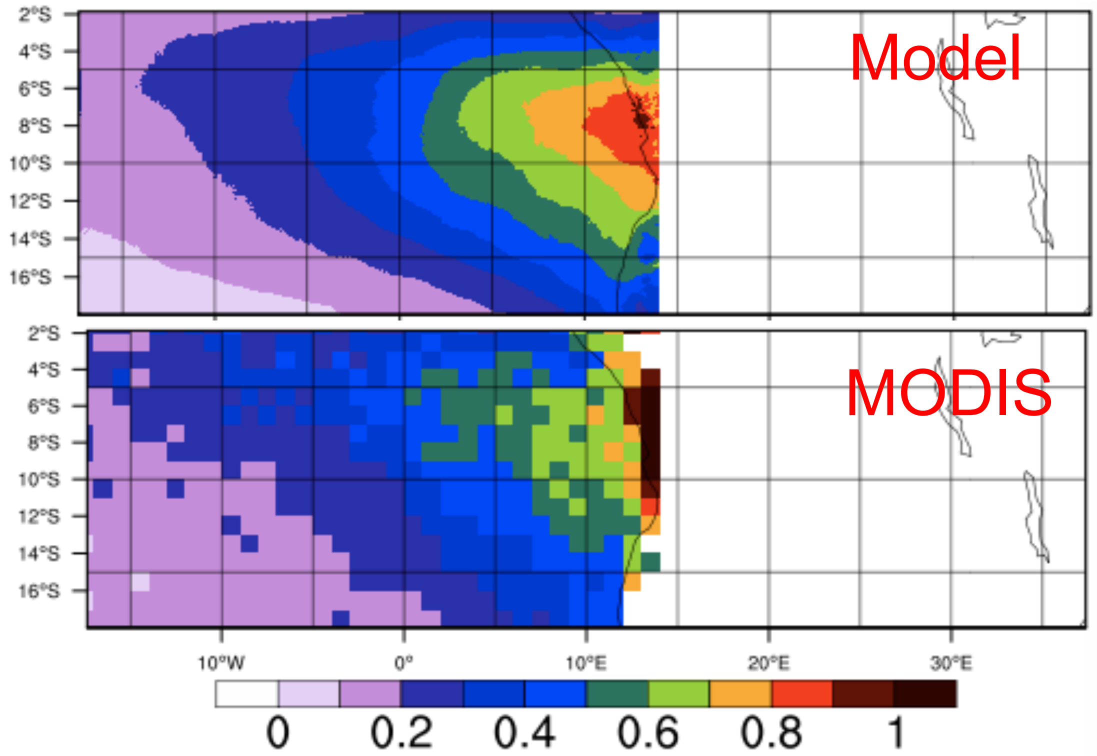
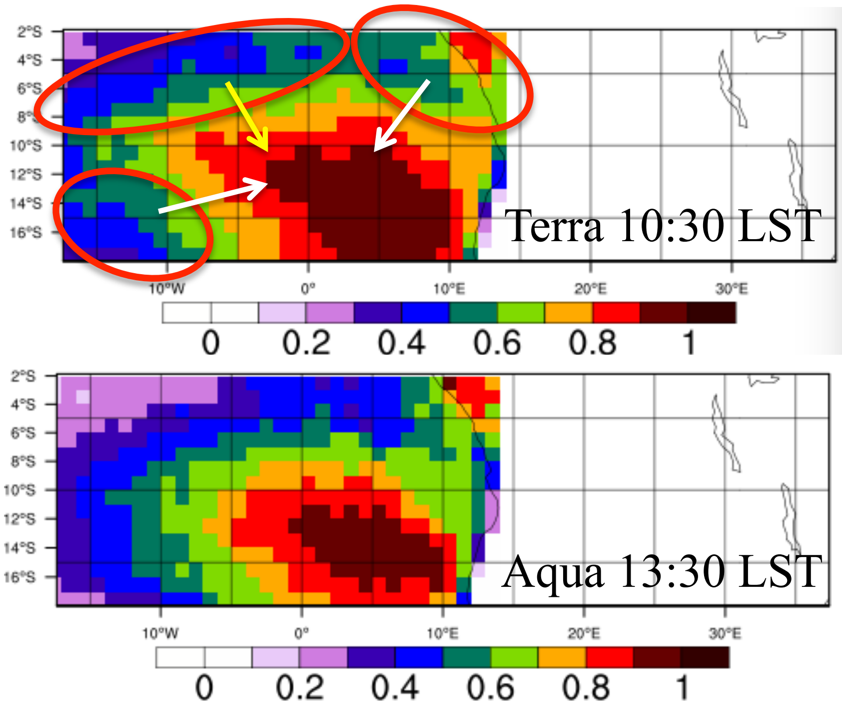
Evaluation – modeled smoke aerosol



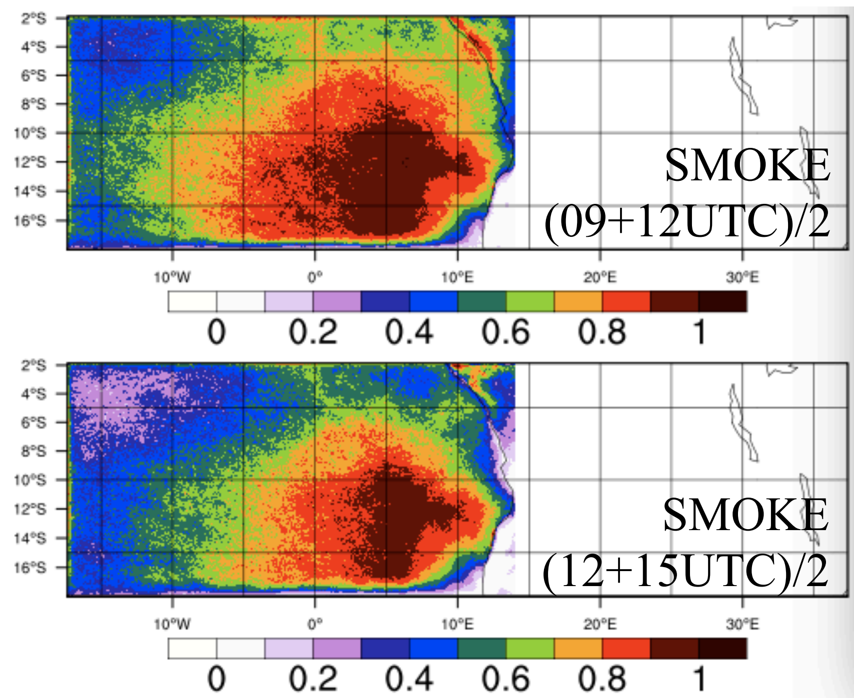
- Modeled above-cloud smoke AOD is compared against above-cloud MODIS AOD from Meyer et al. (2015)
- Model vs. MODIS AOD averaged over Aug. and Sept. 2014: 0.351 vs. 0.354; Pattern well simulated

Evaluation – modeled cloud fraction

Averaged cloud retrieval fraction_liquid by Terra and Aqua Level 3, Aug.~Sept. 2014



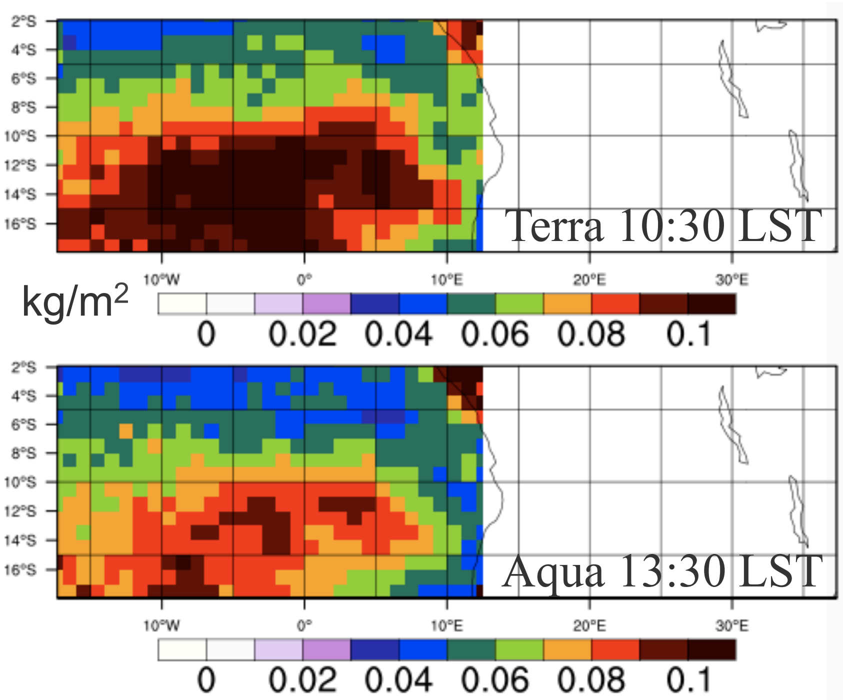
Averaged cloud fraction modeled by SMOKE case, Aug.~Sept. 2014)



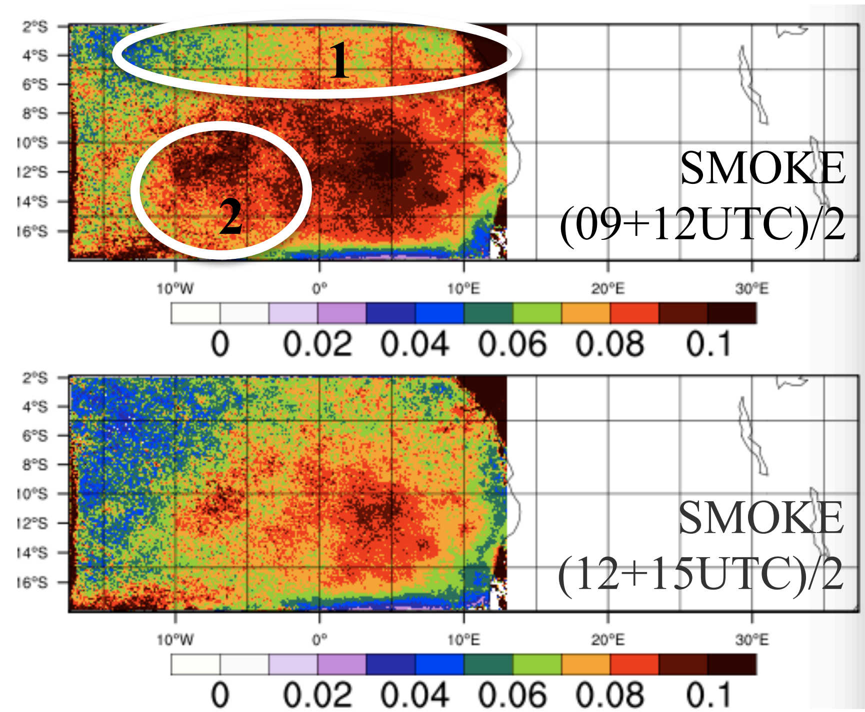
- Model reasonably reproduces cloud patterns.
- Model successfully captures the regions, which experience the largest cloud fraction variation from morning to afternoon/noon.

Evaluation – modeled cloud LWP

Averaged cloud liquid water path product by Terra and Aqua Level 3, Aug.~Sept. 2014

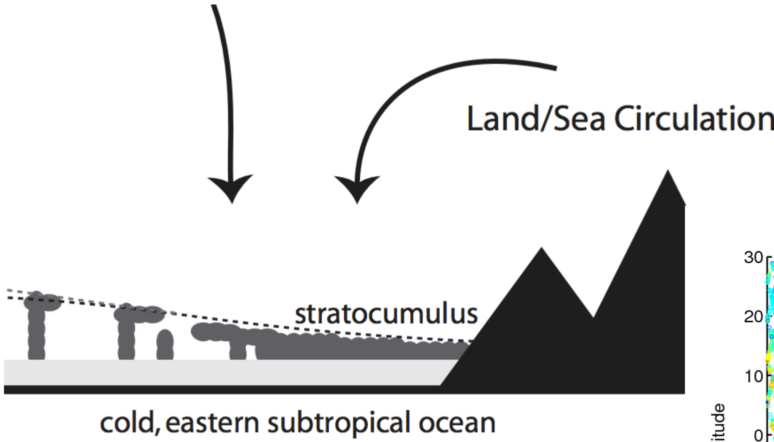


Averaged cloud liquid water path modeled by SMOKE case, Aug.~Sept. 2014)

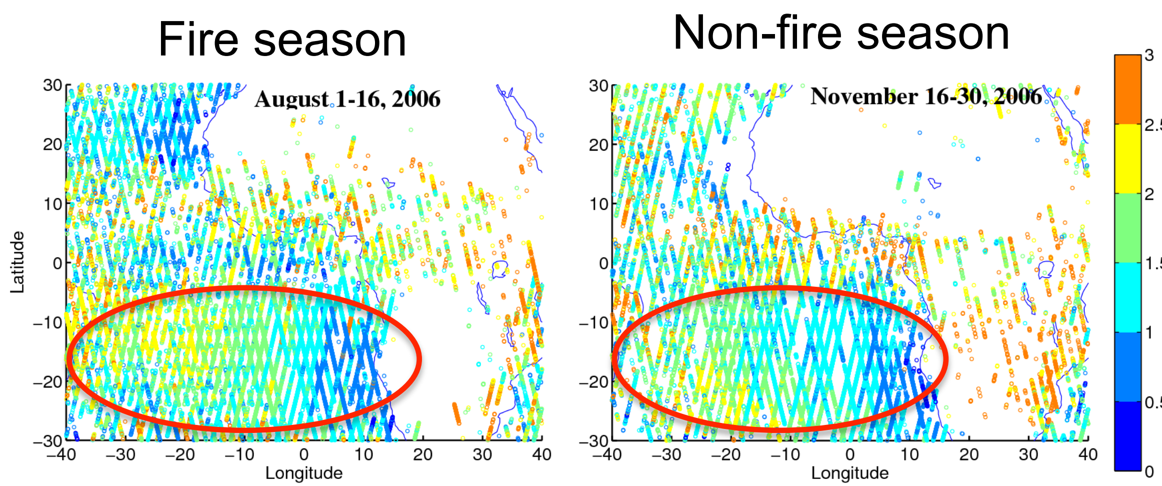


- Model fairly reproduces observed cloud liquid water path (LWP).
- LWP: overestimated by ~20 g/m^2 over region 1; underestimated by ~20 g/m^2 over region 2
- Model successfully captures the rapid decreases in liquid water path from morning to afternoon

Evaluation – cloud top heights



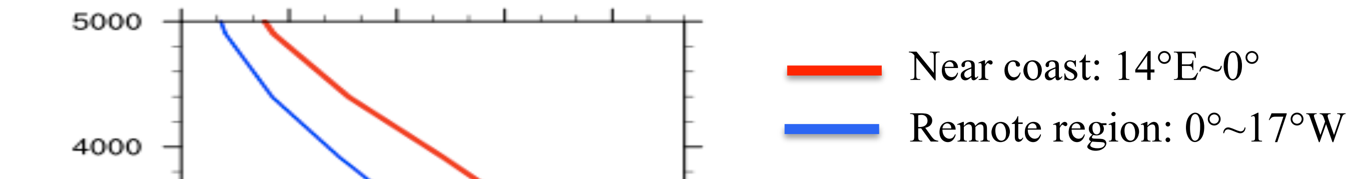
Calipso observation for 2006
(presentation by Rob Wood)

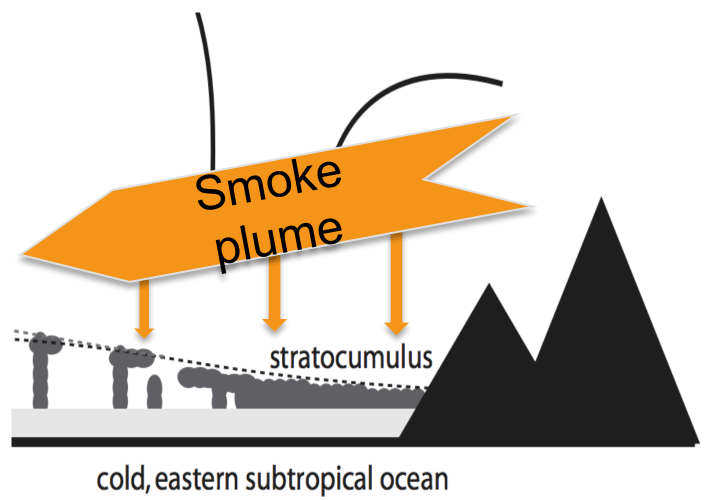


- Cloud top height gradually increases as clouds locate further away from the coast
- Cloud top are higher during the fire season (August) compared to non-fire season (November)
  - Meteorological condition
  - Smoke increases LWP ➔ stronger entrainment at cloud top ➔ higher cloud top

Evaluation – cloud top height

Averaged vertical distribution of layer AOD normalized by column AOD (noon, Aug.~Sept. 2014)





- From coast to remote regions
  - The cloud top height increases (avg. cloud m.m.r.> 0.001 g/kg)
  - The altitude of smoke plume decreases because of gravitational settling
  - More fraction of smoke is in touch with clouds

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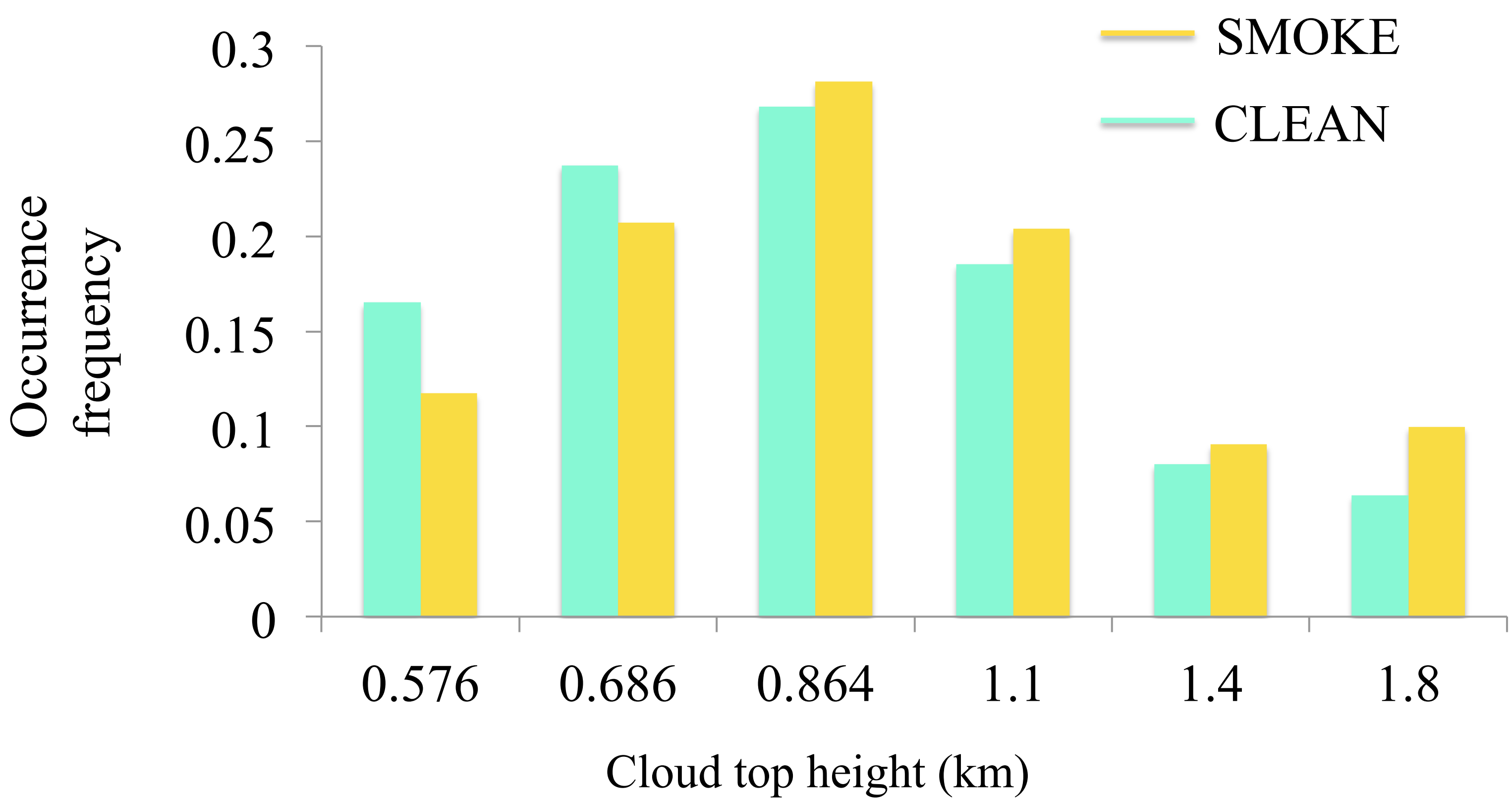
Smoke effect on cloud top height

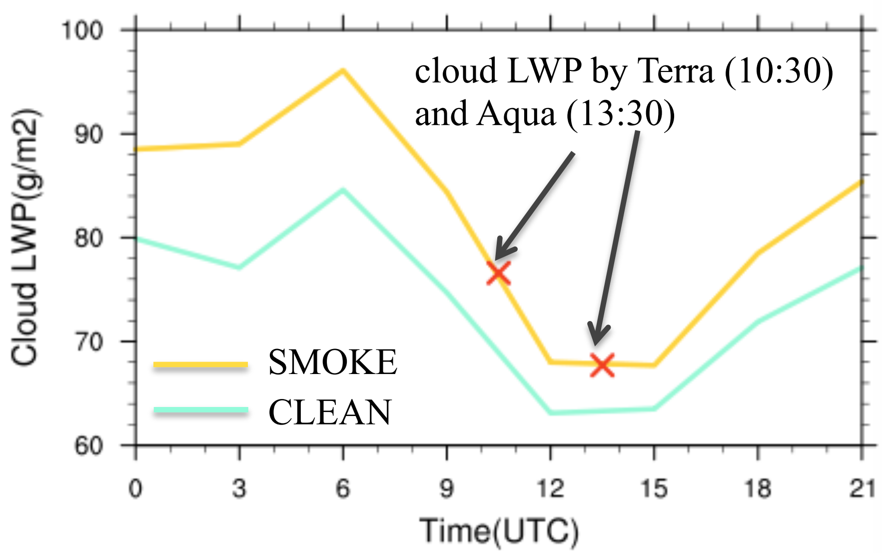
Occurrence frequency of cloud top heights over ocean during 12 UTC over Aug.~Sept. 2014



- The cloud tops in SMOKE are higher than CLEAN, **indicating stronger entrainment rate**

Smoke effect on cloud LWP

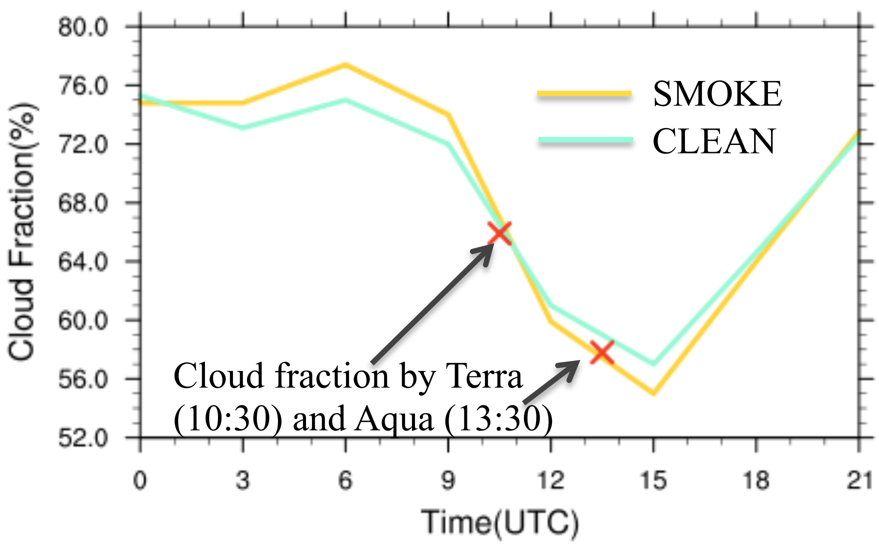
Diurnal cycle of cloud LWP averaged over ocean
modeled by the SMOKE and CLEAN cases, Aug.~Sept. 2014



- Cloud LWP diurnal cycle: Highest at 6 UTC (~ 6 LST); Lowest at 15 UTC
- SMOKE vs. CLEAN: Increase in LWP because of smoke indirect effect

Smoke effect on cloud fraction

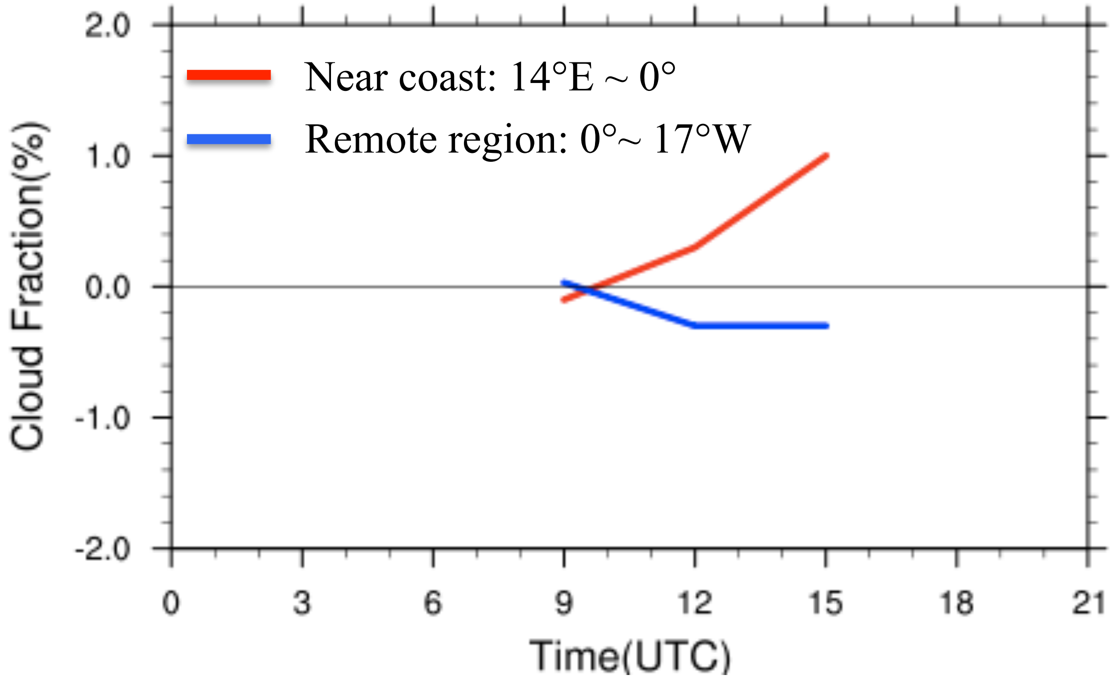
Diurnal cycle of cloud fraction averaged over ocean
modeled by the SMOKE and CLEAN cases, Aug.~Sept. 2014



- Cloud fraction diurnal cycle: Highest at 6 UTC (~6 LST); Lowest at 15 UTC
- SMOKE vs. CLEAN: increase at night because of smoke indirect effect, and decrease at daytime due to enhanced entrainment rates and a quicker decoupling caused by higher LWP

Smoke effect on cloud fraction

ΔCF between SMOKE and NO_RAD, Aug.~Sept. 2014



Near the coast: the radiative effect can increase CF by 1%, comparable to other modeling studies, e.g. 1~2% in Sakaeda et al., 2011.
Remote region: slightly decrease CF, probably due to large fraction of smoke in touch with clouds

Summary

- We investigate the impact of wildfire aerosols from Southern Africa on stratocumulus over Southeastern Atlantic Ocean using the WRF-Chem model
- Smoke plumes and cloud fields are reasonably well simulated
- Smoke causes positive changes in LWP and cloud fraction during the night and early morning (due to the indirect effect); however, higher LWP leads to a quicker decoupling process (due to a stronger entrainment process) at daytime; the radiative effect of smoke can mitigate or slow down the decoupling process near the coast.