Climatology of low-level clouds in km-scale climate models

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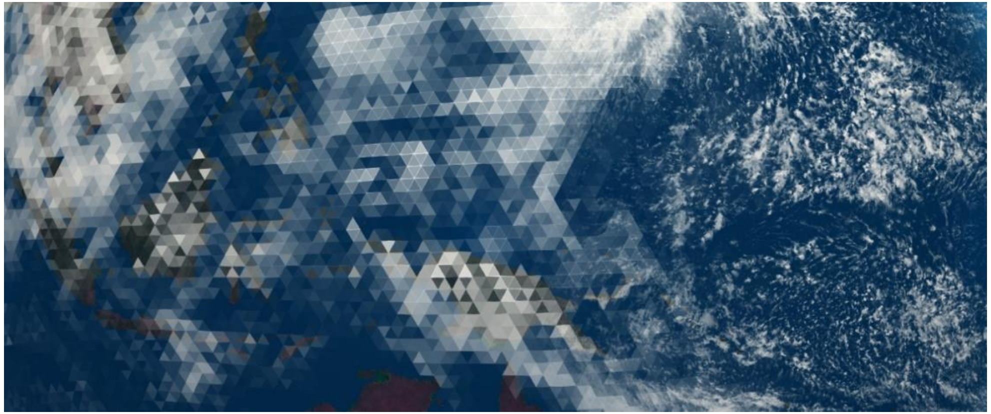
nextGEMS

Atmospheric Physics Seminar, 29 Nov 2024

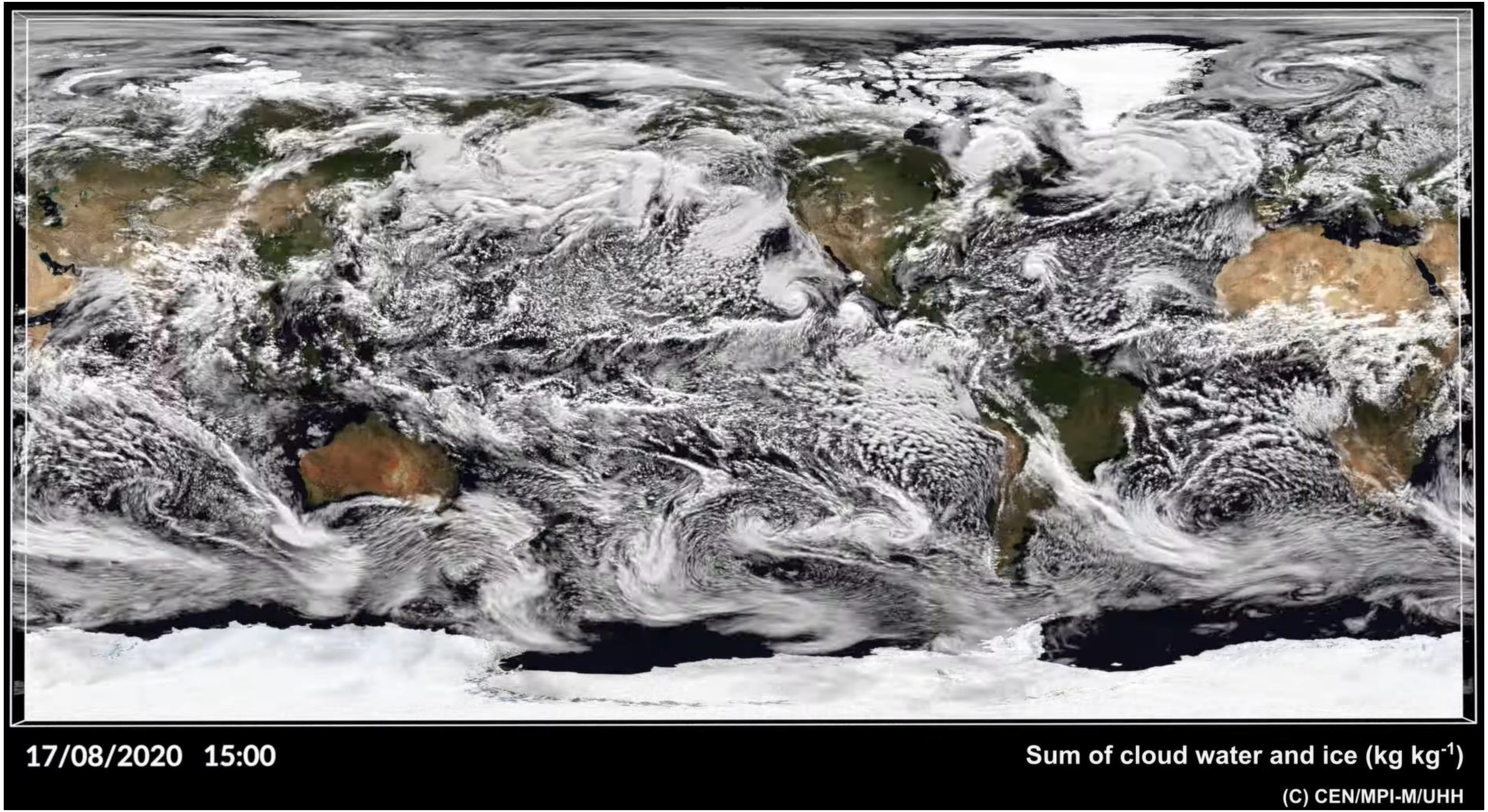
Standard coarse-resolution models have many deficiencies

Traditional CMIP6 models with~100 km grids

- represent many processes statistically relying on empirical parameterizations
    - vertical transport of energy and water due to atmospheric convection
    - uptake of heat and carbon by the deep ocean due to mesoscale eddies
    - effect of heterogeneous land surface, bathymetry and coastal/ice shelves
    - atmospheric waves
    - extremes of precipitation and temperature
- suffer from well-known biases
    - tropical precipitation: too early,
      too little over continents, double ITCZ
    - SST: too warm in the upwelling regions,
      too cold in tropical Atlantic and Pacific,
      too cold in subpolar North Atlantic
    - low-level clouds: too few, too bright

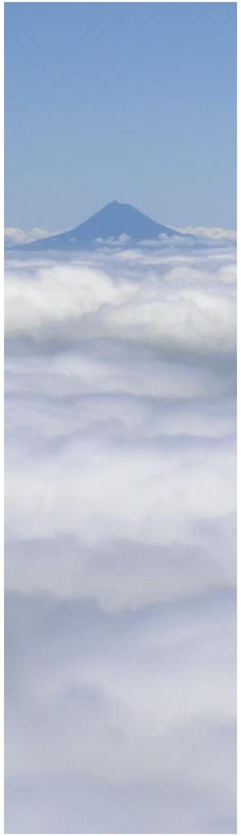


Despite consumed resources, there are advantages of km-scale modeling

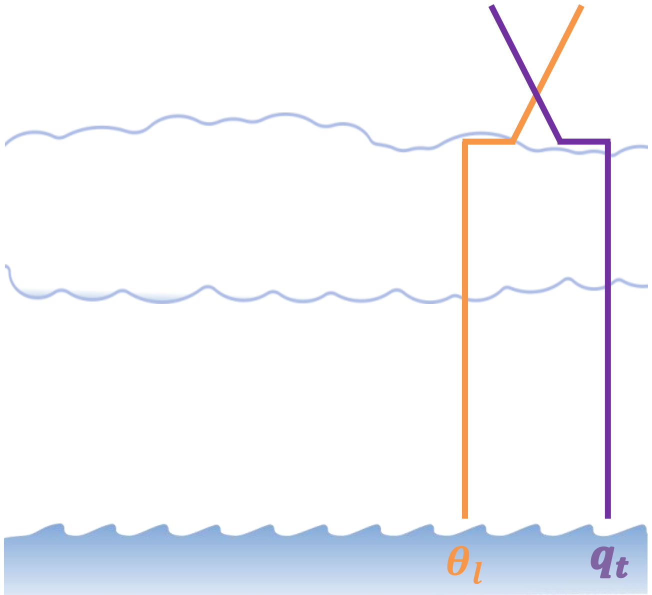


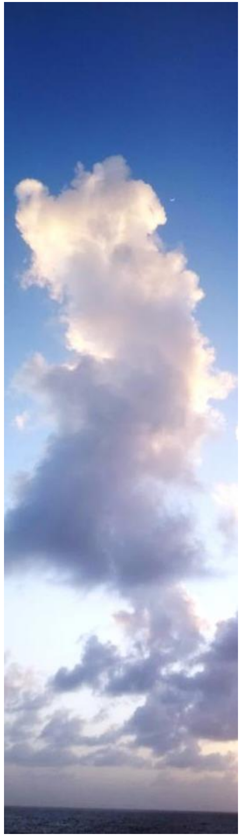
ICON-Saphirre 5 km

Two subtropical low cloud regimes differ in thermodynamic structure of the BL

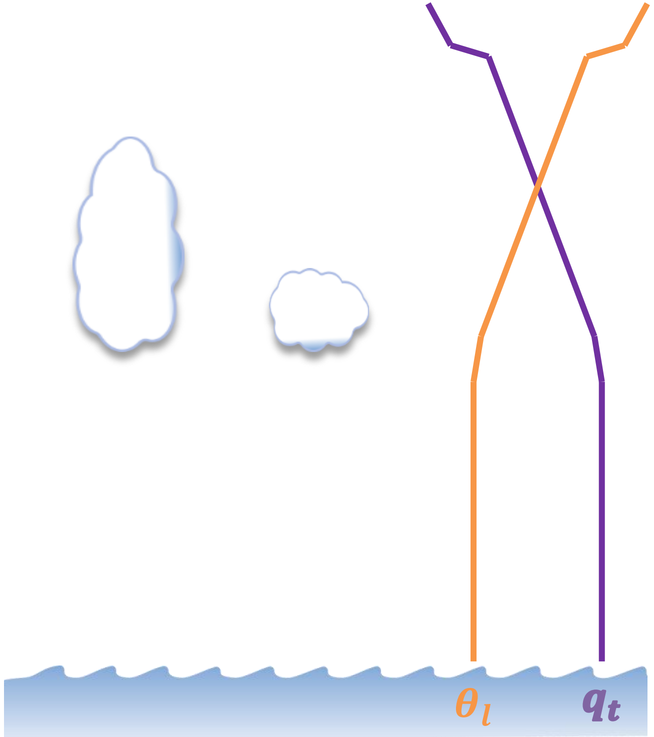


StCu: stratocumulus





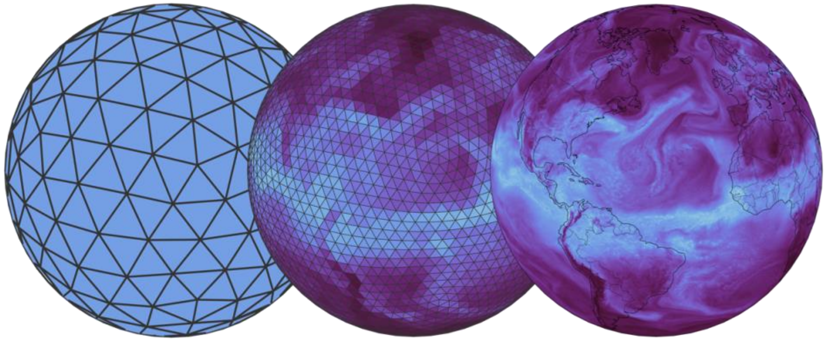
TrCu: trade-wind cumulus

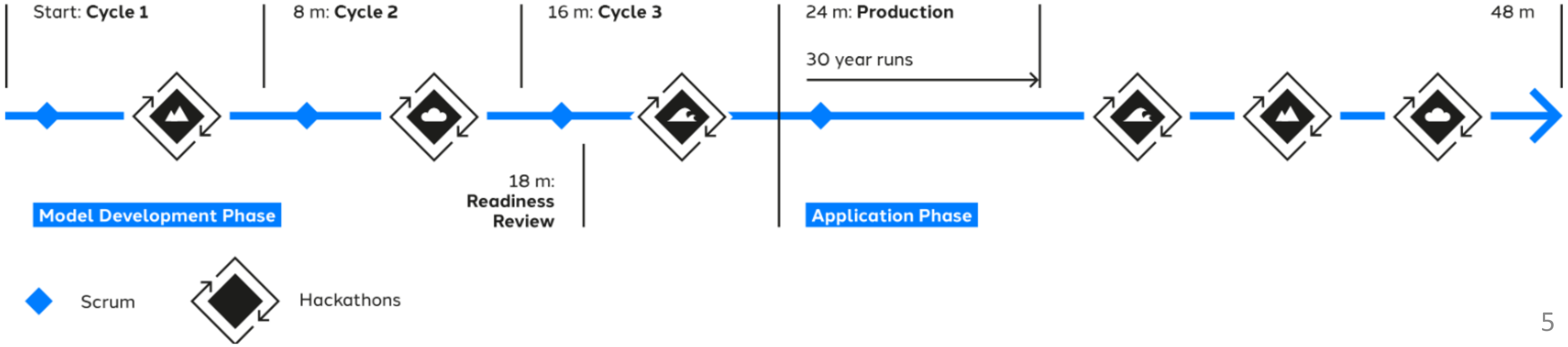


θ_l - liquid water potential temperature, q_t - total water mass fraction

Next Generation Earth Modeling Systems

1. develop two storm-resolving Earth system models and demonstrate their capacity to realistically represent the coupled (land-ocean-atmosphere) climate system
2. perform the first global multi-decadal (30 y) km-scale climate projections
3. use the models to test long-standing hypotheses underpinning the understanding of climate change, e.g. convective organization, cloud-aerosol interactions, mesoscale circulations, selection of circulation regimes, role of landscape for regional climate
4. build new and more integrated user communities





NextGEMS develops two km-scale global coupled climate models

Model	IFS-FESOM Integrated Forecasting System Finite-volumE Sea ice-Ocean Model	ICON ICOsahedral Non-hydrostatic model
Institutions	ECMWF, AWI	DWD, MPI, DKRZ, KIT, C2SM
Model configuration	Cycle 48r1 (Rackow et al. 2024)	Saphirre (Hohenegger et al. 2023)
Governing equations	primitive hydrostatic	compressible Navier-Stokes
Horizontal grid	Gaussian octahedral	icosahedral-triangular C
Vertical grid	pressure-based, 137 levels	geopotential-based, 90 levels
Microphysics	1-moment bulk vapor, liquid, ice, rain, snow	1-moment bulk vapor, liquid, ice, rain, snow, graupel
Cloud fraction	parameterized	binary + global cloud inhomogeneity
Convection	shallow, mid, deep	none
Turbulent mixing	EDMF, K-diffusion	Smagorinsky-Lilly

See also: easy.gems.dkrz.de

Subgrid turbulence in ICON: Smagorinsky-Lilly

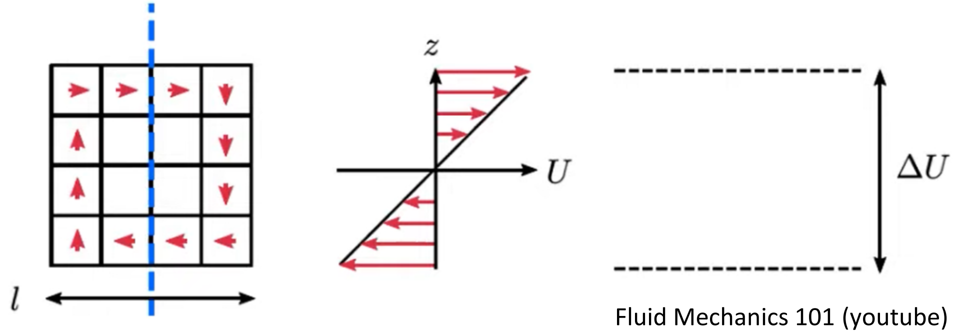
1D

$$\overline{w'\phi'} = -K\frac{\partial\bar{\phi}}{\partial z}$$

$$K \sim U_0 l$$

$$U_0 \sim \Delta U \sim l\frac{\partial U}{\partial z} \qquad K \sim l^2\frac{\partial U}{\partial z}$$

$$l = C_s\Delta \qquad 0 < \mathrm{C_s} < 1$$



Fluid Mechanics 101 (youtube)

3D

$$K = (C_s\Delta)^2\sqrt{2S_{ij}S_{ij}}f(Ri)$$

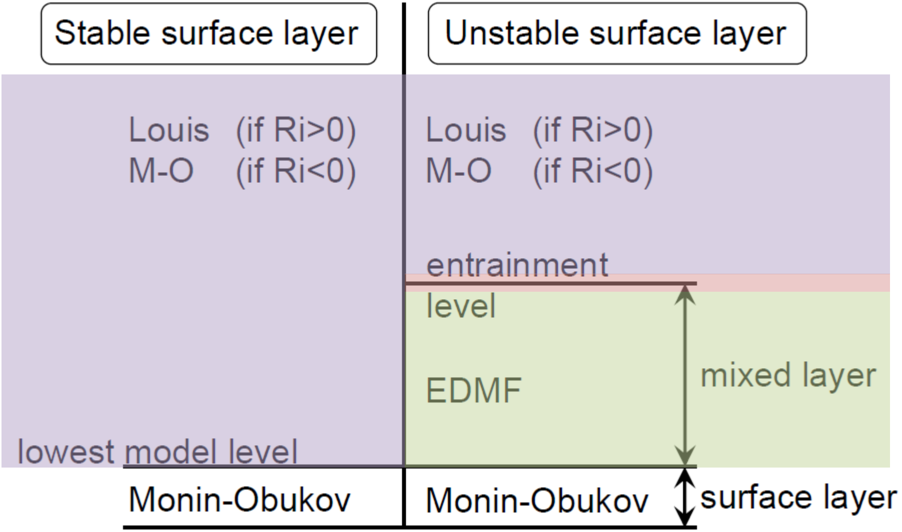
$$f(Ri) = \begin{cases}\sqrt{1 - Ri/Pr} & \text{if } 1 - Ri/Pr \geq 0 \\ 0 & \text{if } 1 - Ri/Pr < 0\end{cases}$$

Subgrid turbulence in IFS: eddy-diffusivity mass-flux and K-diffusion

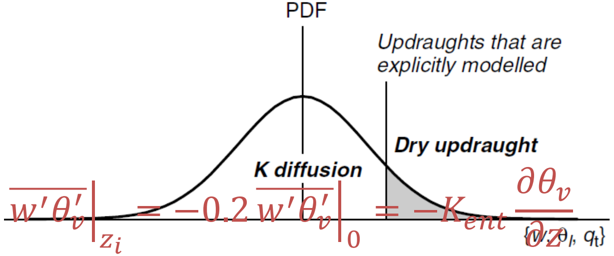
$$\overline{w'\phi'} = -K\frac{\partial\bar{\phi}}{\partial z}$$

$$K \sim l^2 \left|\frac{\partial U}{\partial z}\right| f(Ri)$$

$$\frac{1}{l} = \frac{1}{\kappa z} + \frac{1}{\lambda}$$



Eddy-diffusivity mass-flux



$$\overline{w'\theta_v'}\Big|_{z_i} = -0.2\,\overline{w'\theta_v'}\Big|_0 = -K_{ent}\frac{\partial\theta_v}{\partial z}$$

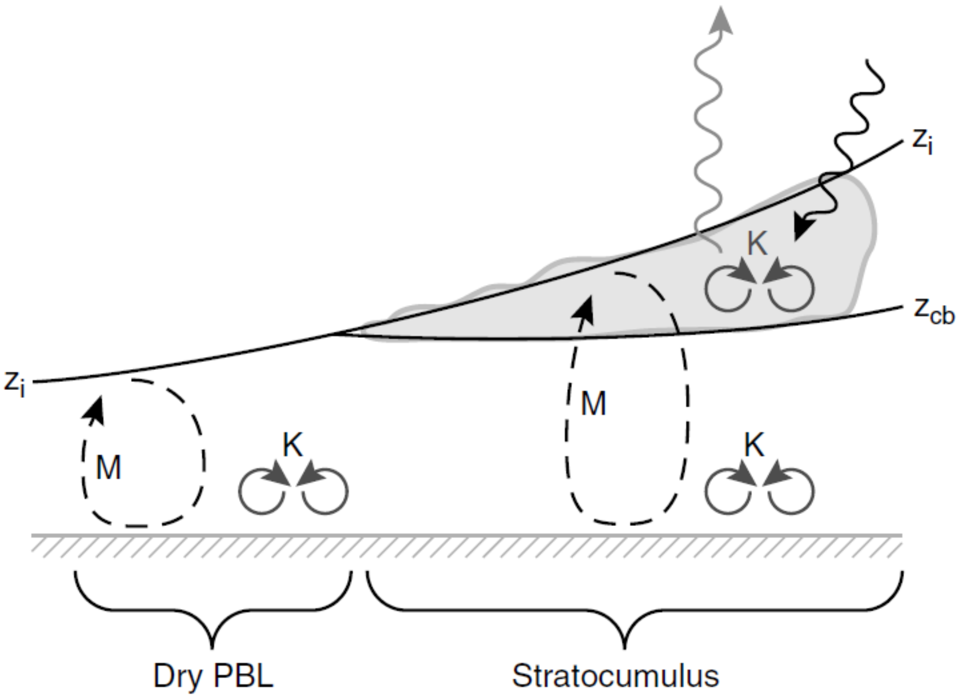
$$\overline{w'\phi'} = -K_{bot}\frac{\partial\bar{\phi}}{\partial z} + M(\bar{\phi}^u - \bar{\phi})$$

$$K_{bot}(z) \sim u_* z f(z/L, z/z_i)$$

M: surface-driven plume model

IFS Documentation Cy48r1, Koehler et al. 2011

Subgrid turbulence in IFS: stratocumulus-topped BL



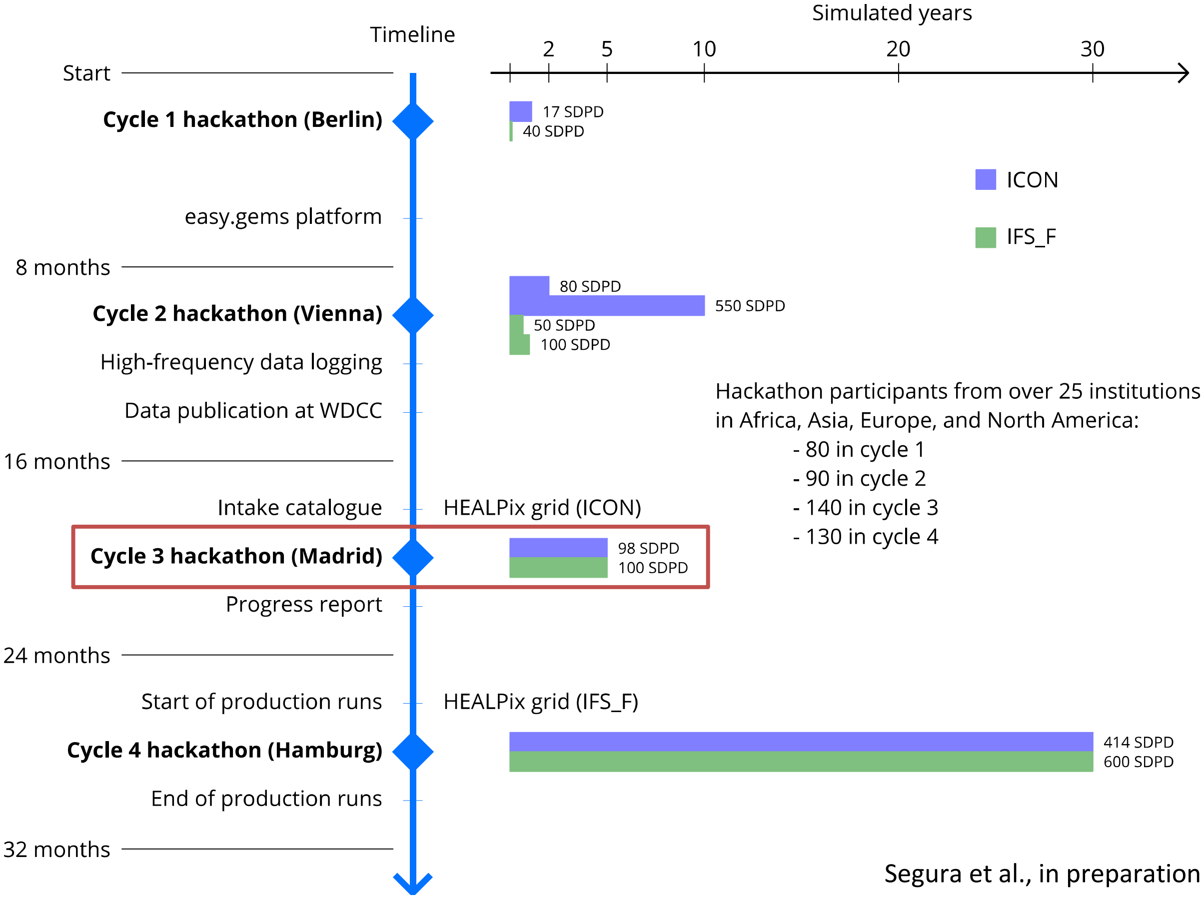
$$\left.\overline{w'\theta_v'}\right|_{z_i} = -0.2\,\left.\overline{w'\theta_v'}\right|_0 - 0.2\,\frac{\Delta R}{\rho c_p} = -K_{ent}\,\frac{\partial \theta_v}{\partial z}$$

$$\overline{w'\phi'} = -\left(K_{bot} + K_{top}\right)\frac{\partial \bar{\phi}}{\partial z} + M(\bar{\phi}^u - \bar{\phi})$$

$$K_{top}(z) \sim (\Delta R z_i)^{\frac{1}{3}} f(z/z_i)$$

IFS Documentation Cy48r1, Koehler et al. 2011

NextGEMS released 4 cycles of simulations



Hackathon participants from over 25 institutions in Africa, Asia, Europe, and North America:

- 80 in cycle 1
- 90 in cycle 2
- 140 in cycle 3
- 130 in cycle 4

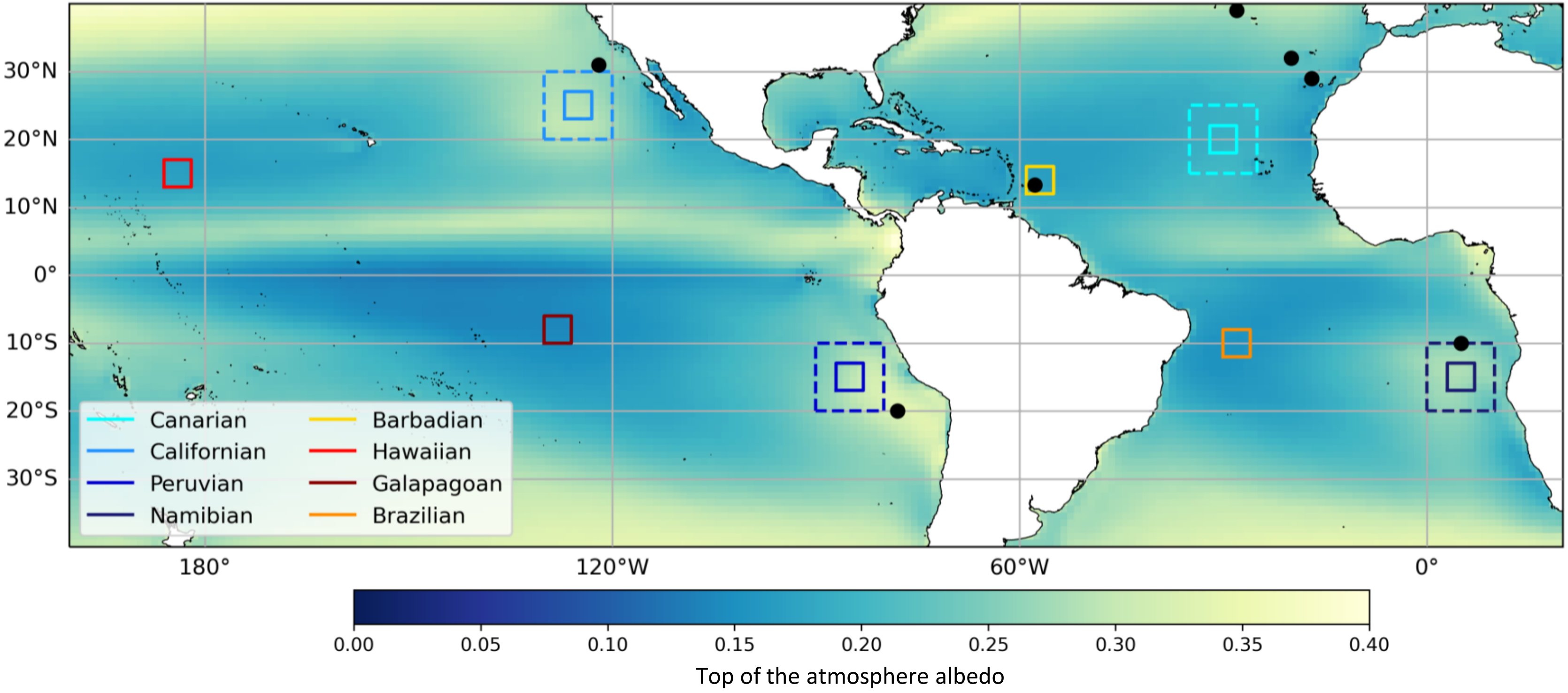
Segura et al., in preparation

NextGEMS simulations: resolution, length and forcing

	Δx_A (km)	Δx_O (km)	Period	Nodes	Throughput (SDPD)	Forcing	Energetically consistent
Cycle 1							
ICON-C1	5	5	406 days	100*	17	Perpetual 2020	No
IFS_F-C1	4.4	25	40 days	20*	40	Perpetual 2020	No
Cycle 2 (Wieners et al., 2023)							
ICON-C2-A	5	5	2 years	400	80	Perpetual 2020	No
ICON-C2-B	10	10	10 years	400	550	Perpetual 2020	No
IFS_F-C2-A	2.8	5	8 months	864*	50	Perpetual 2020	No
IFS_F-C2-B	4.4	5	1 year	864*	100	Perpetual 2020	No
Cycle 3 (Koldunov et al., 2023)							
ICON-C3	5	5	5 years	530	98	Perpetual 2020	No
IFS_F-C3	4.4	5	5 years	269	100	Perpetual 2020	Yes
Cycle 4 (Wieners et al., 2024)							
ICON-C4	10	5	30 years	464	414	SSP3-7.0	Yes
IFS_F-C4	9	5	30 years	269	600	SSP3-7.0	Yes

Segura et al., in preparation

Focus on representative geographical regions

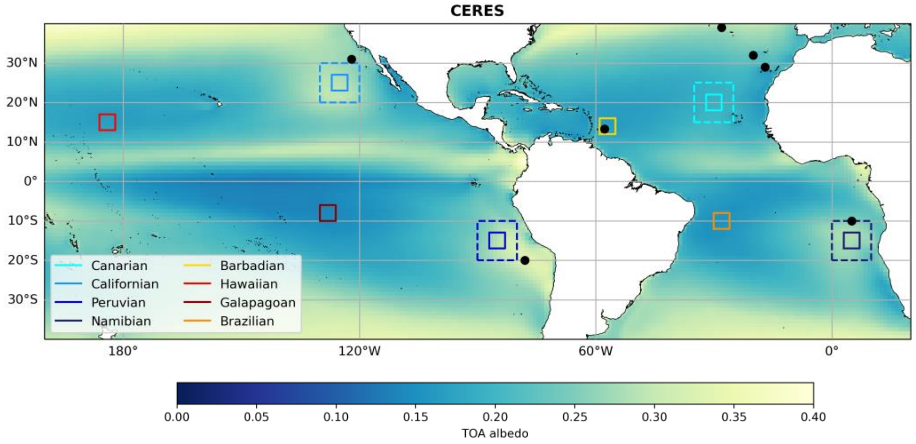


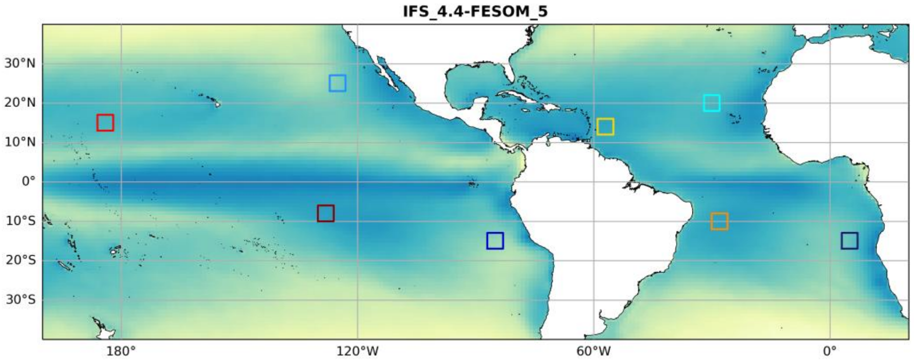
CERES EBAF TOA monthly means data in netcdf edition 4.2. NASA Langley Atmospheric Science Data Center. Years 2000-2022.

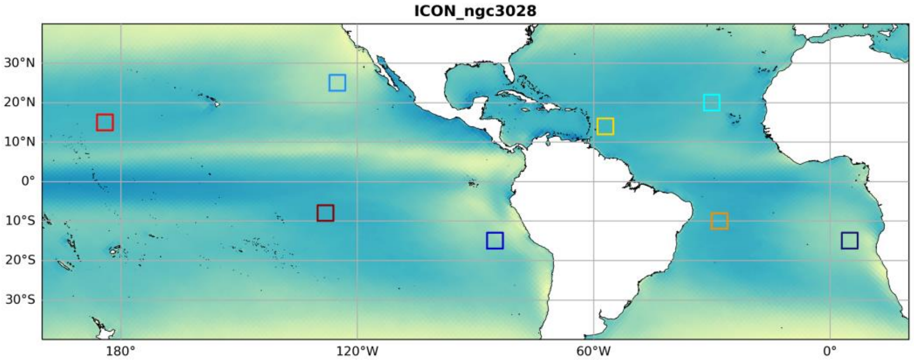
solid squares – our 4x4 deg regions of interest, dashed squares – 10x10 deg StCu regions of Klein & Hartman 1993

dots – selected field campaigns (DYCOMS, EUREC4A, ASTEX, ACE-2, ACE-ENA, VOCALS-REx, ORACLES)

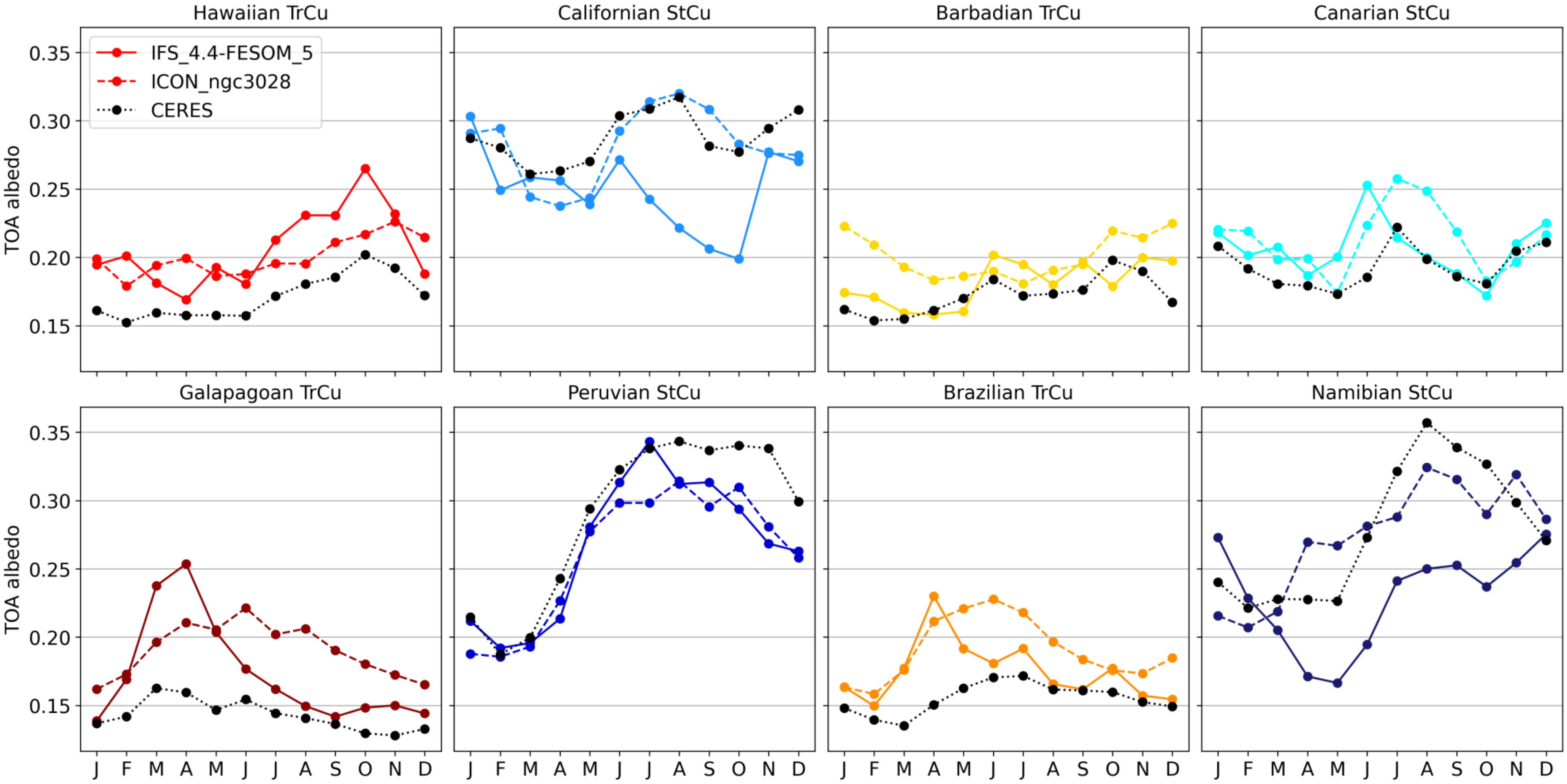
The models simulate correct general pattern of albedo







Annual cycle is reasonable in StCu regions; fair in most TrCu regions



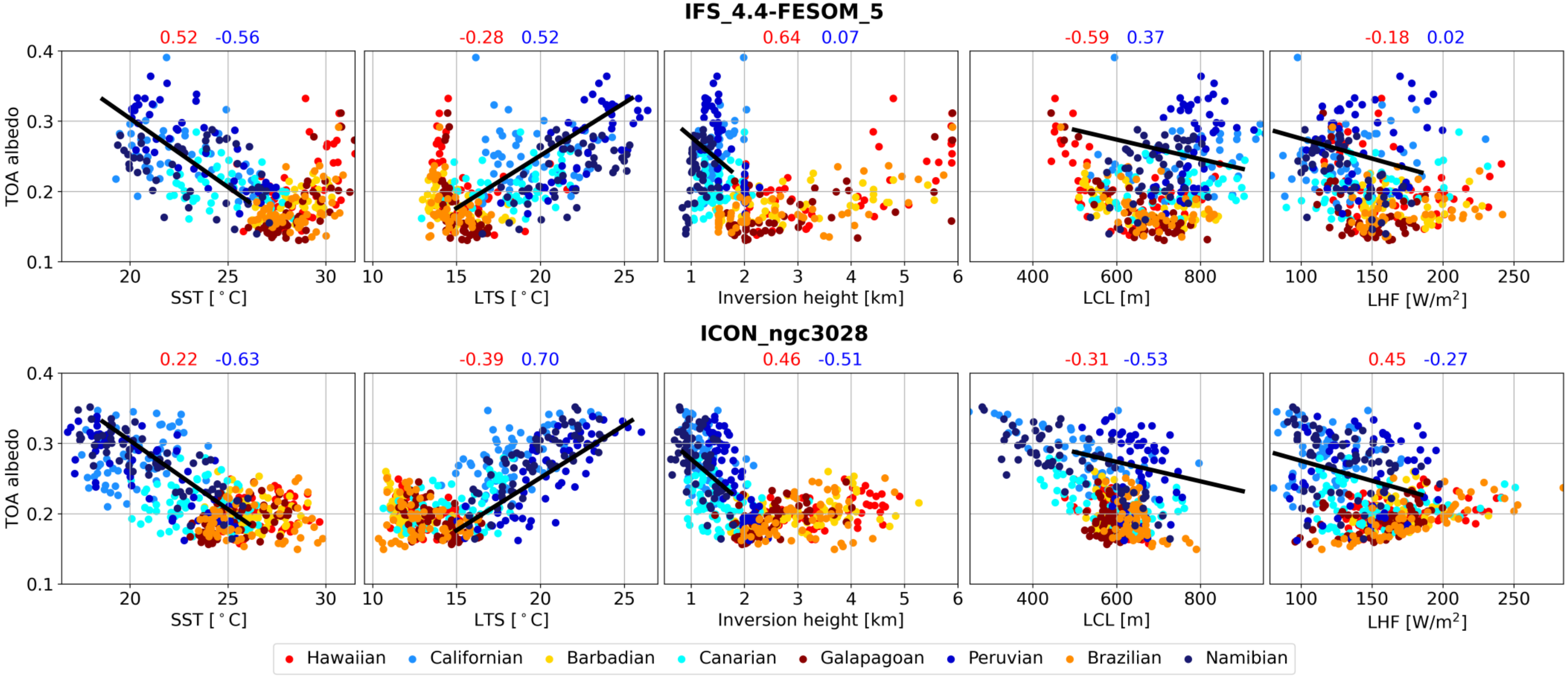
What factors control the cloudiness?

Relation between TOA albedo and 12 parameters

- sea surface temperature (SST)
- surface wind speed
- surface sensible heat flux (SHF)
- surface latent heat flux (LHF)
- lifting condensation level (LCL)
- inversion height
- inversion strength
- liquid water path (LWP)
- lower tropospheric stability (LTS)
- vertical velocity, potential temperature and specific humidity at 700 hPa (w@700hPa, θ@700hPa, q@700hPa)

$$LTS = \theta_{700hPa} - \theta_{surface}$$

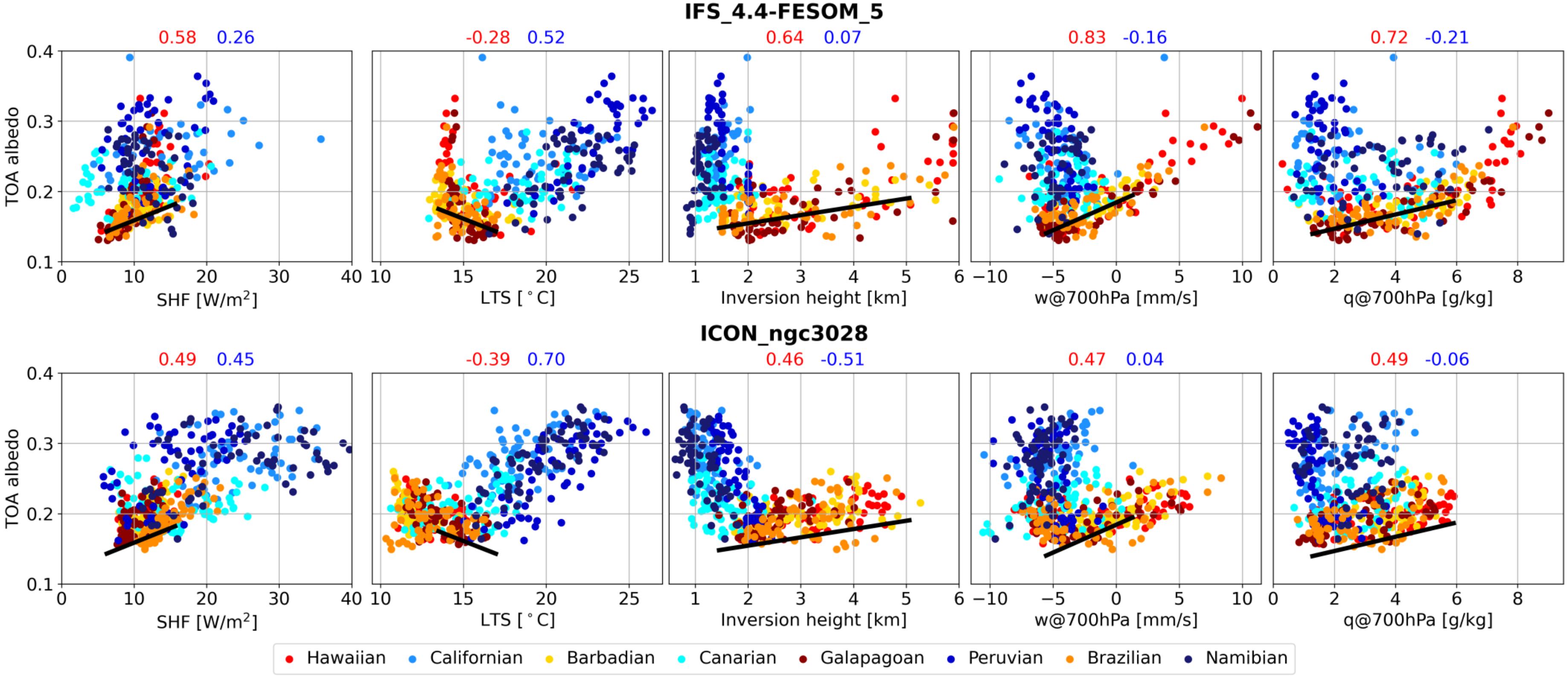
For StCu, albedo correlates with stability



black lines – linear trends from ERA5 + CERES in 2010-2021 for StCu

above the panels – correlation coefficients: blue for StCu and red for TrCu

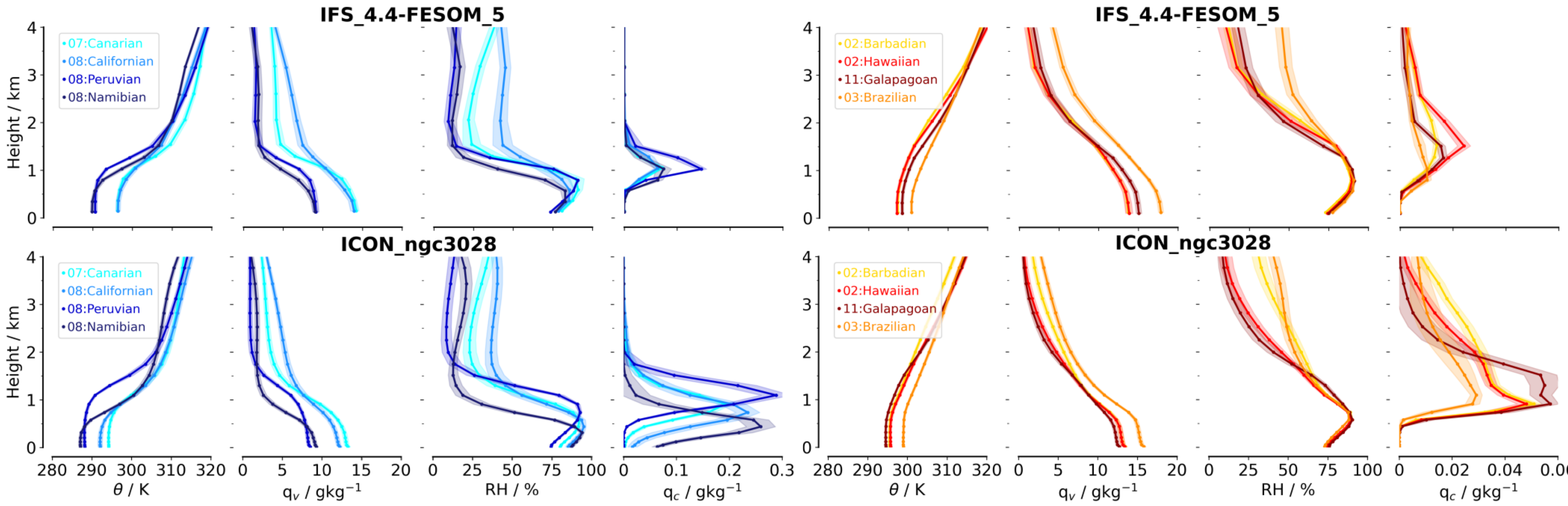
For TrCu, albedo correlates with dry & wet seasons



black lines – linear trends from ERA5 + CERES in 2010-2021 for TrCu

above the panels – correlation coefficients: blue for StCu and red for TrCu

The models differ in cloud water; and cloud base height of StCu



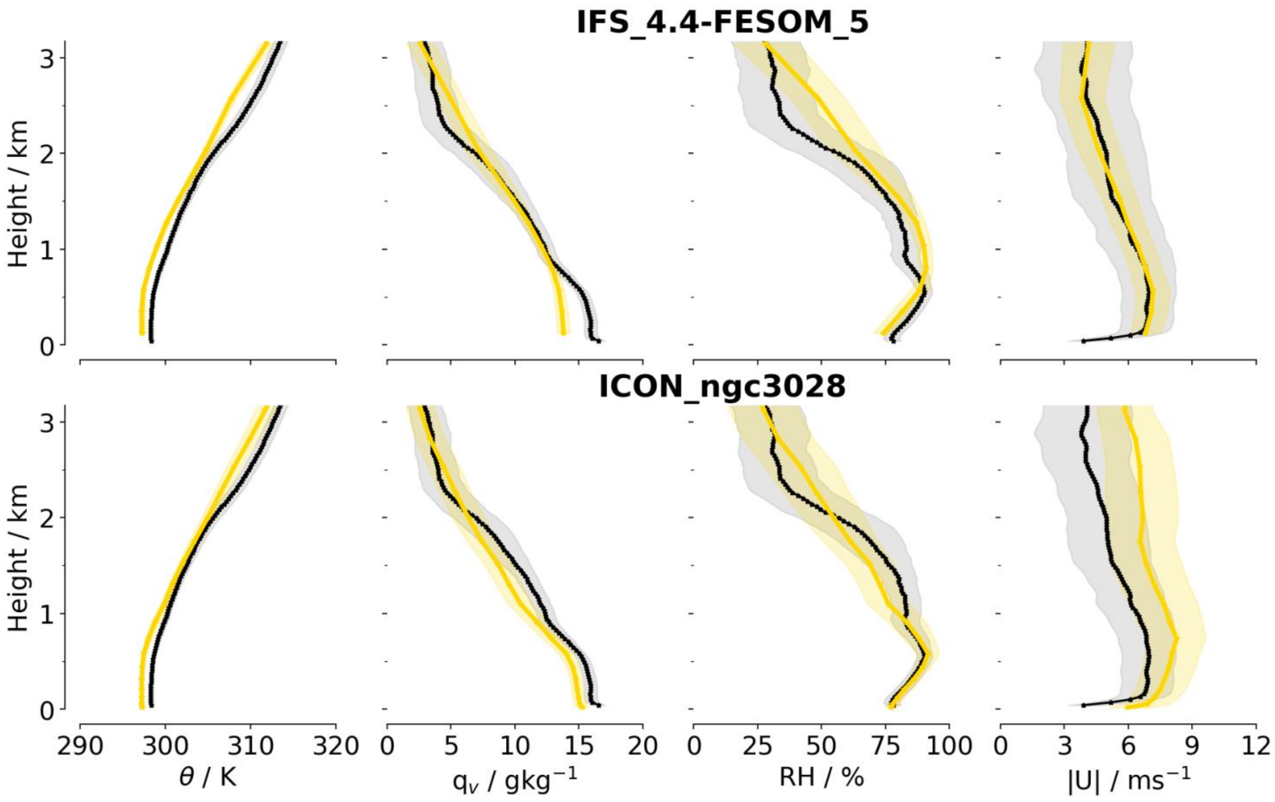
Months of maximum albedo

- Canarian: July
- Californian, Peruvian, Namibian: August

Months of minimum albedo

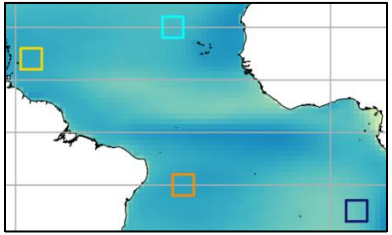
- Hawaiian, Barbadian: February
- Brazilian: March
- Galapagoan: November

Both models miss trade-wind inversion for TrCu



Model (yellow) and radiosonde (black; Stephan et al. 2021) profiles at the Barbados Cloud Observatory during 1st half of the EUREC4A campaign (Jan 21 – Feb 4, 2020)

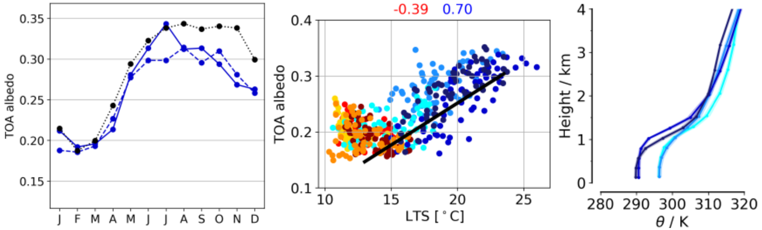
Summary: low clouds in km-scale models are fair on monthly timescale



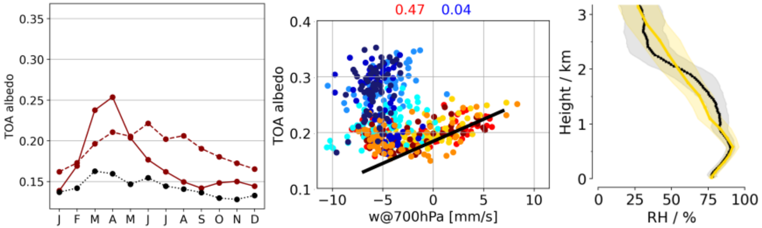
- 5-year simulations with two km-scale global coupled climate models
- 8 regions of interests over subtropical Atlantic and Pacific

StCu

+ average and annual cycle of albedo
+ relation between albedo and tropospheric stability
+ thermodynamic vertical structure
- radiation-entrainment feedback
- cloudiness in coastal areas



TrCu



+ BL properties distinct from StCu
+ dry&wet seasons in annual cycles and parameter correlations
- overestimated average albedo
- trade-wind inversion
- too dry cloud layer in ICON