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Improved representation of marine stratocumulus clouds in ECHAM6-HAM2 and resulting changes in the anthropogenic aerosol effect

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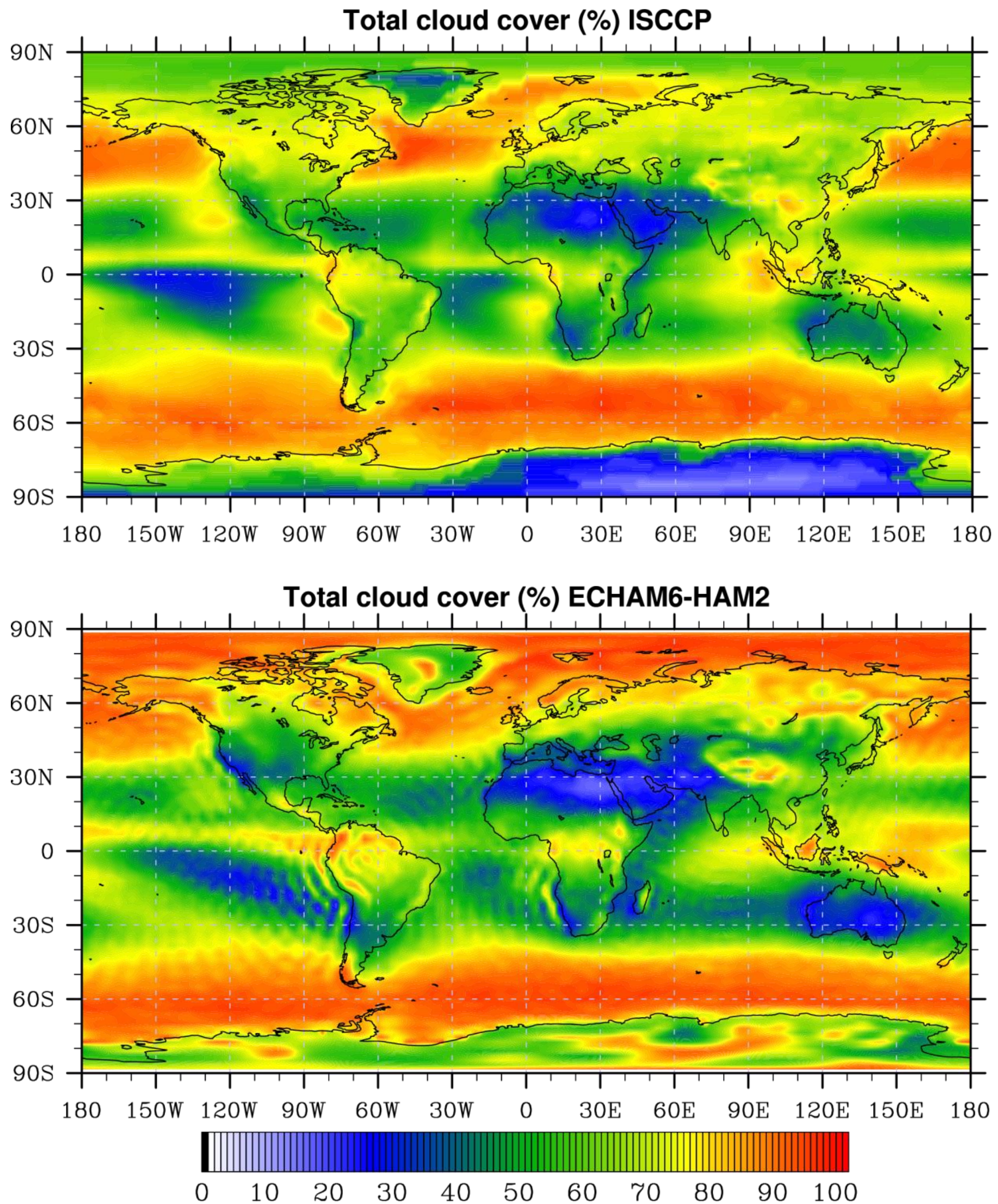
18 December 2013

Remote sensing of atmospheric aerosol, clouds and aerosol-cloud interactions, Bremen

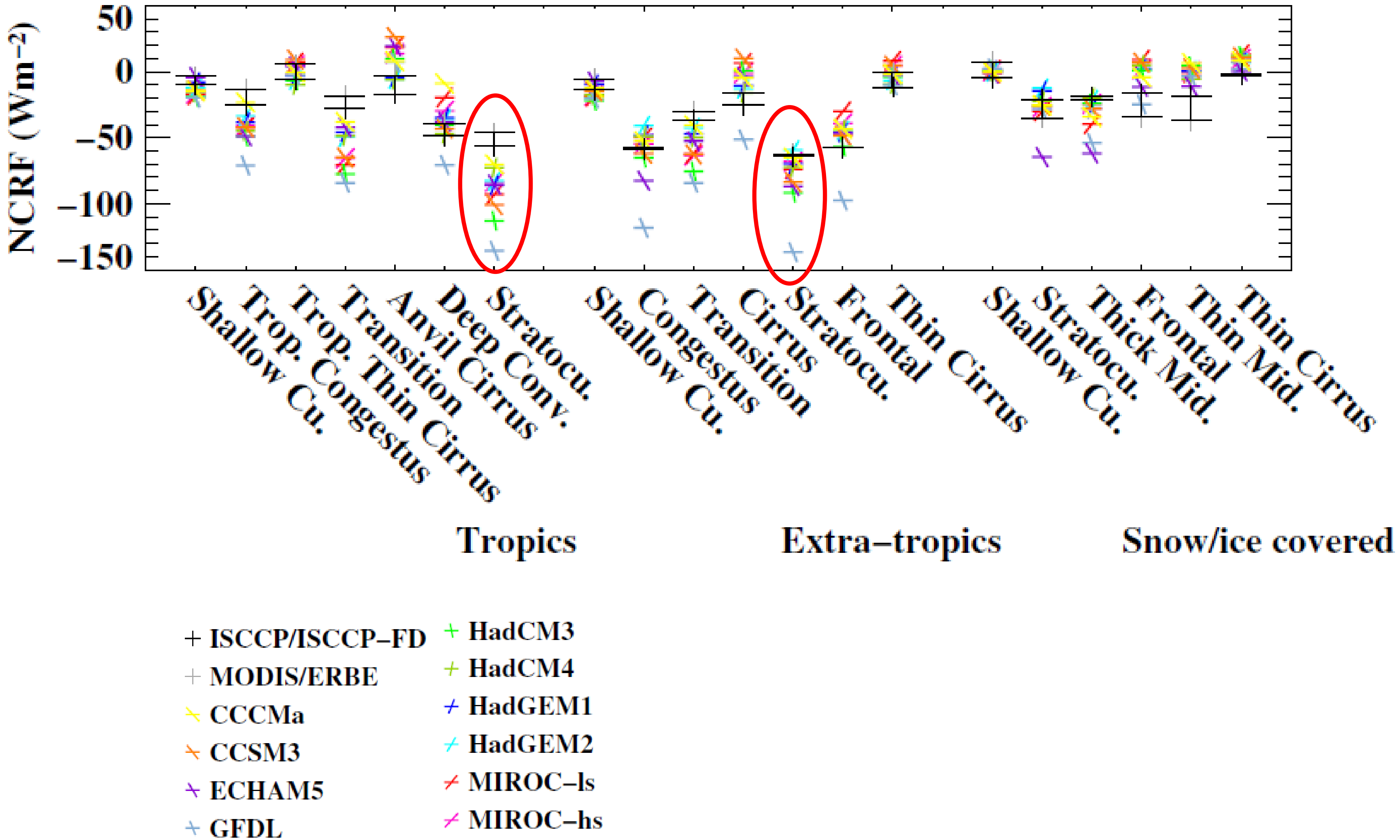
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

FWF
Der Wissenschaftsfonds.

Marine stratocumulus clouds



Importance of marine stratocumulus clouds



Adapted from Williams and Webb, 2009

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Anthropogenic aerosol effect

- Uncertainty sources of anthropogenic aerosol effect
- Natural/anthropogenic emissions most important
- Aerosol processes cause 14% of variance
- Low-level stratified clouds from ISCCP data

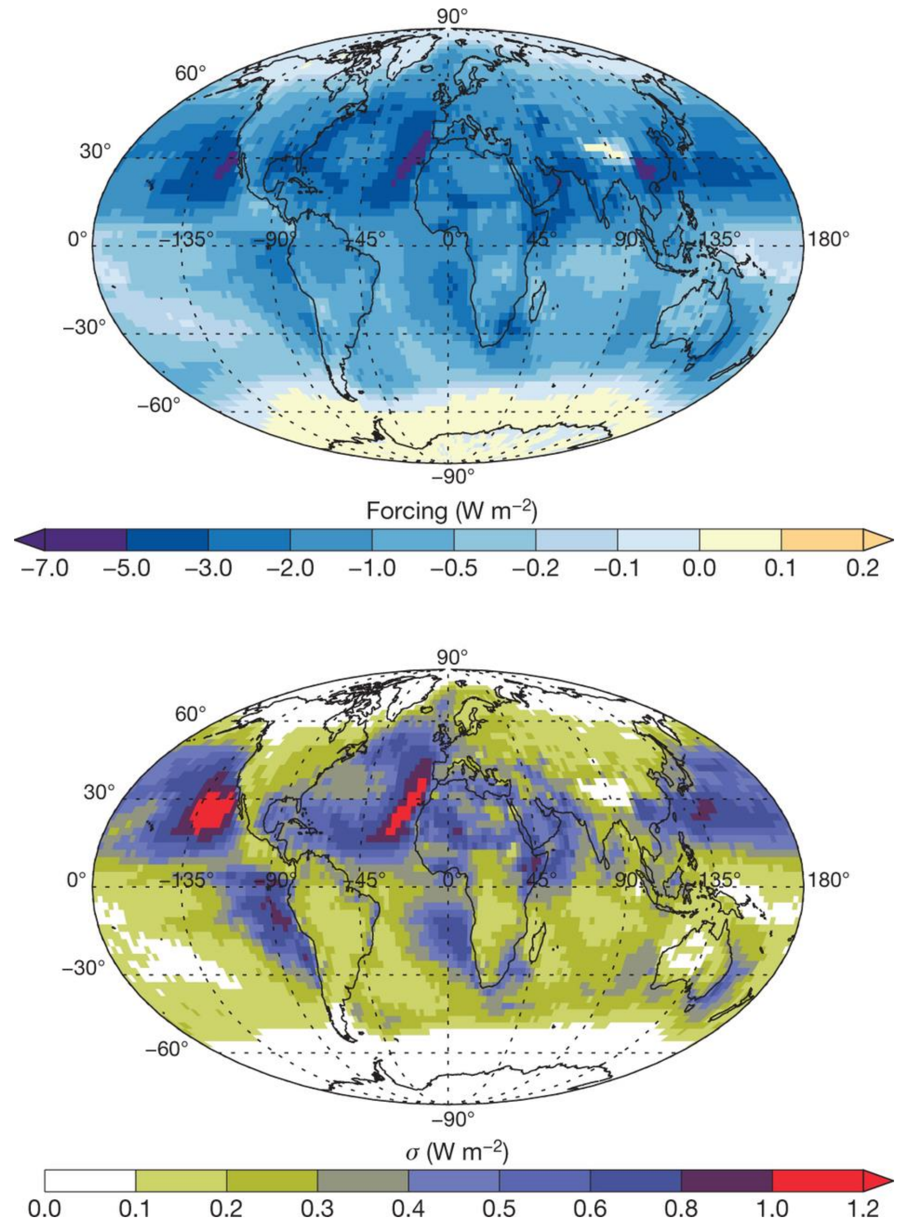

Figure from Carslaw et al., 2013

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Improved representation of marine stratocumulus clouds in ECHAM6-HAM2

- Physical properties:
  - Reduction of turbulent mixing in stable conditions
- Microphysical properties:
  - Aerosol processing
- Model simulations:
  - 5 years in T63L31
  - AMIP simulations

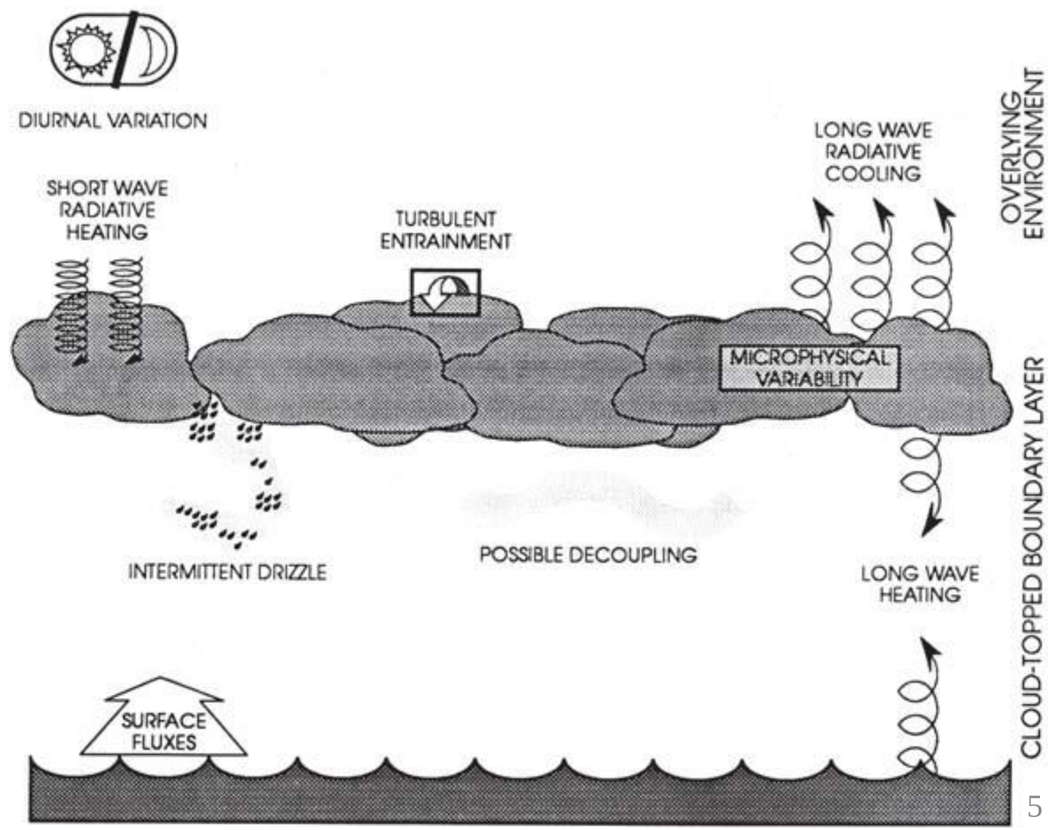

Figure from Bretherton et al., 2004

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Analysis of GCM clouds

- Stratocumulus regimes sampled from environmental conditions:

  based on dynamic and/or thermodynamic regimes

  (Tselioudis et al. 2000; Norris and Weaver2001; Tselioudis and Jakob 2002; Bony et al. 2004; Williams et al. 2006; Medeiros and Stevens 2011)

- Stratocumulus regimes sampled by cloud characteristics:

  cluster analysis method e.g. applied to τ-CTP histograms of cloud amount

  (Jakob and Tselioudis 2003; Gordon et al. 2005; Williams and Tselioudis 2007; Zhang 2007; Williams and Webb 2009; Tsushima et al. 2012)

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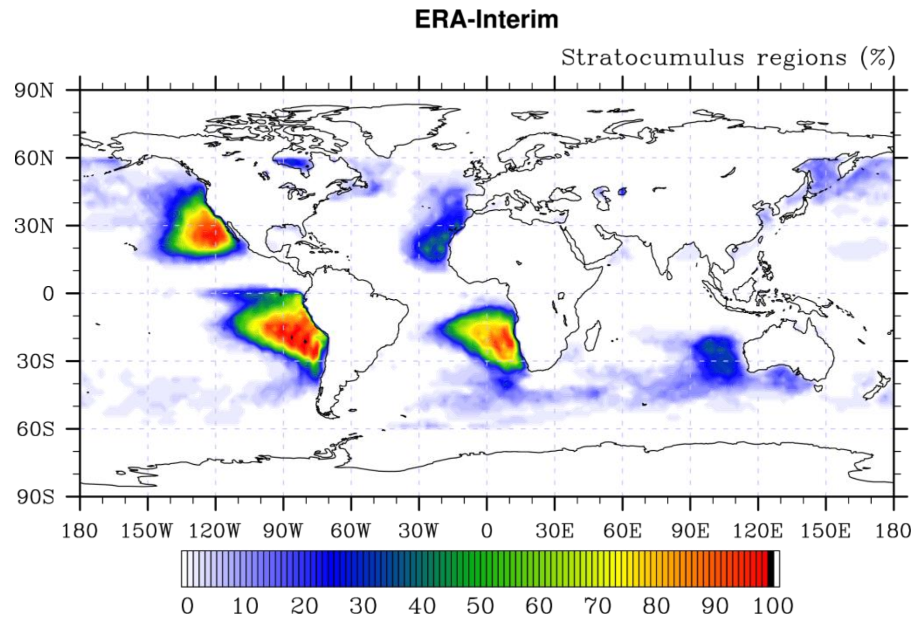
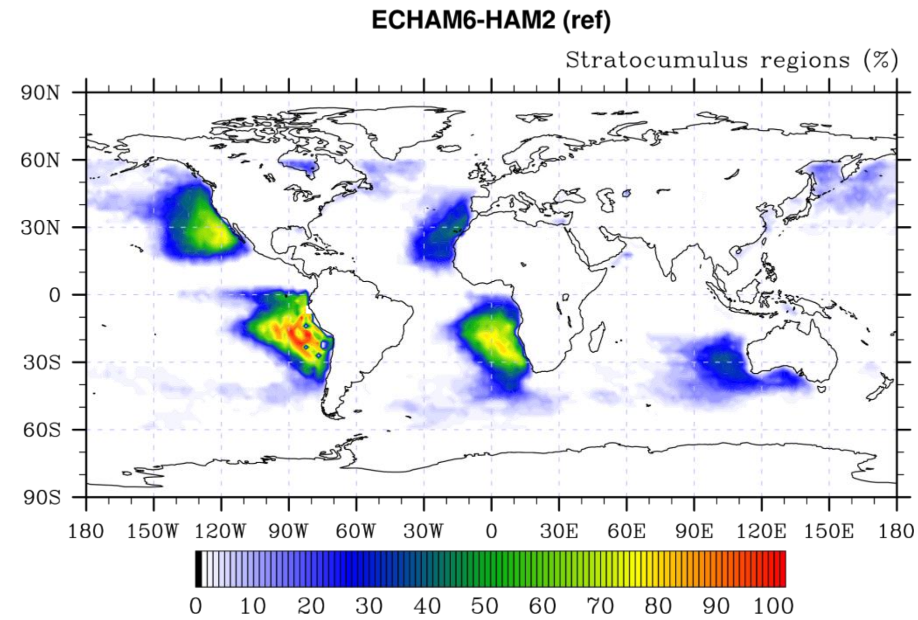
ERA-Interim/ECHAM6-HAM2

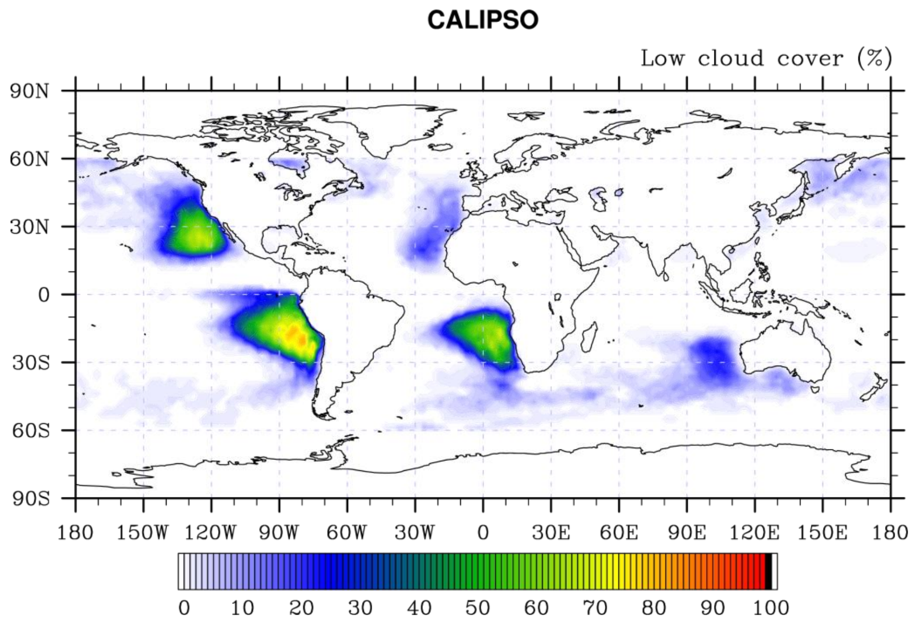




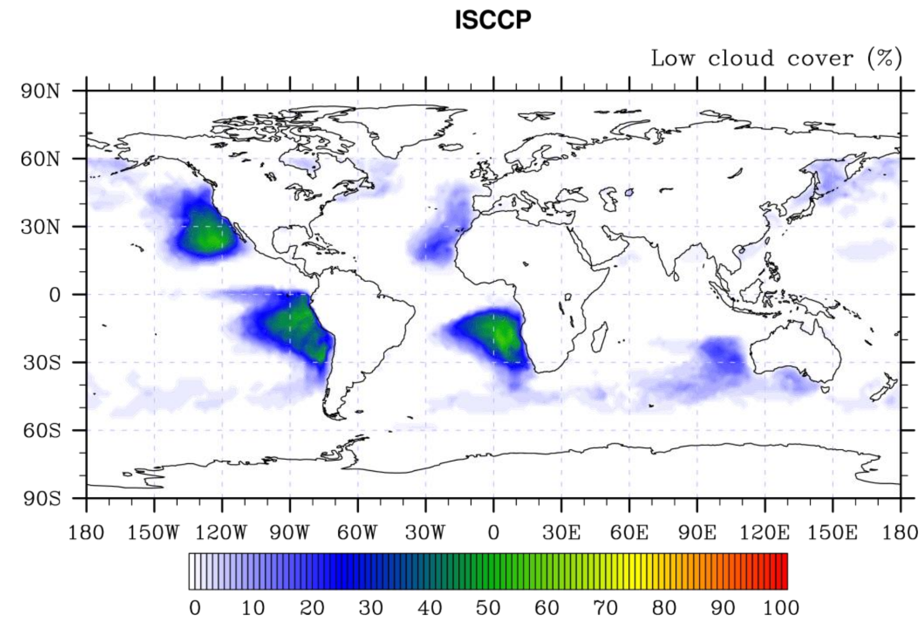
- Similar areas as in re-analyis data
- Less frequent/persistent
- Two uncertainty sources:
  - 1. frequency of occurence
  - 2. in-regime uncertainty

- Definition of stratocumulus regions:
  - 1. LTS ≥ 18.55 K
  - 2. w500 ≥ 10 hPa day^{-1}
- CFMIP Observation Simulator Package (COSP)

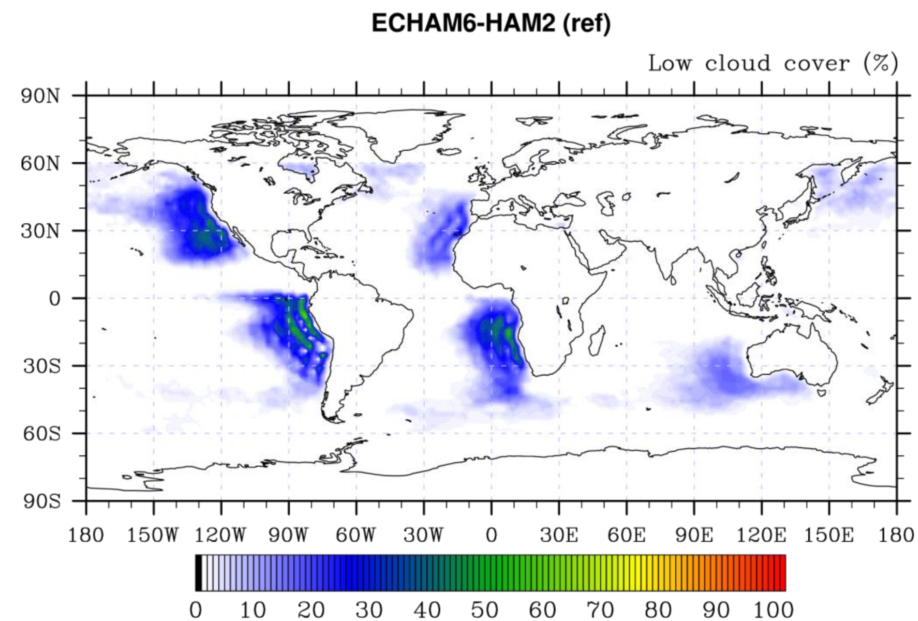
Low clouds



CF_{SC}: 64.7 (%)



CF_{SC}: 47.9 (%)



CF_{SC}: 47.7 (%)

- CALIPSO is taken as reference
- Fewer low coulds in ISCCP data
- Underestimation by COSP-ECHAM6-HAM2

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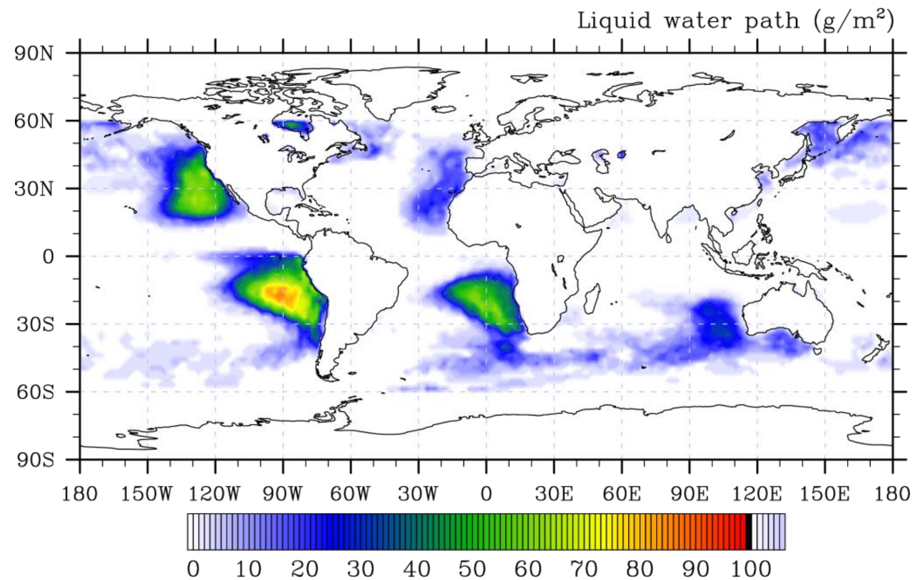
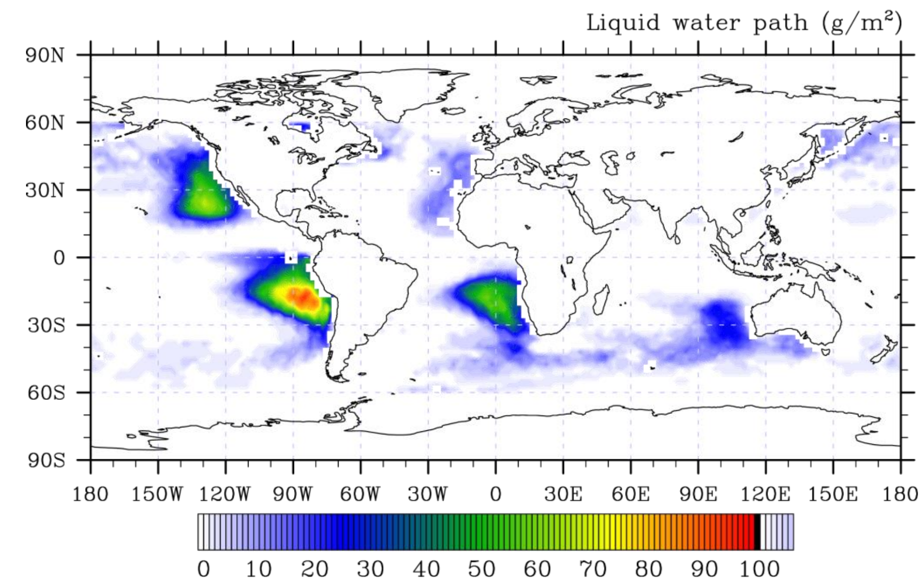
Liquid water path (LWP)

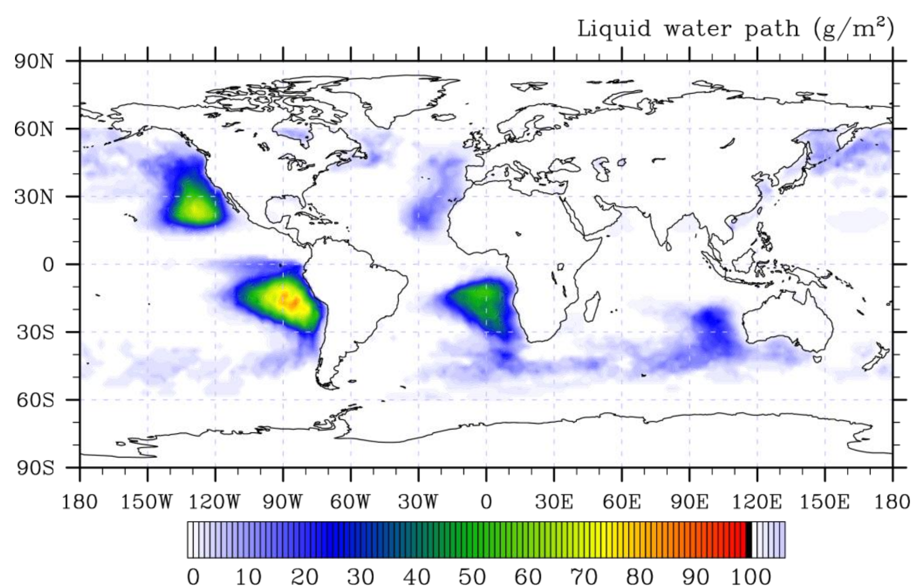
MODIS



UWisc climatology

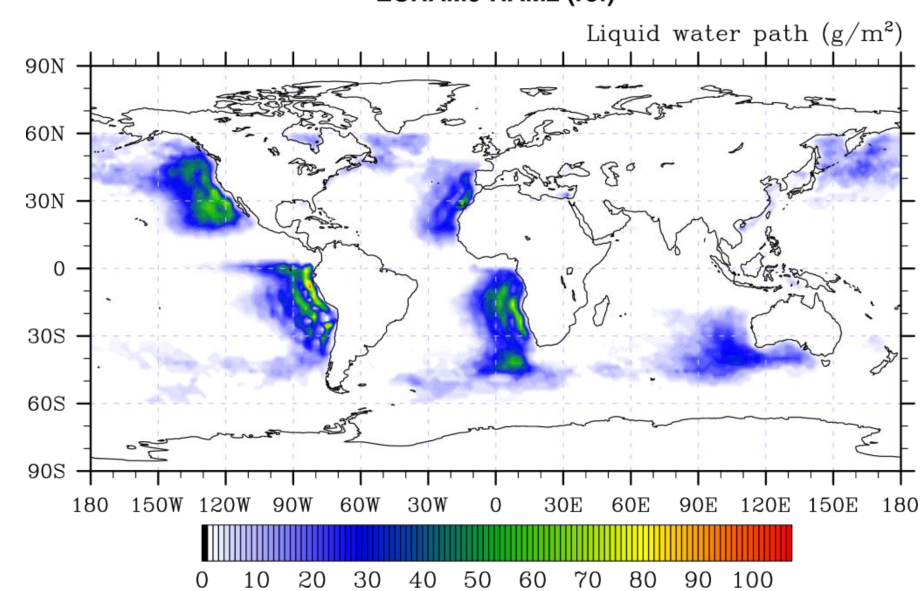


ERA-Interim



LWP_{SC} : 59.9 (g/m^2)

ECHAM6-HAM2 (ref)



LWP_{SC} : 74.1 (g/m^2)

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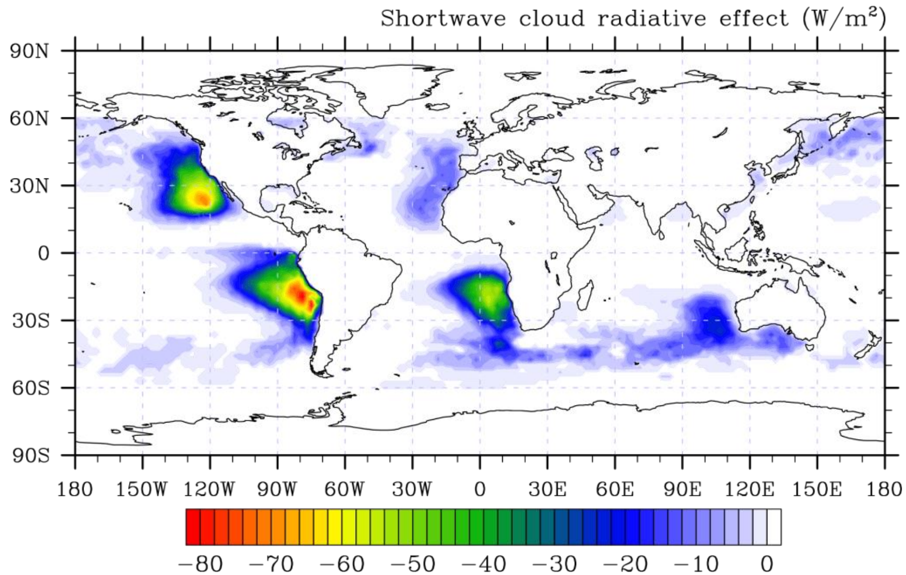
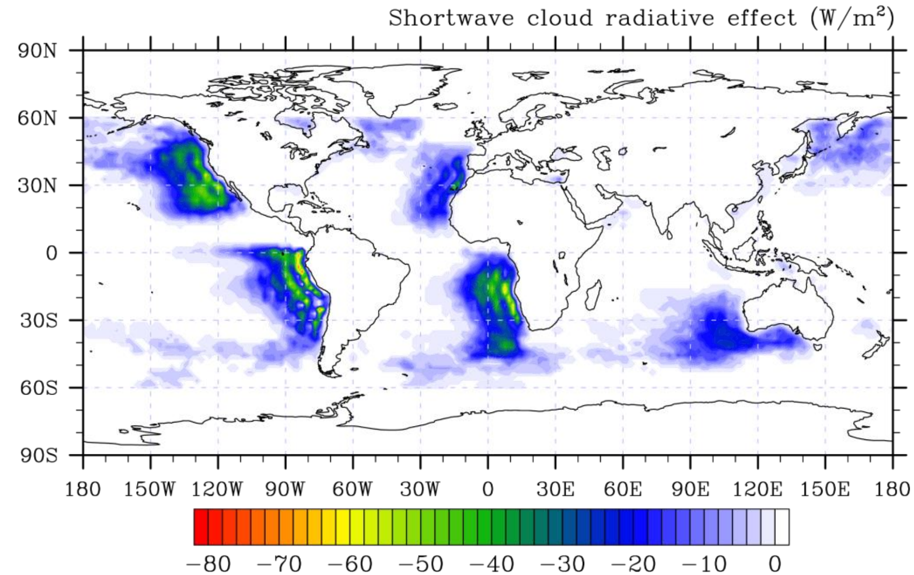
Cloud radiative effect (CRE)

CERES 5 year climatology



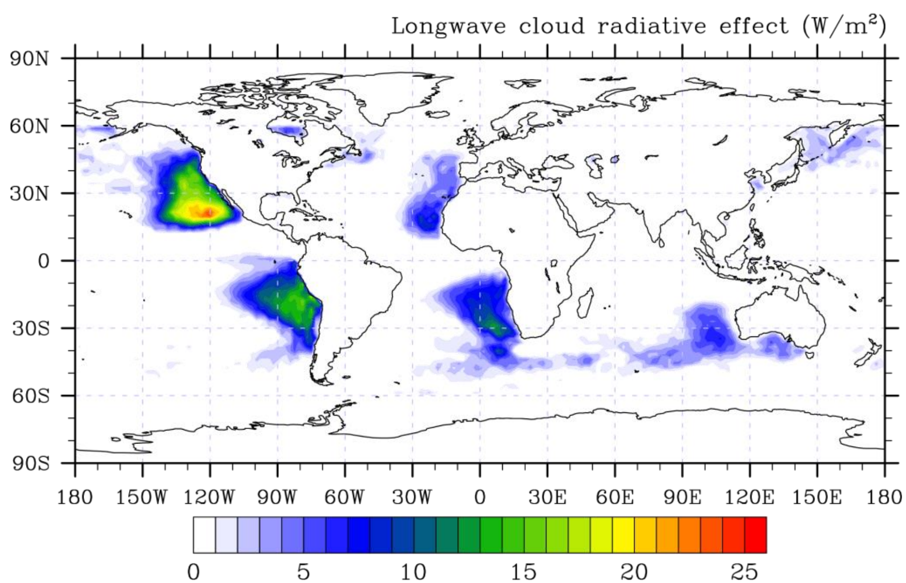
$SWCRE_{SC}$: -57.4 (W/m^2)

ECHAM6-HAM2 (ref)



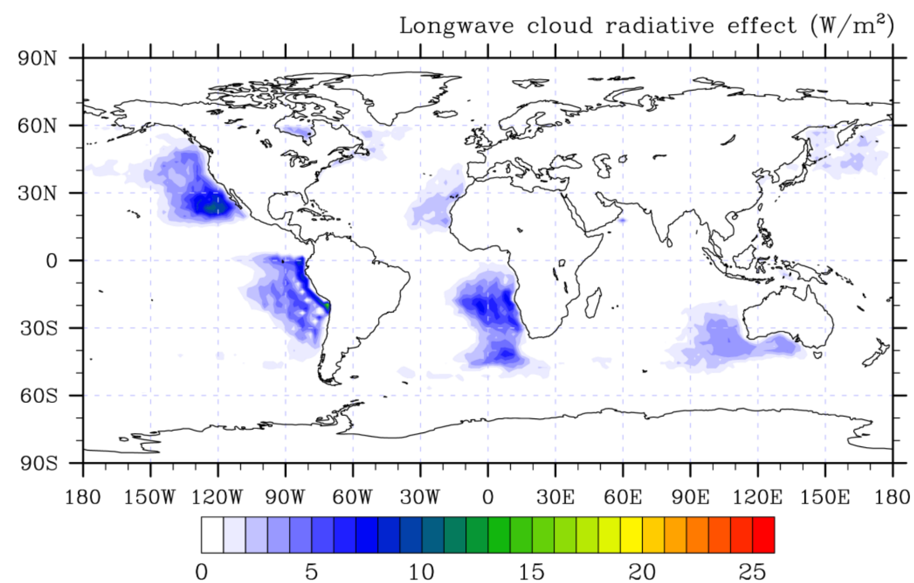
$SWCRE_{SC}$: -60.0 (W/m^2)

CERES 5 year climatology



$LWCRE_{SC}$: 19.0 (W/m^2)

ECHAM6-HAM2 (ref)



$LWCRE_{SC}$: 10.0 (W/m^2)

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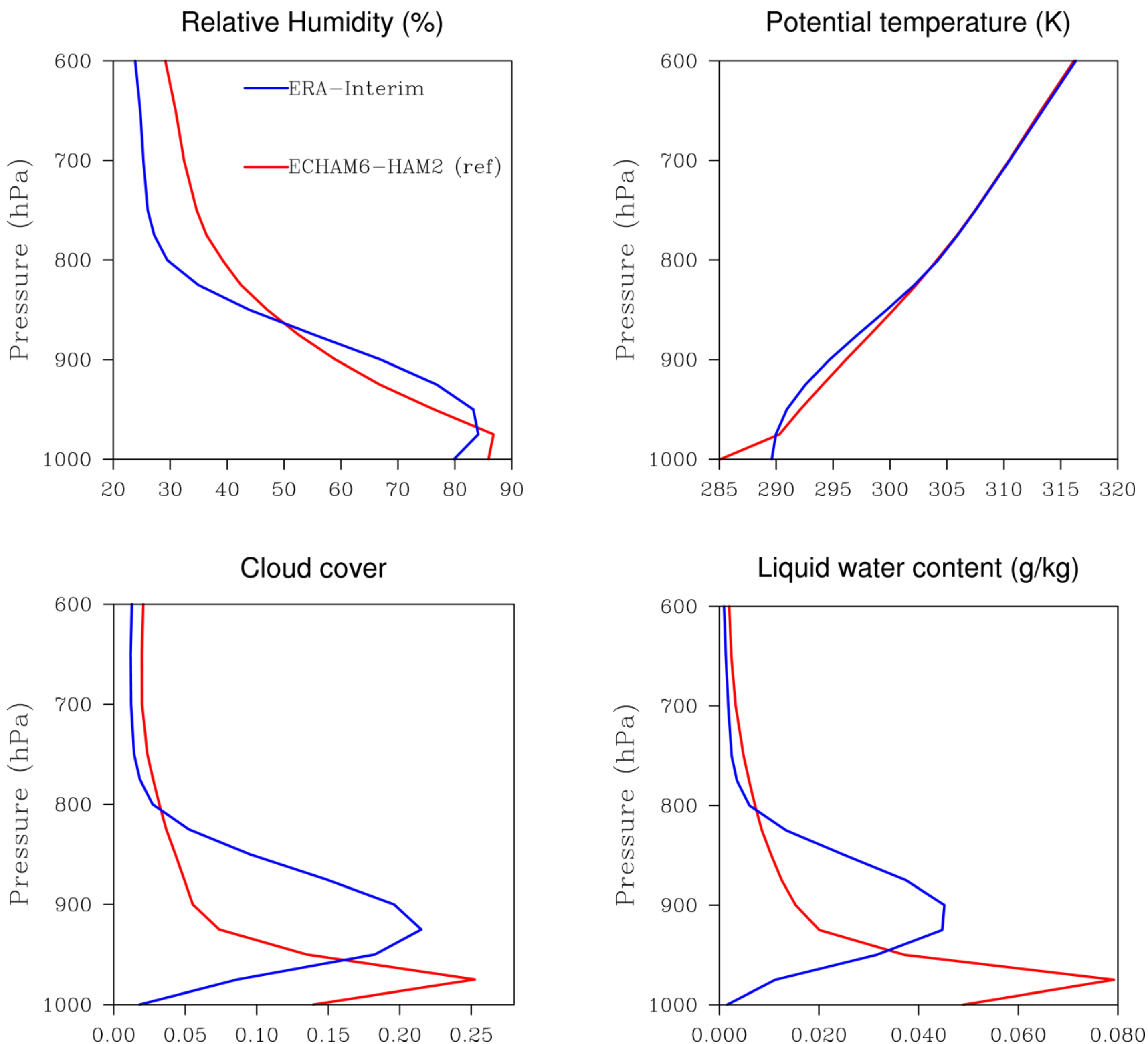
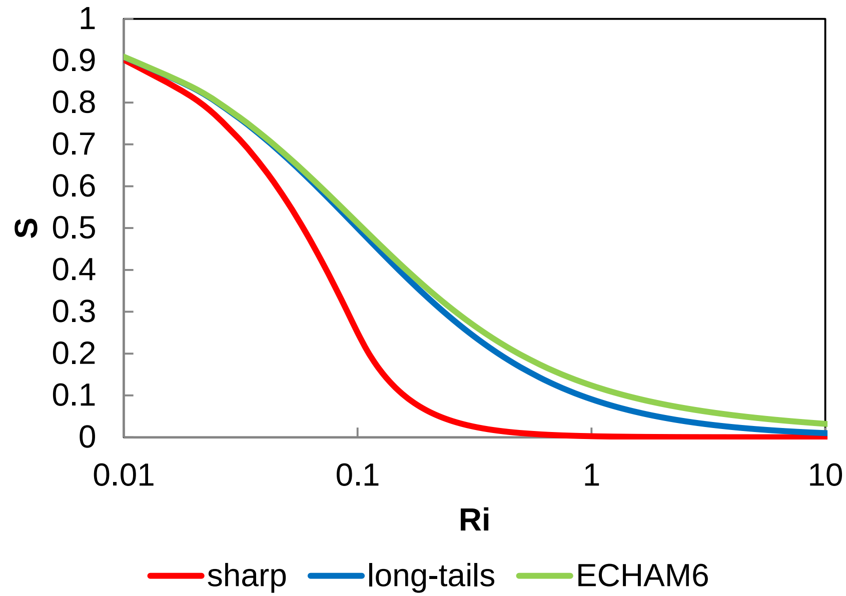
Vertical profiles



Reduced turbulent mixing in stable conditions

- ‘sharp’ stability functions only over the ocean leeds to improved operational verification scores without degrading the model skill (Brown et al. 2008)
- More cloud liquid water in stratocumuli regions in ECHAM6 (Felix Pithan; MPI-M; pers. comm.) with ‘sharp’ stability functions

$$K_{\text{turb}} = l * S * \sqrt{TKE}$$



Ri= potential energy/ kinetic energy

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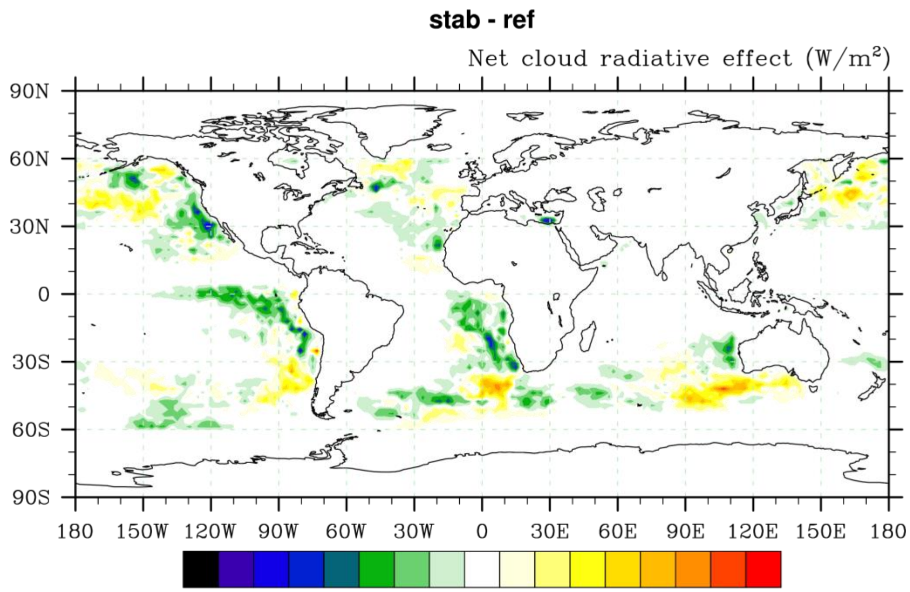
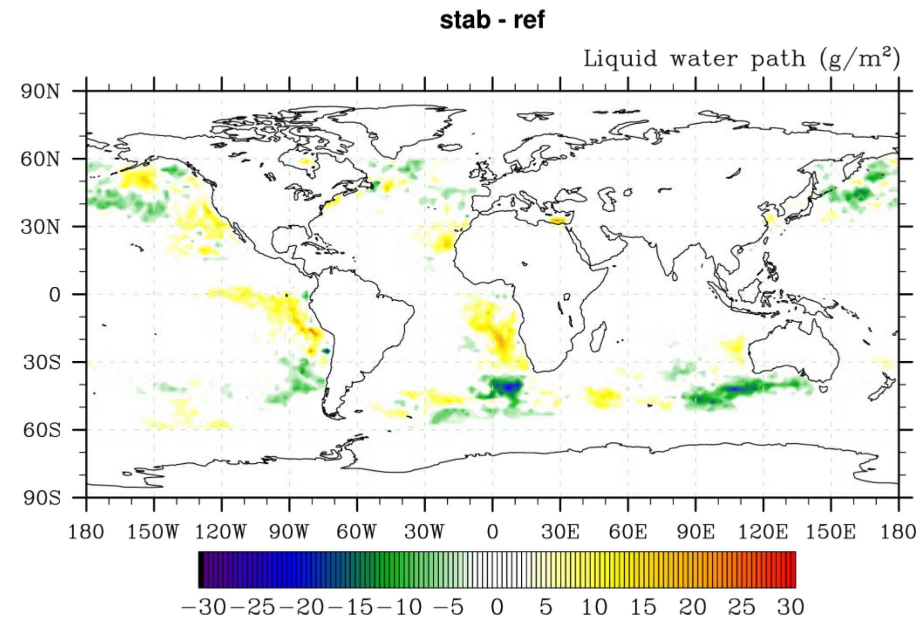
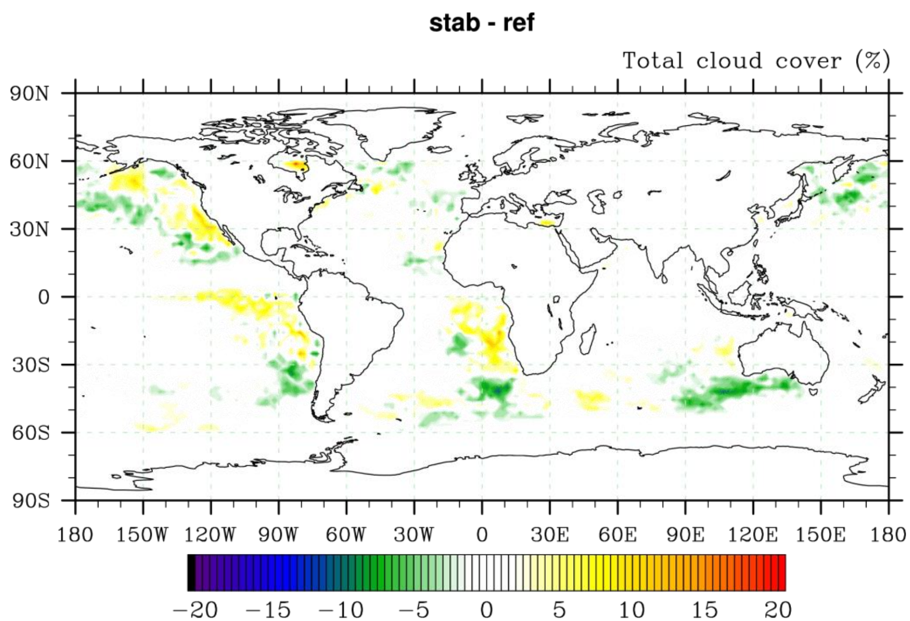
Reduced turbulent mixing in stable conditions



CF_{SC} : +4.2 (%)



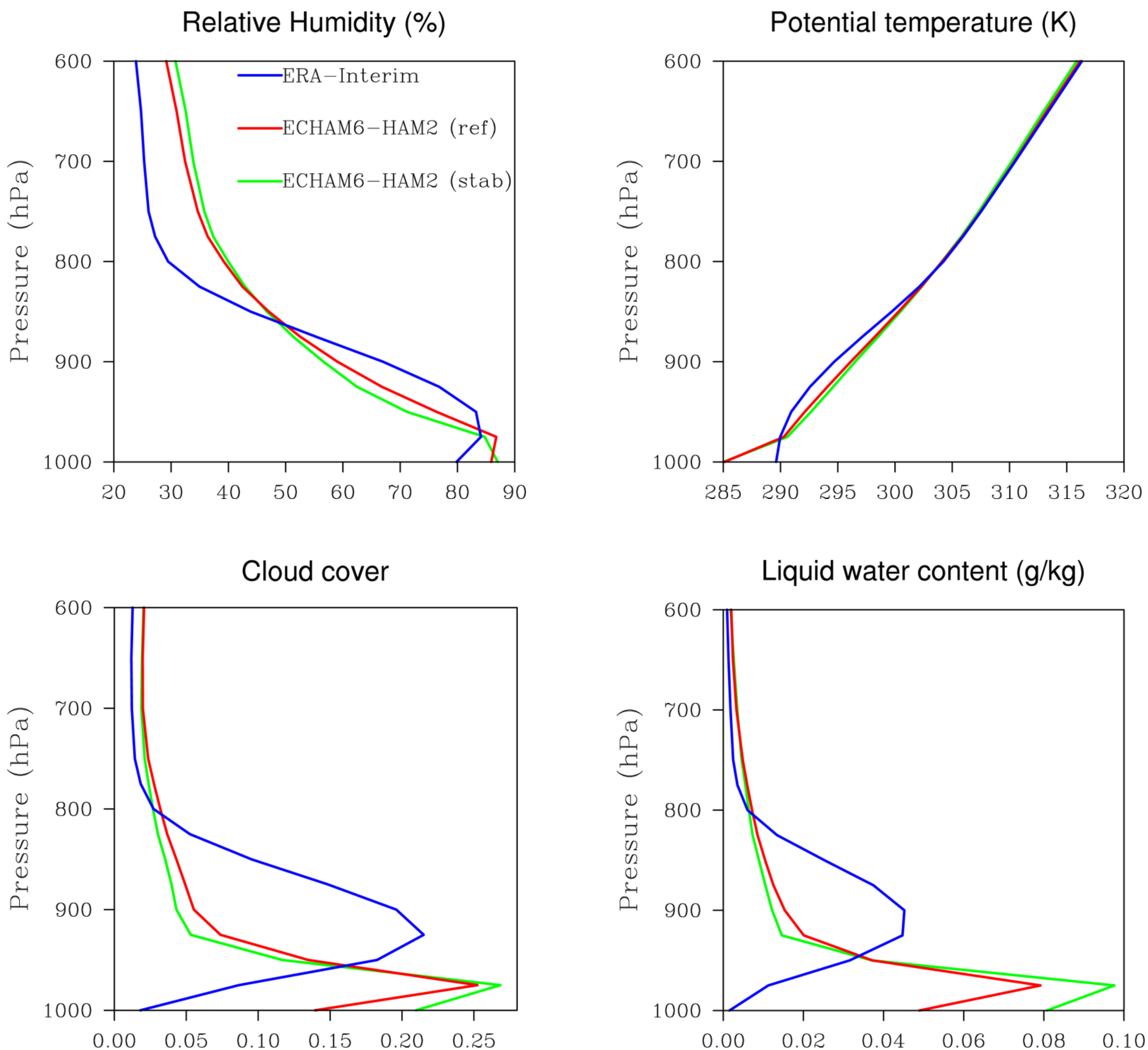
LWP_{SC} : +8.2 (g/m^2)



$NETCRE_{SC}$: -2.9 (W/m^2)

- Increase in cloud cover
- Increase in liquid water path
- More negative cloud radiative effect (stronger cooling)

Reduced turbulent mixing in stable conditions



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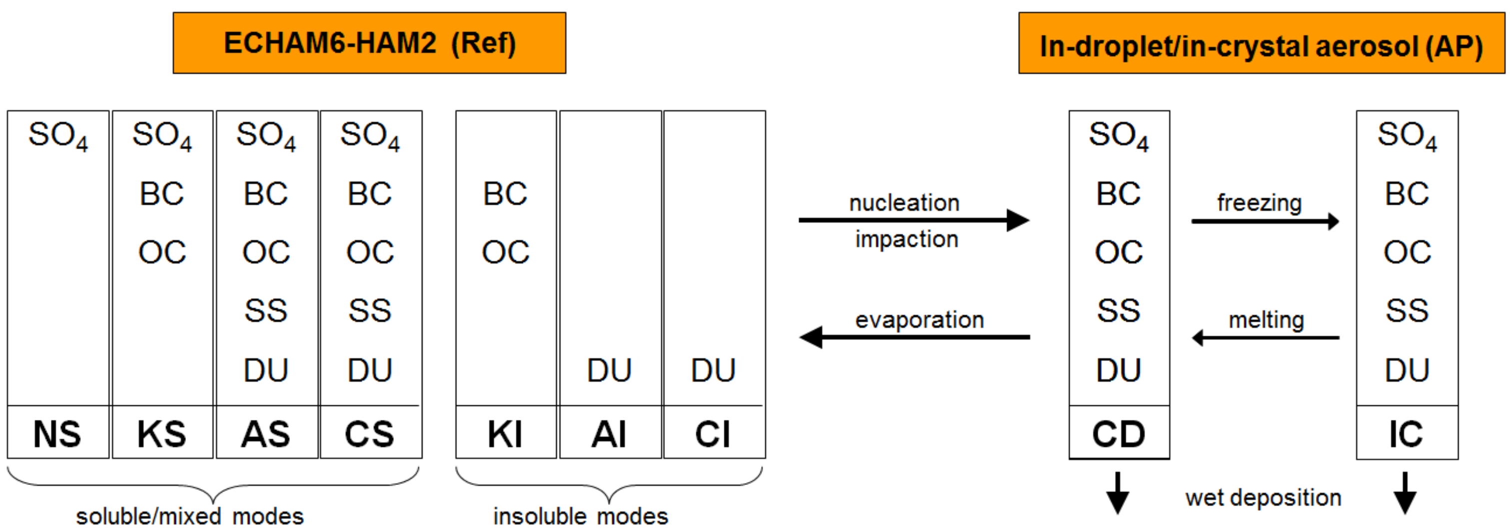
Aerosol processing

- Explicit representation of aerosol particles in cloud droplets and ice crystals in stratiform clouds (Hoose et al. 2008a,b)
- Uptake of aerosol by nucleation and collision scavenging
- Aerosol mass transfers by freezing and evaporation of cloud droplets and melting and sublimation of ice crystals
- Aerosol particles from evaporating cloud particles and precipitation are released to modes which correspond to their size



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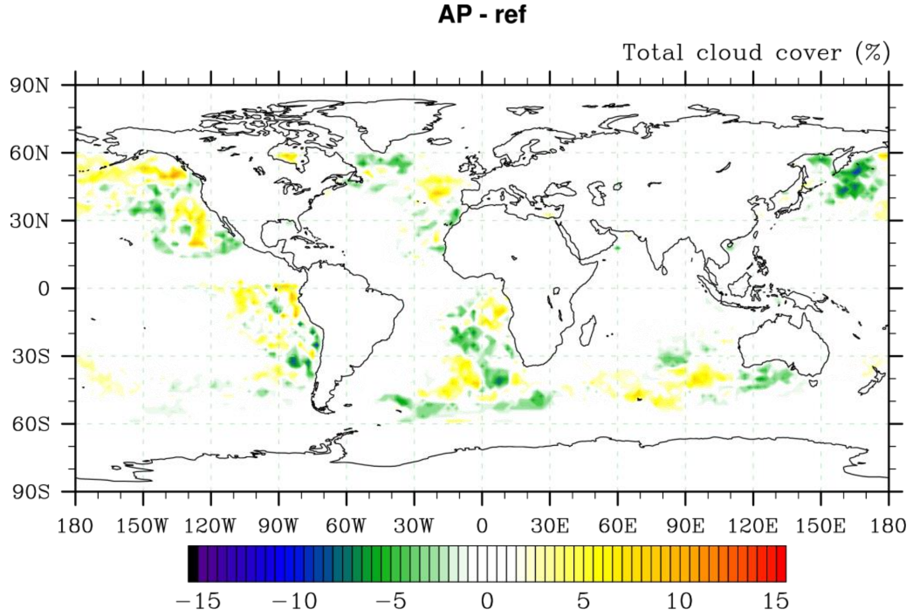
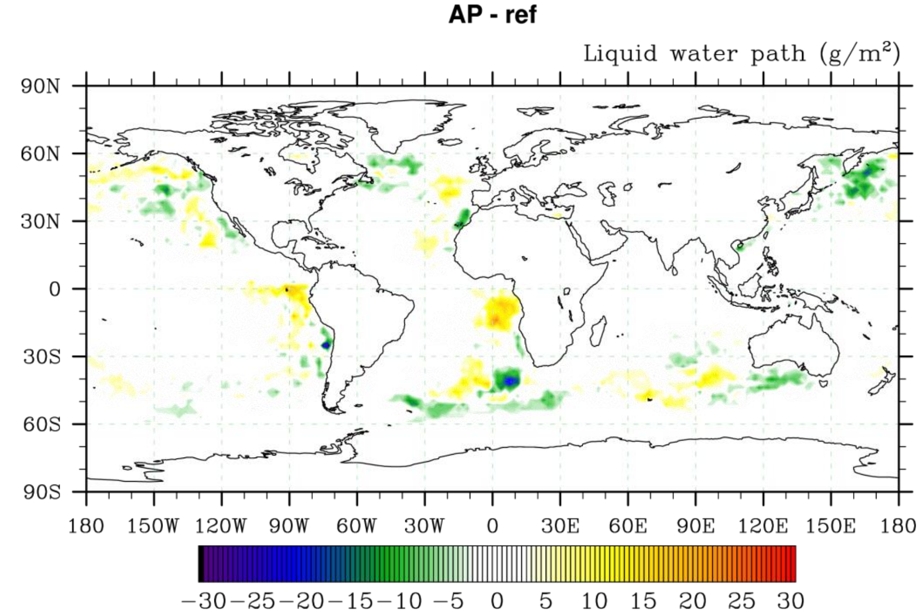
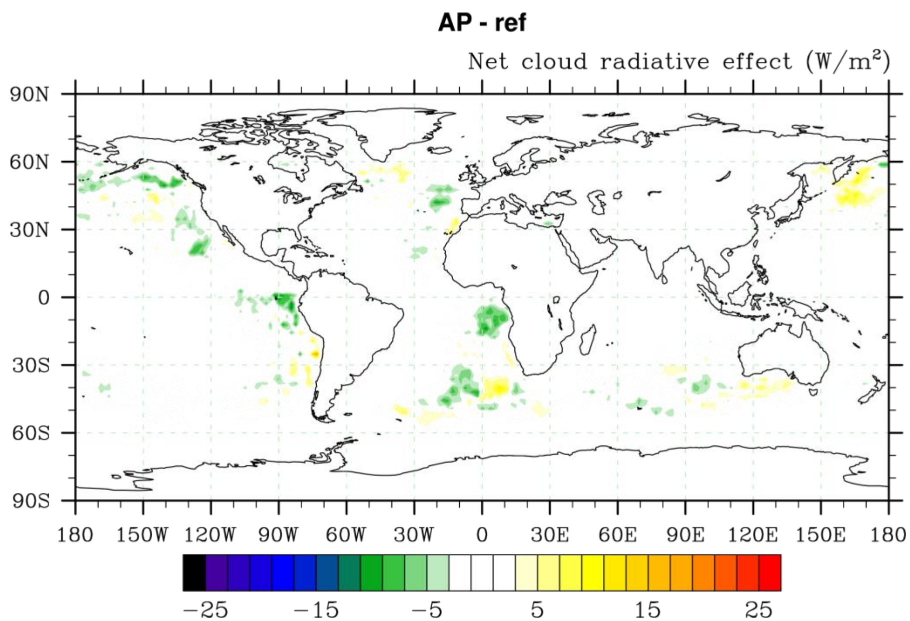
Aerosol processing



CF_{SC} : -0.3 (%)



LWP_{SC} : +0.4 (g/m^2)



$NETCRE_{SC}$: +0.8 (W/m^2)

- Almost no change in average stratocumulus properties

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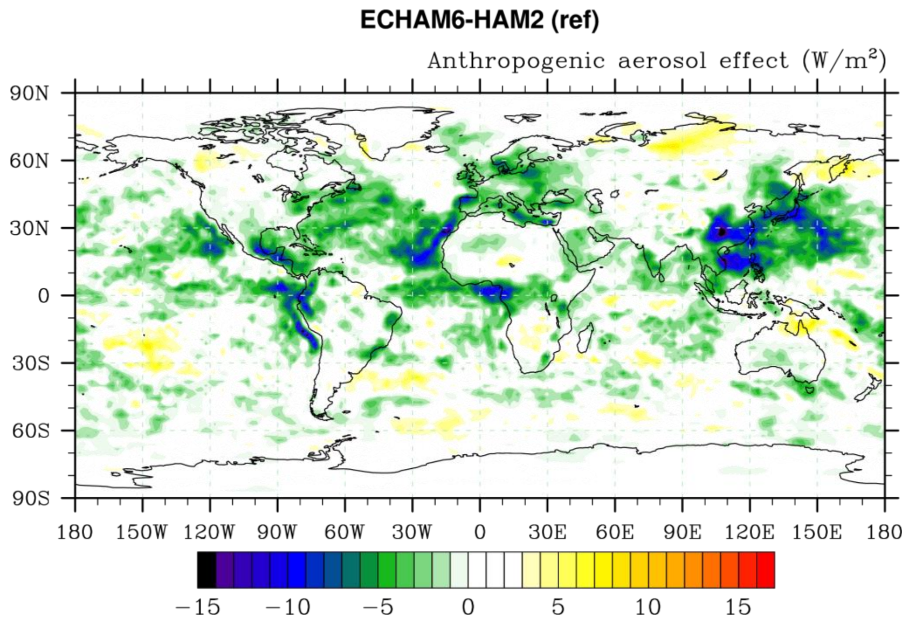
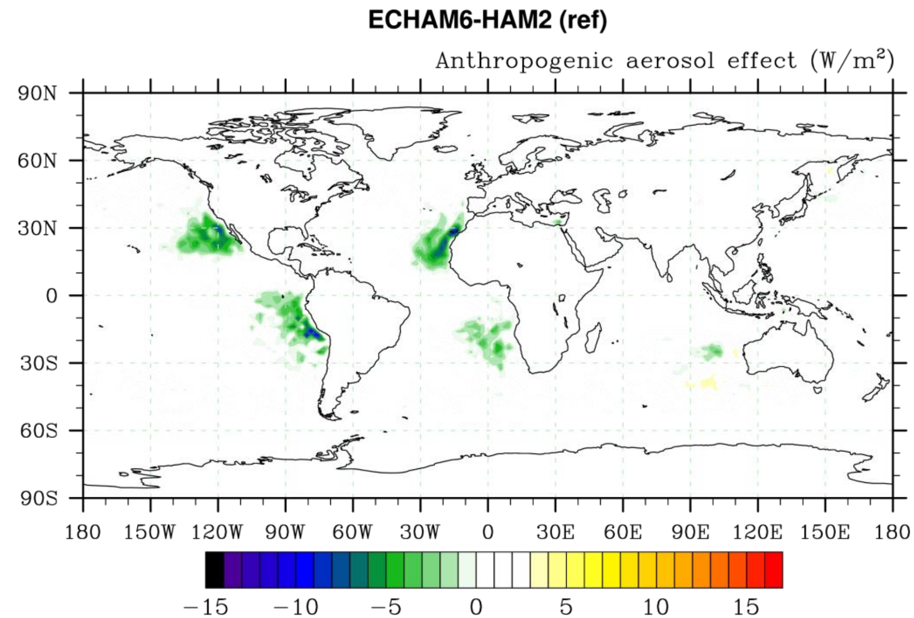
Anthropogenic aerosol effect



AAE_{global} : -1.46 (W/m^2)



AAE_{SC}: -3.20 (W/m^2)

- Large anthropogenic aerosol effect in stratocumulus regions

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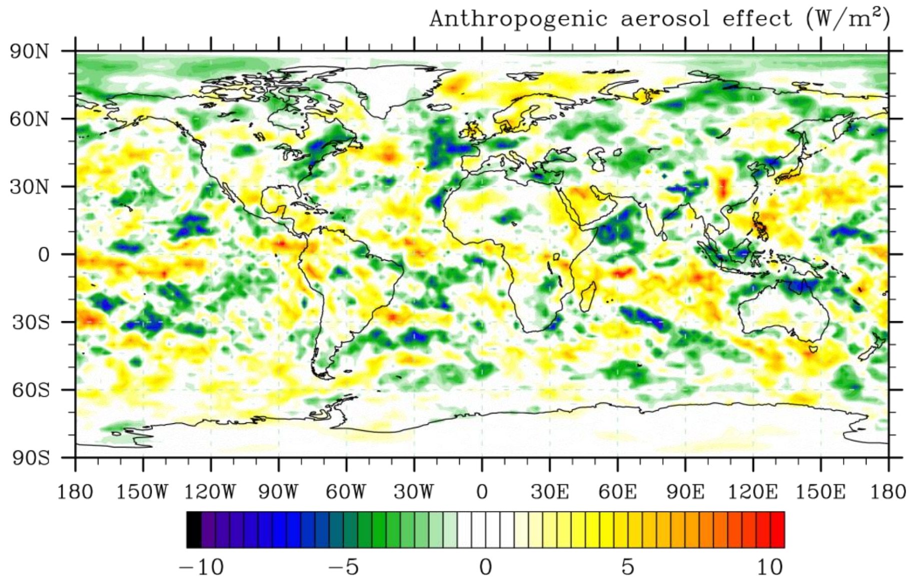
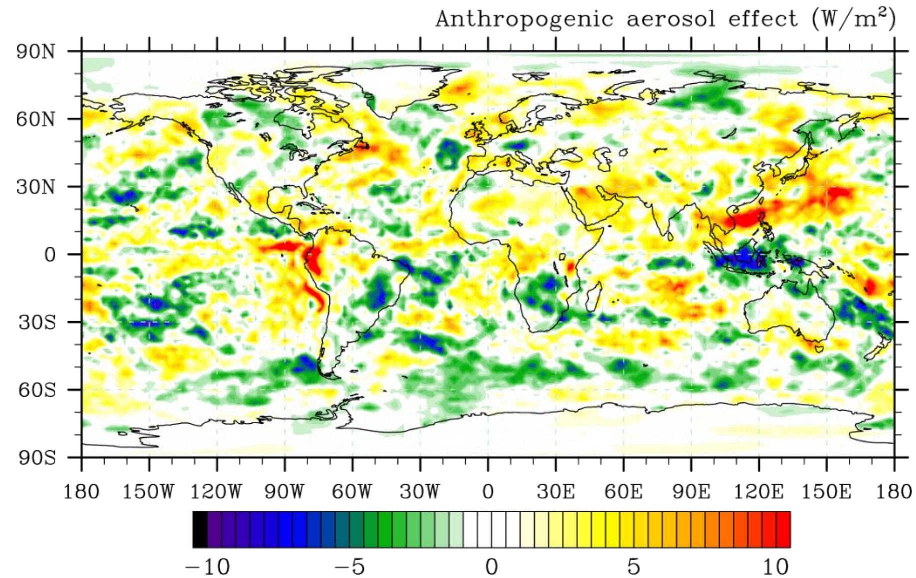
Anthropogenic aerosol effect

stab - ref



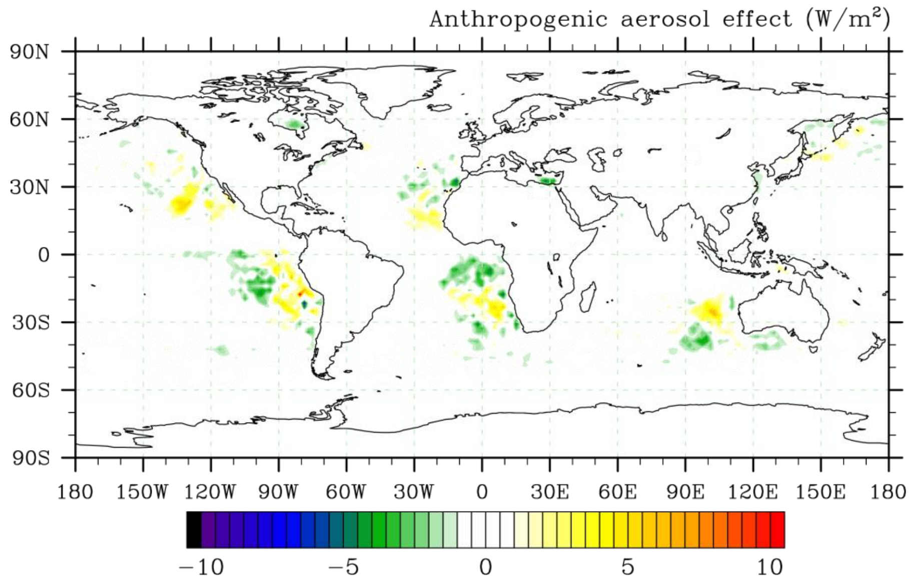
global: +0.28 (W/m^2)

AP - ref



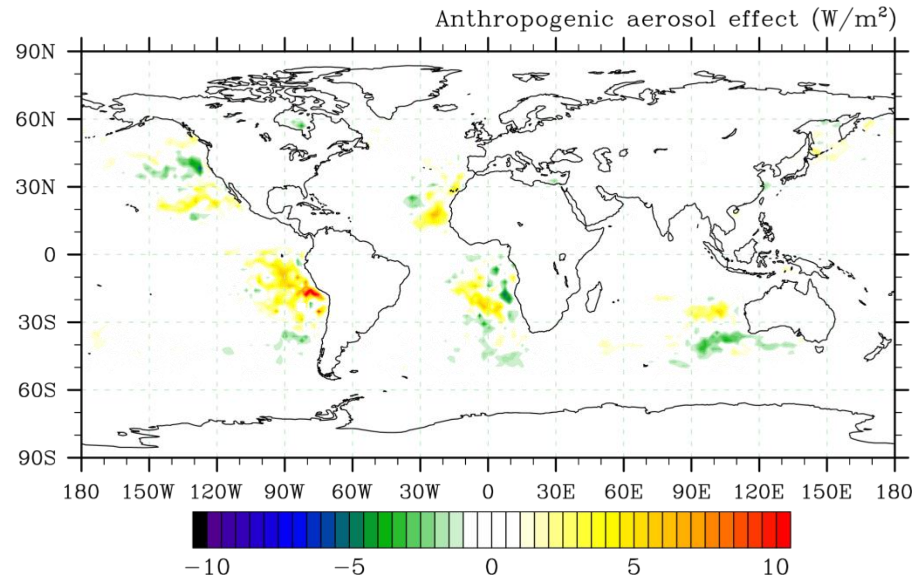
global: +0.67 (W/m^2)

stab - ref



AAE_{SC}: -0.09 (W/m^2)

AP - ref



AAE_{SC}: +1.82 (W/m^2)

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Summary

- Stratocumulus clouds are important for the climate but difficult to simulate in GCMs because of the sharp inversion
- Sharp stability function improves cloud cover in stratocumulus regions
- Dependence of anthropogenic aerosol effect on changes in stratocumulus clouds in ECHAM6-HAM2

Outlook

- Moist conserved variables
- Vertical resolution
- Reconstruction/restricted method by Grenier and Bretherton (2001), Siegenthaler-Le Drian (2010)
- Improved drizzle scheme

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Thank you for your attention!

Importance of marine stratocumulus clouds

- Vast “climate refrigerators” of the Tropics and subtropics (Bretherton et al., 2004)
- Uncertainties in the warming by doubling CO_2 corresponds to the feedback of low clouds (Stephens, 2005)

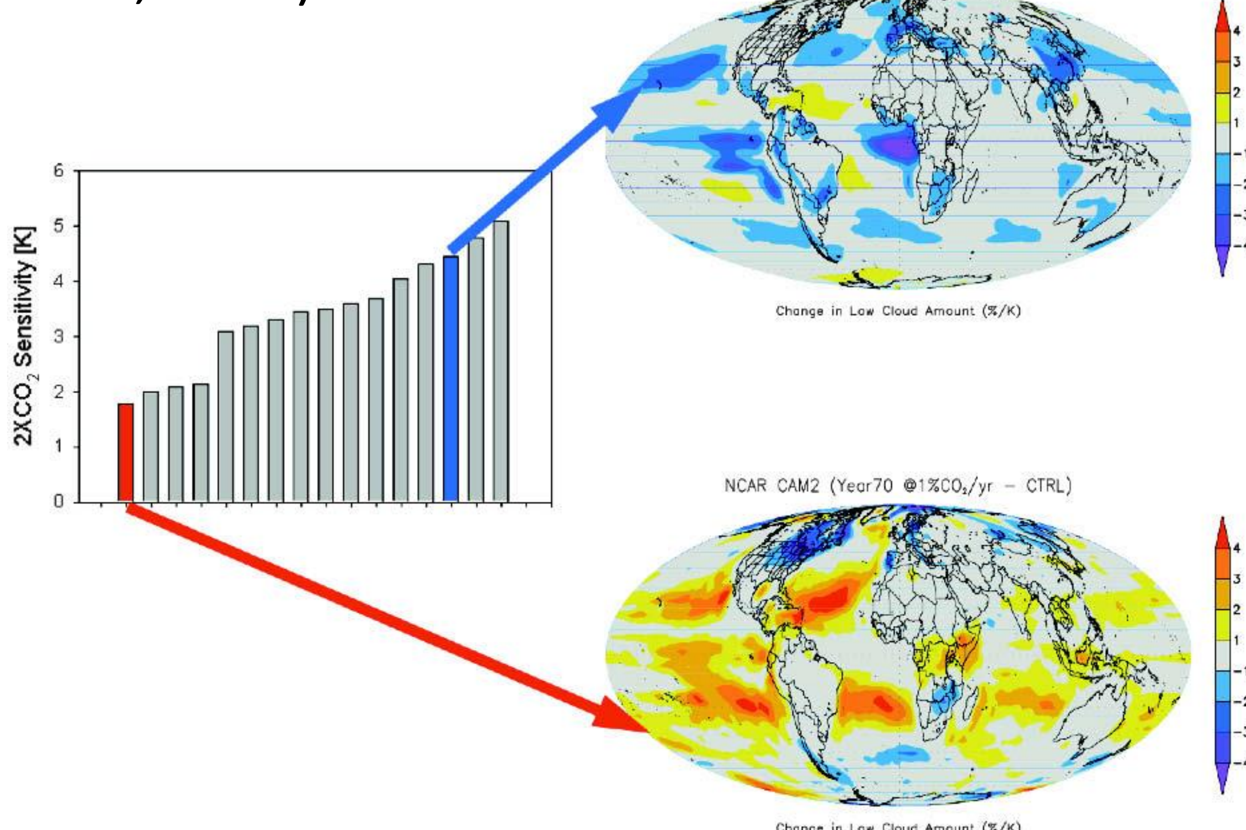

Figure from Stephens, 2005

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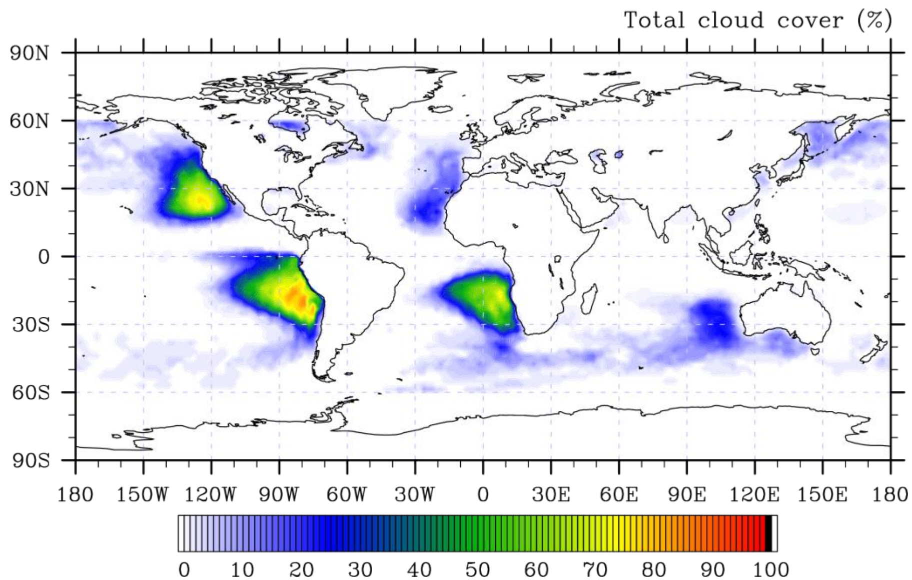
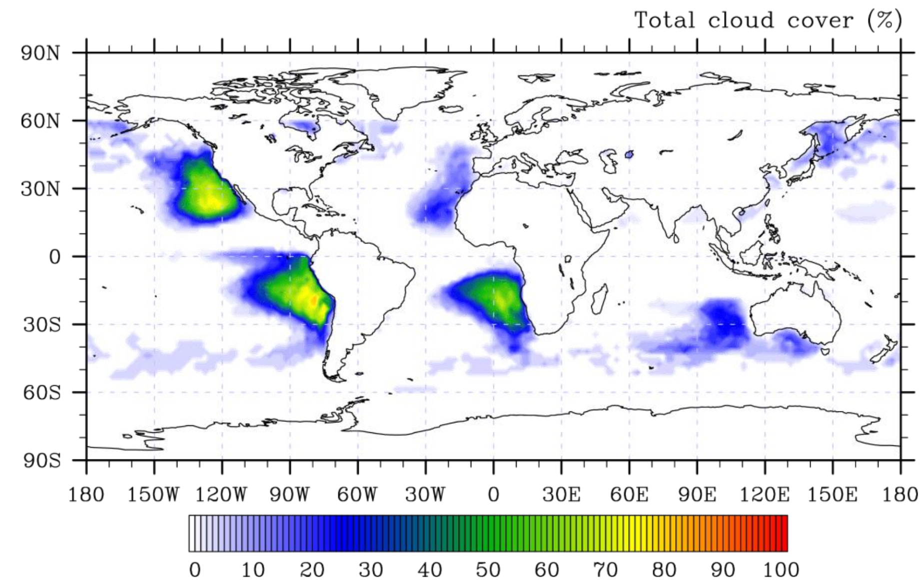
Cloud fraction (CF)

CALIPSO



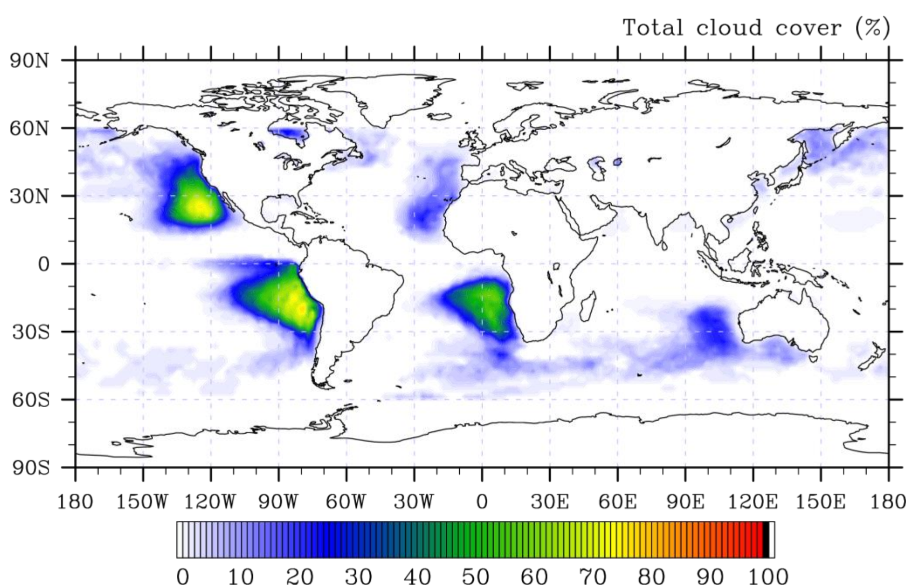
CF_{SC}: 73.4 (%)

ISCCP



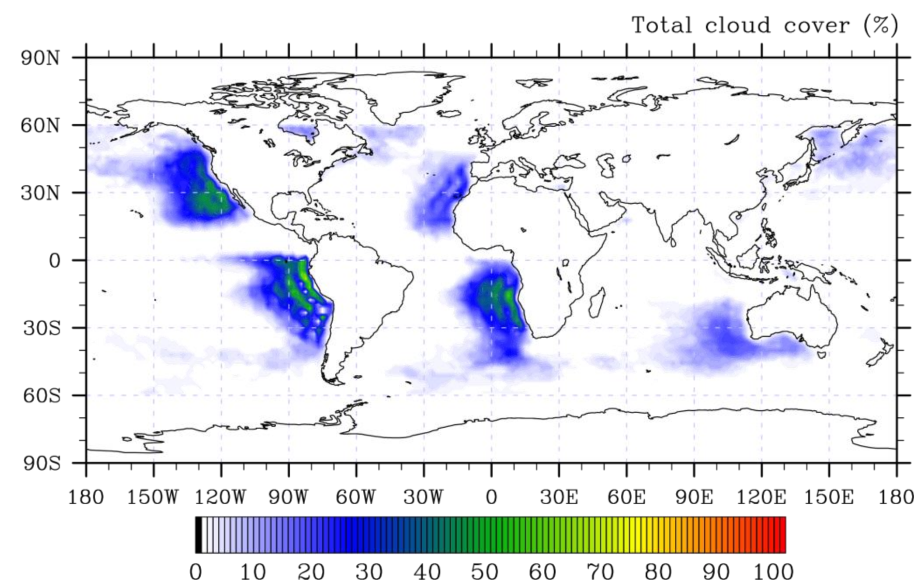
CF_{SC}: 68.9 (%)

ERA-Interim



CF_{SC}: 64.1 (%)

ECHAM6-HAM2 (ref)



CF_{SC}: 56.5 (%)

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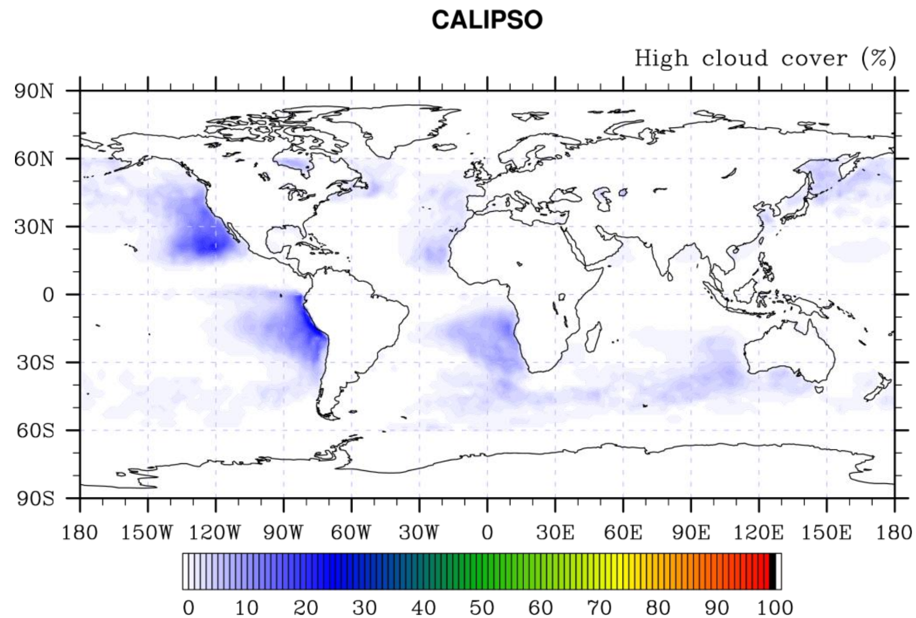
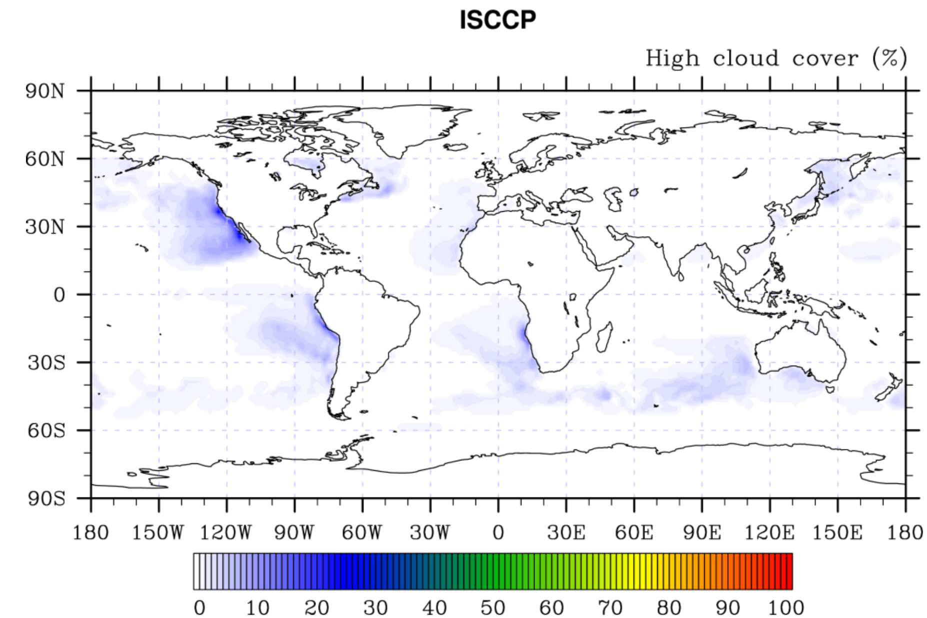
High clouds

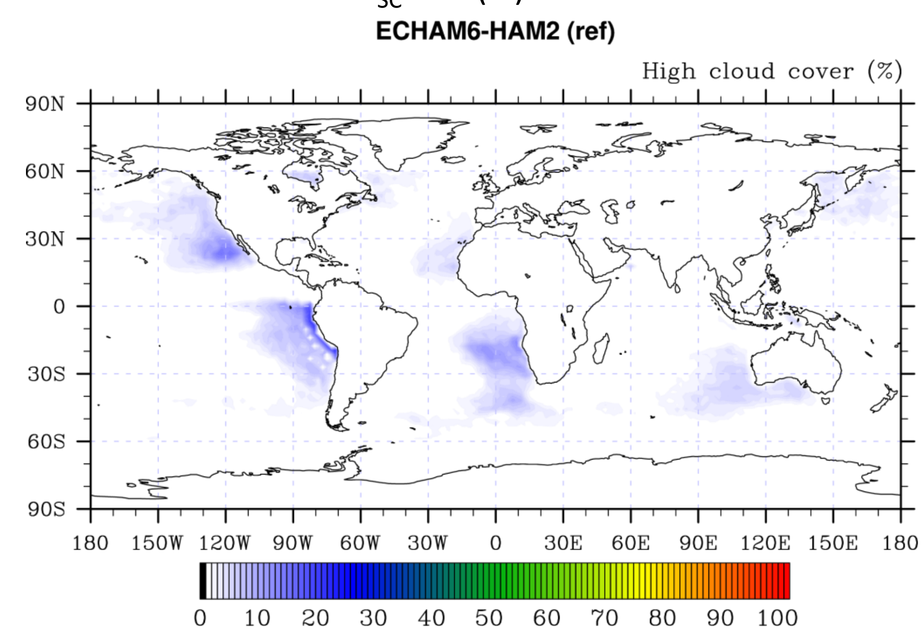


CF_{SC}: 15.9 (%)



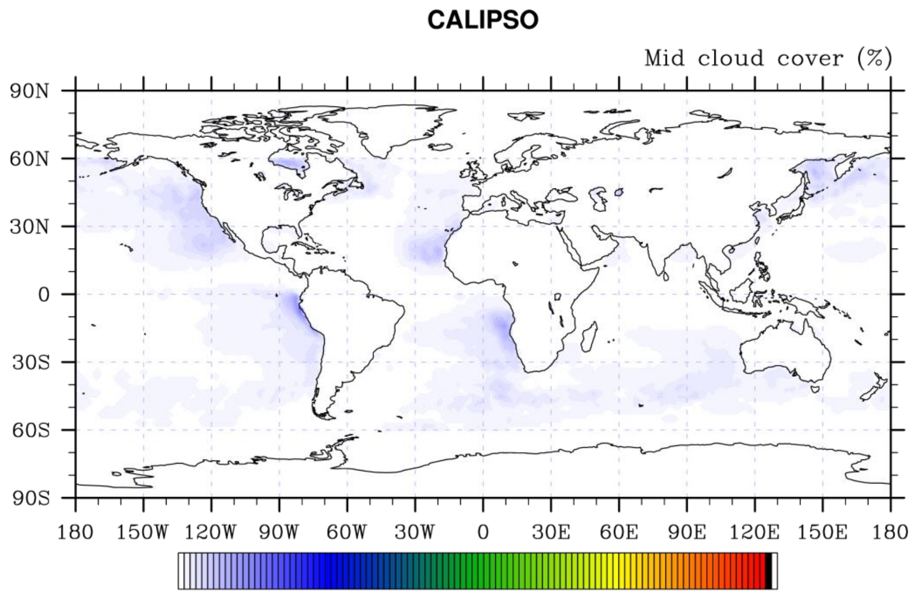
CF_{SC}: 8.5 (%)

- CALIPSO is taken as reference
- Underestimation by ISCCP
- Underestimation by COSP-ECHAM6-HAM2

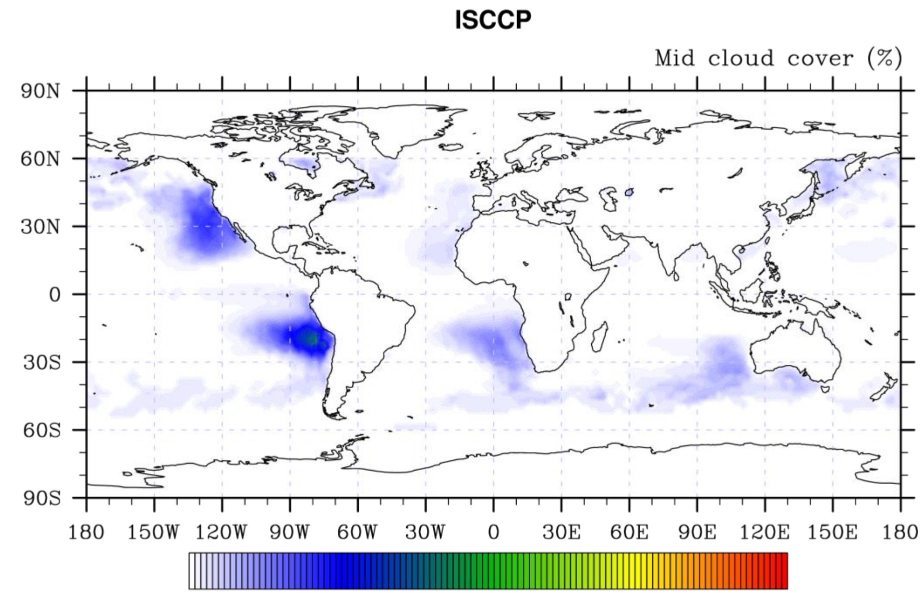


CF_{SC}: 13.5 (%)

Mid level clouds

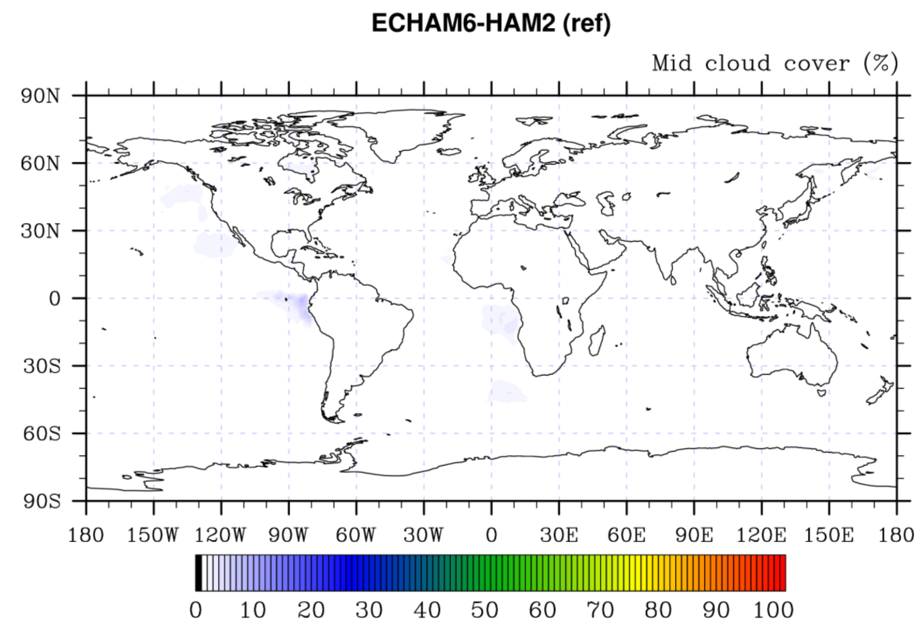


CF_{SC}: 5.7 (%)



CF_{SC}: 18.5 (%)

- Very High ISCCP mid cloud fraction
- Underestimation by COSP-ECHAM6-HAM2



CF_{SC}: 2.3 (%)

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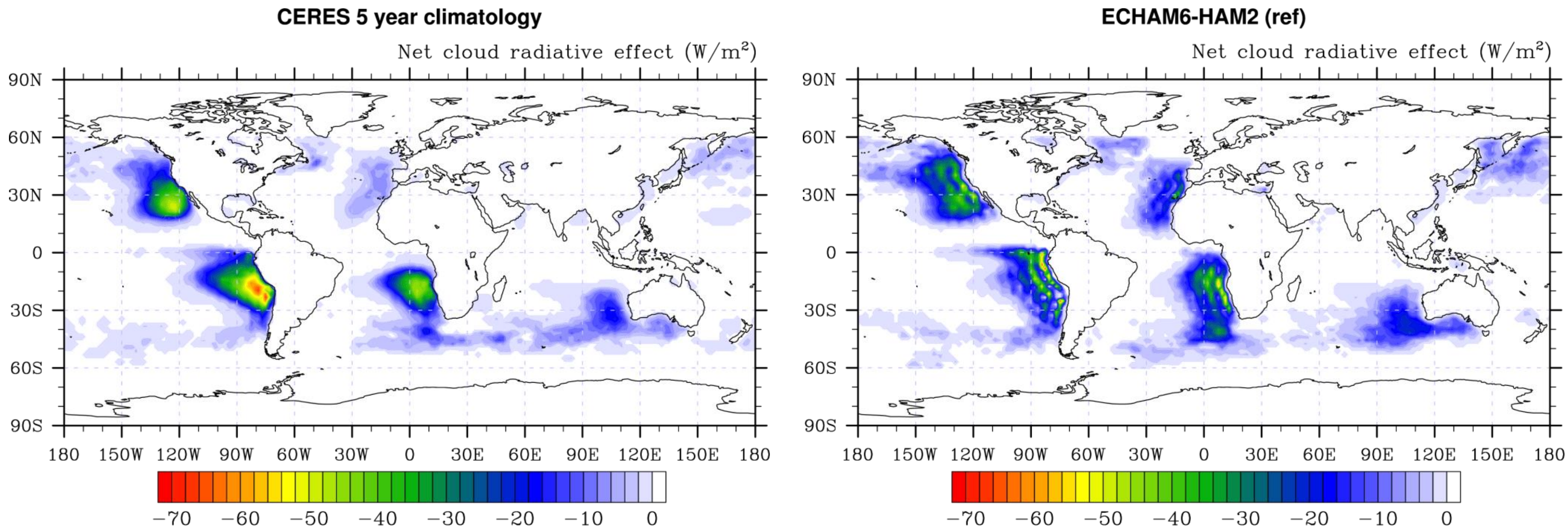
Net cloud radiative effect



$NETCRE_{SC}$: -38.4 (W/m^2)

$NETCRE_{SC}$: -50.0 (W/m^2)

- Net cloud radiative effect is too negative as the longwave cloud radiative effect is too low when stratocumulus are present
- Too few high/ice clouds in ECHAM6-HAM2
- Shortwave cloud radiative effect agrees well

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Reduced turbulent mixing in stable conditions

- Large scale subsidence can lead to stable conditions/an inversion at the top of the PBL
- Turbulence – entrainment counteracts subsidence
- More mixing than observed for ‘long-tails’ stability functions at high stabilities

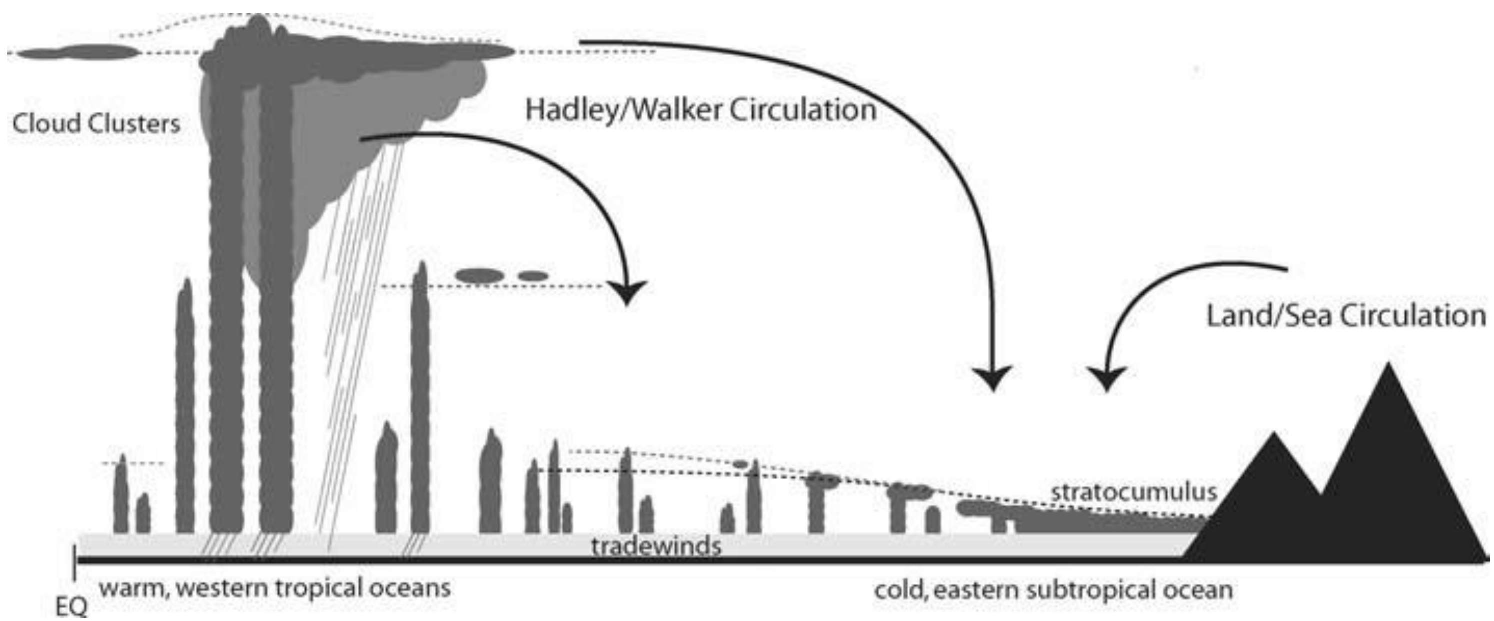

Figure from Stevens, 2005

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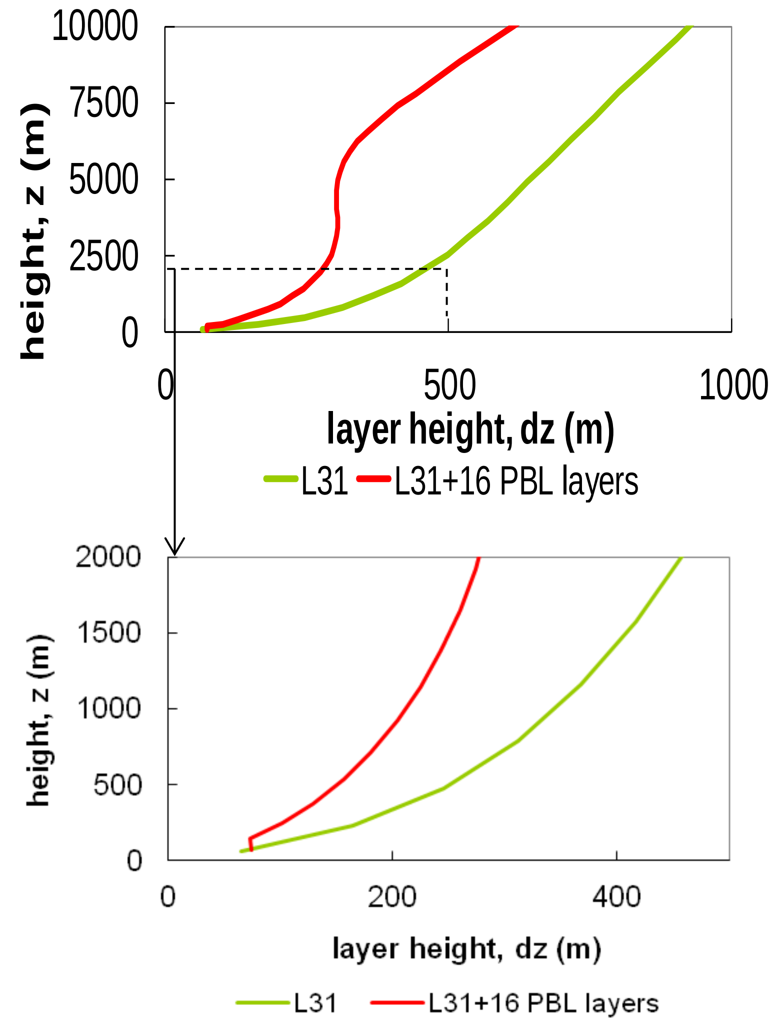
Vertical resolution

- 16 additional vertical levels in the boundary layer
- Turbulent kinetic energy (TKE) scheme good for dry boundary layer
- Also for cloud topped PBL at high vertical resolution (SCM)



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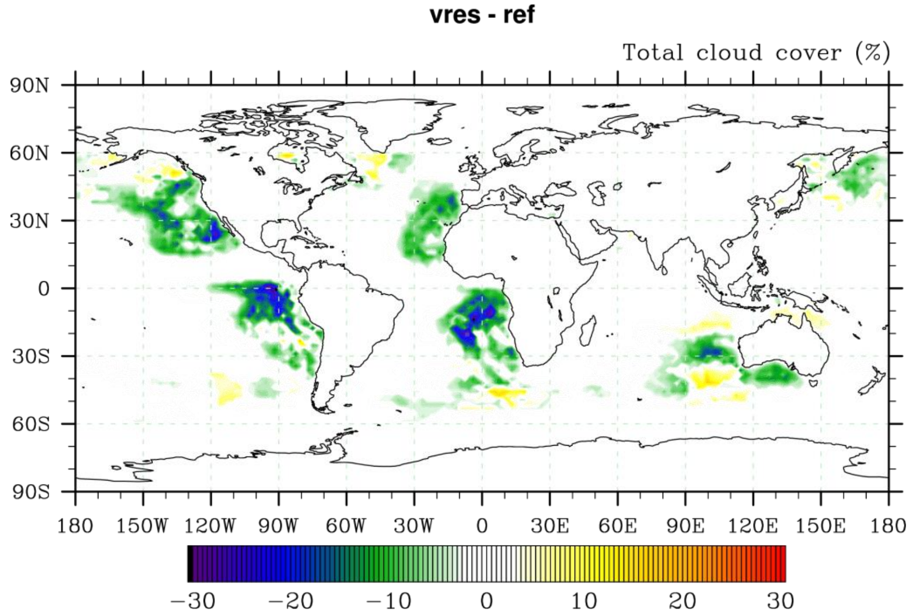
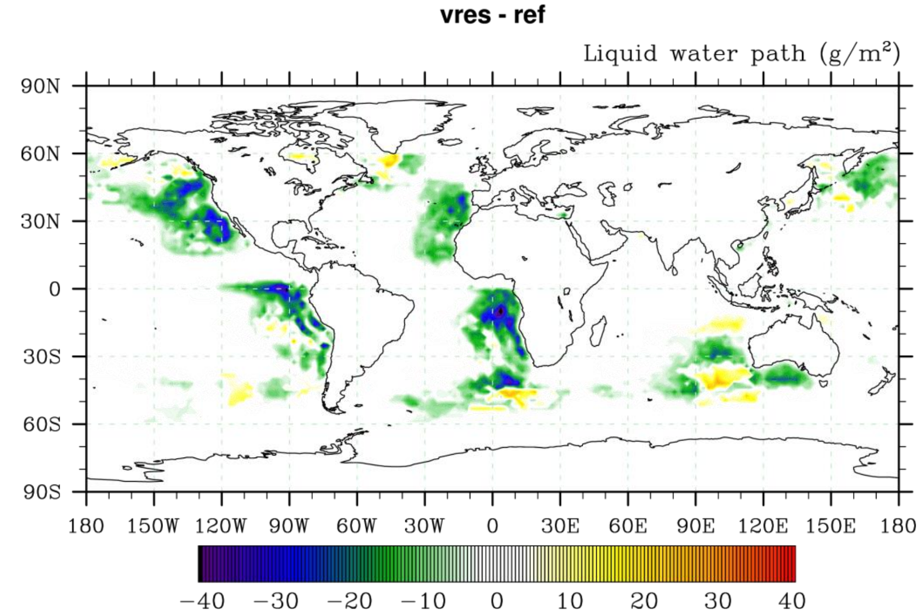
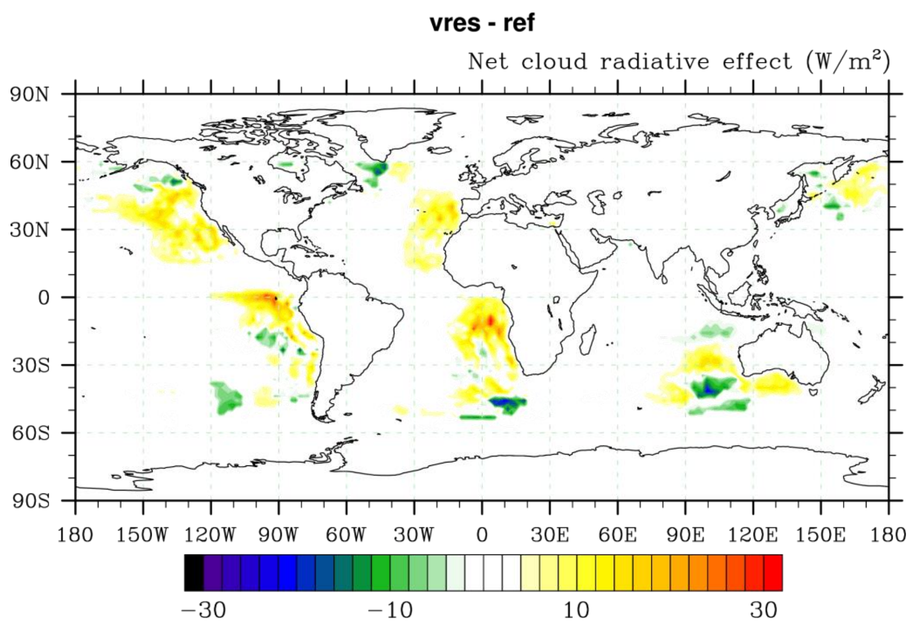
Vertical resolution



CF_{SC} : -0.5 (%)



LWP_{SC} : -6.4 (g/m^2)



$NETCRE_{SC}$: -1.0 (W/m^2)

- Lower cloud fraction and liquid water path
- Decreases in low clouds are compensated by increases in mid level clouds

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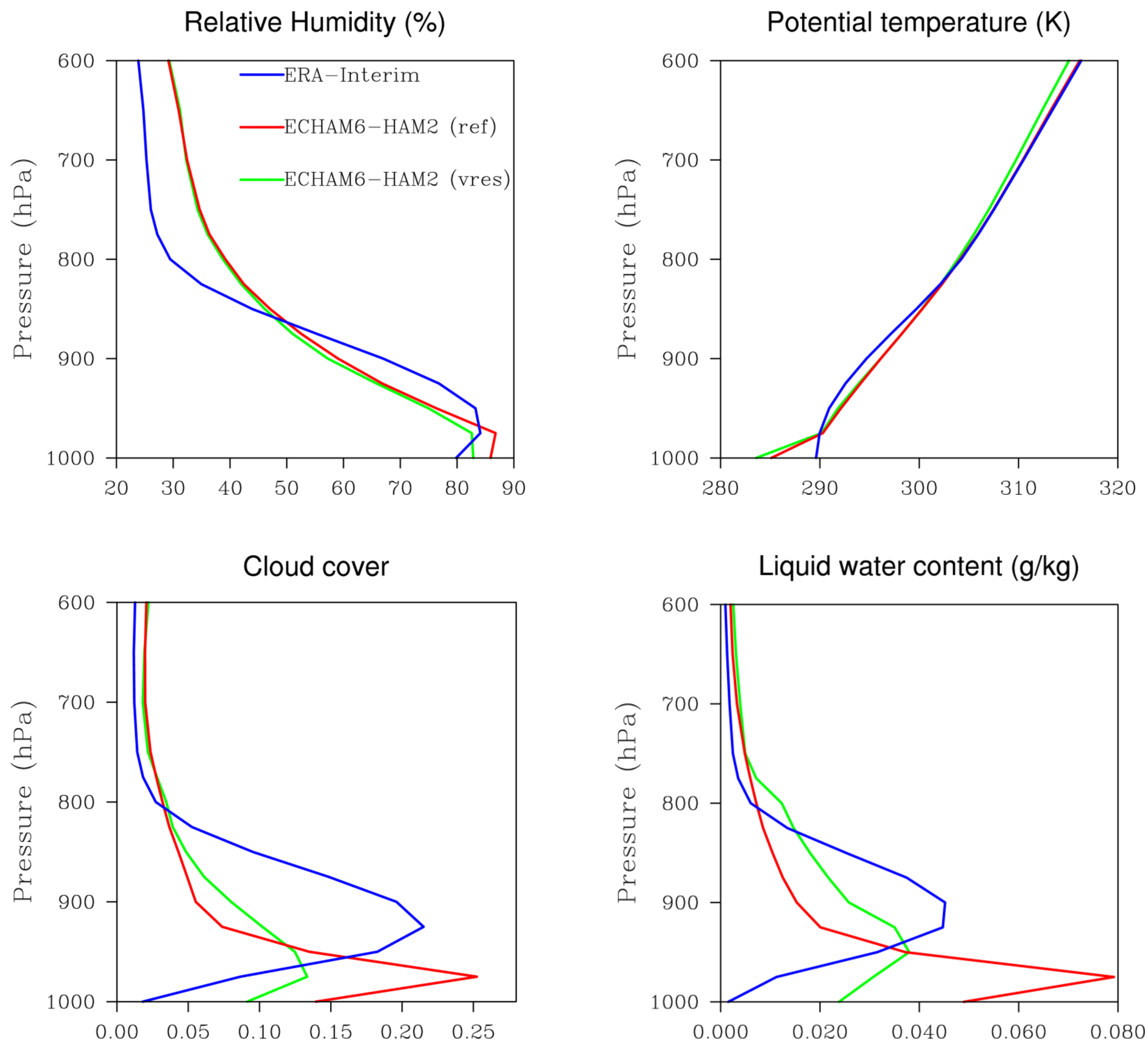
Vertical resolution



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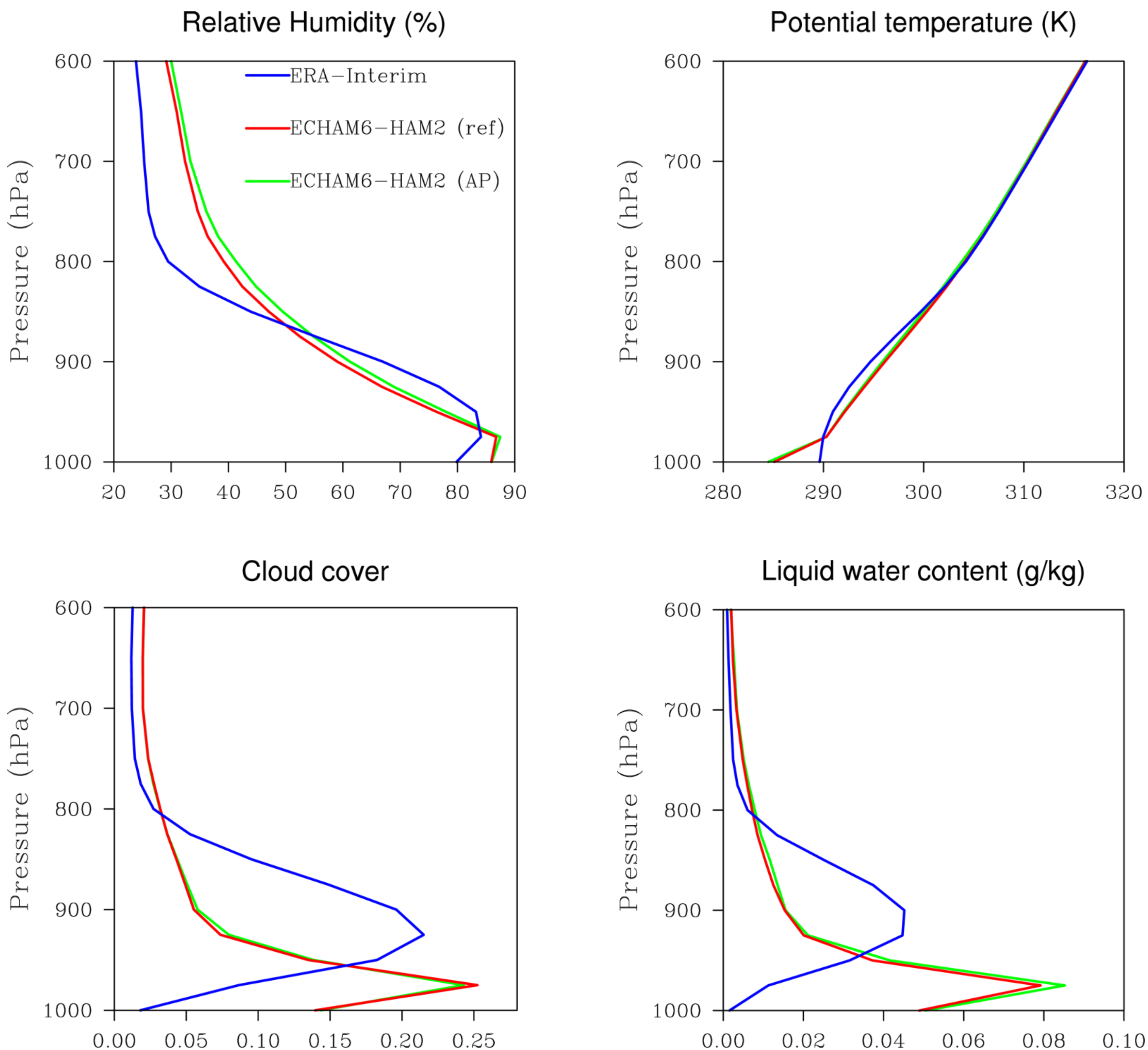
Aerosol processing



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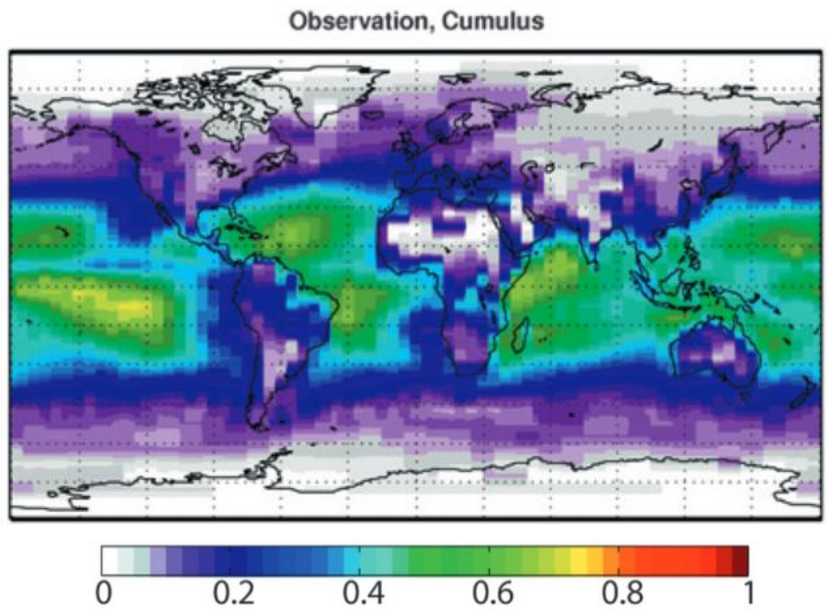
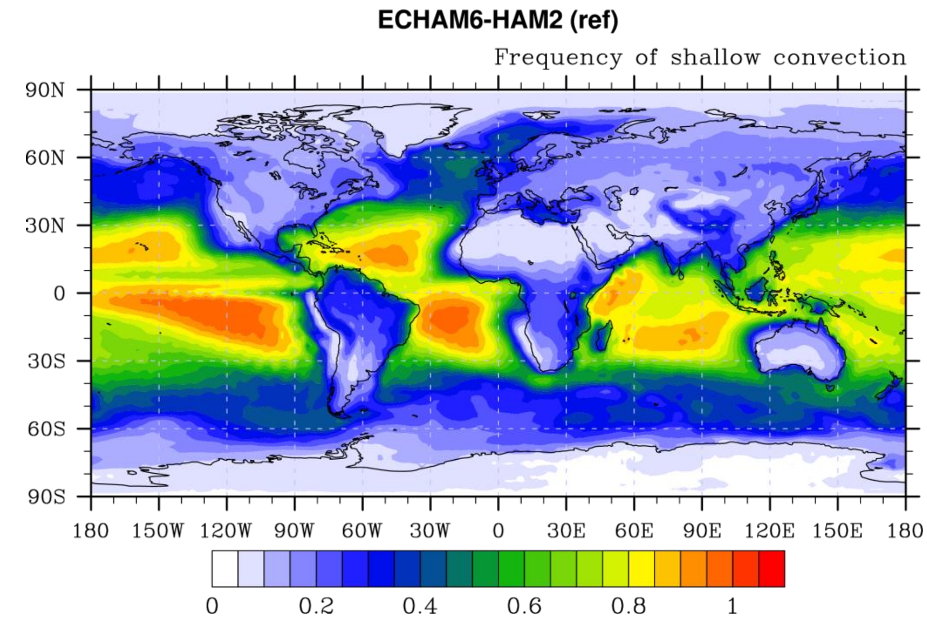
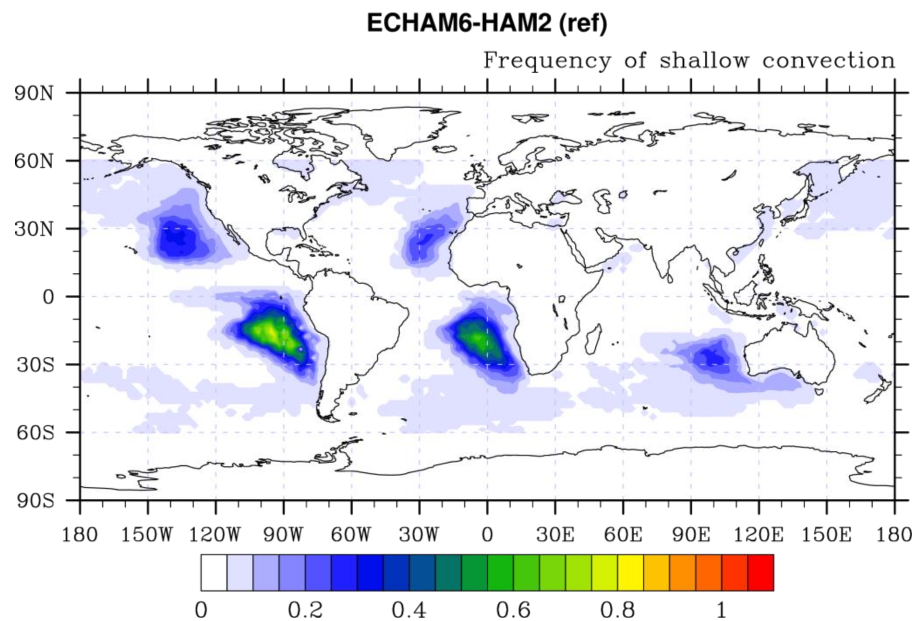
Parameterization of convection







- Too frequent shallow convection in ECHAM6-HAM2
- Shallow convection scheme active in stratocumulus regions

Observation figure adapted from Isotta et al., 2011

No precipitation

- Simulation with no precipitation in stratocumulus cloud regions
- Increased liquid water path, cloud optical depth and shortwave cloud radiative effect
- Net cloud radiative effect more negative
- Very small increases in cloud frequency/cloud cover

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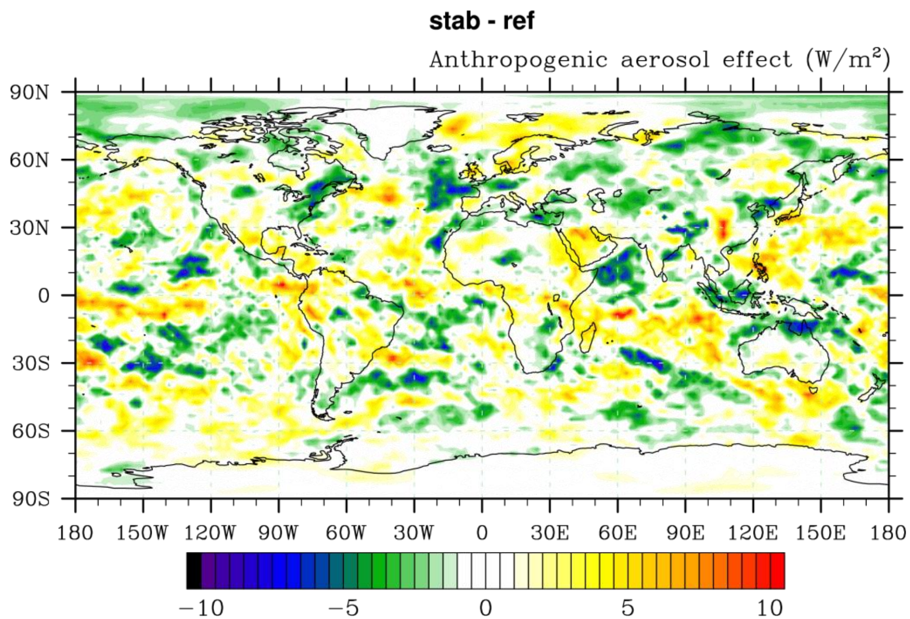
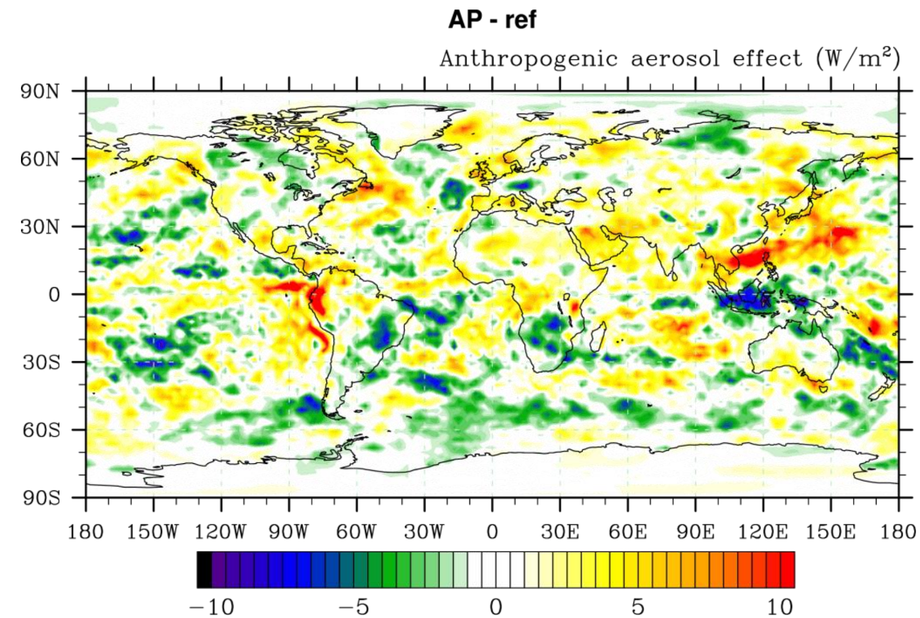
Anthropogenic aerosol effect



global: +0.28 (W/m²)



global: +0.67 (W/m²)

- Weaker aerosol effect
- Especially with aerosol processing as the background aerosol load is increased

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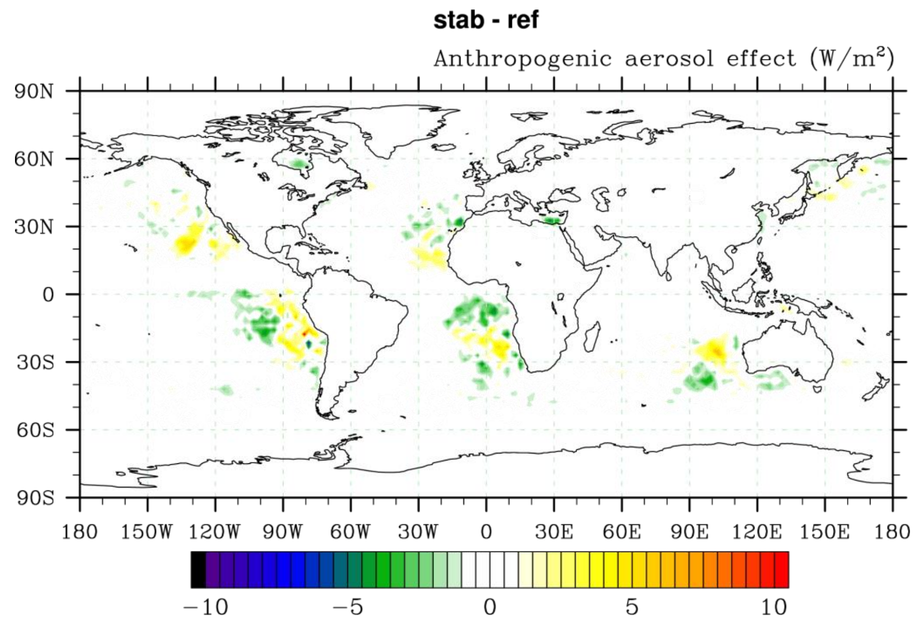
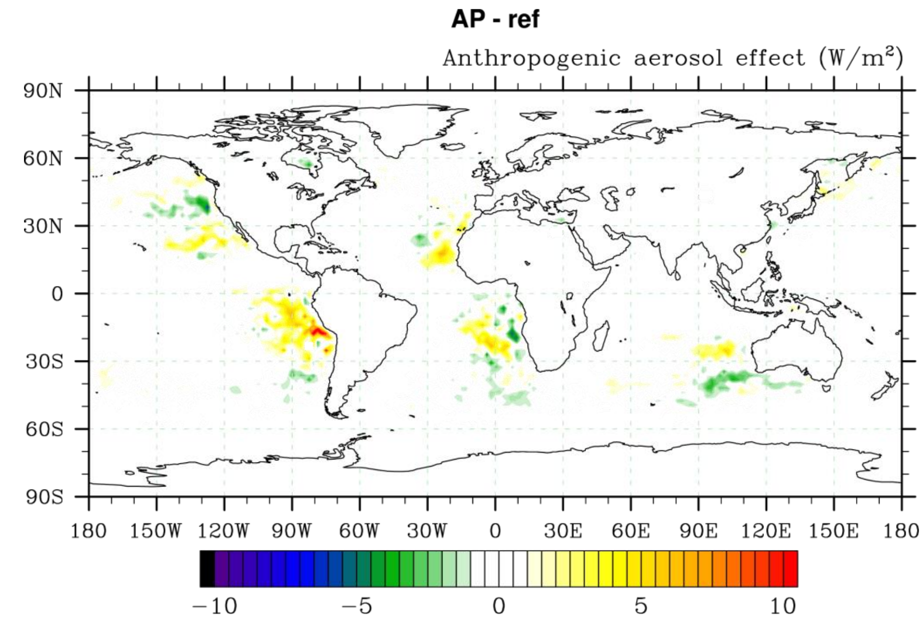


AAE_{SC}: -0.09 (W/m^2)



AAE_{SC}: +1.82 (W/m^2)

- Similar results in stratocumulus regions as global

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Moist conserved variables

- Turbulent mixing ‘smoothes’ mixing ratio profiles of non-conserved variables → less stratocumuli
- Moist conserved variables: total mixing ratio $q_t = q_v + q_l$ and moist static energy $s_l = c_pT + gz - L_vq_l - L_sq_i$

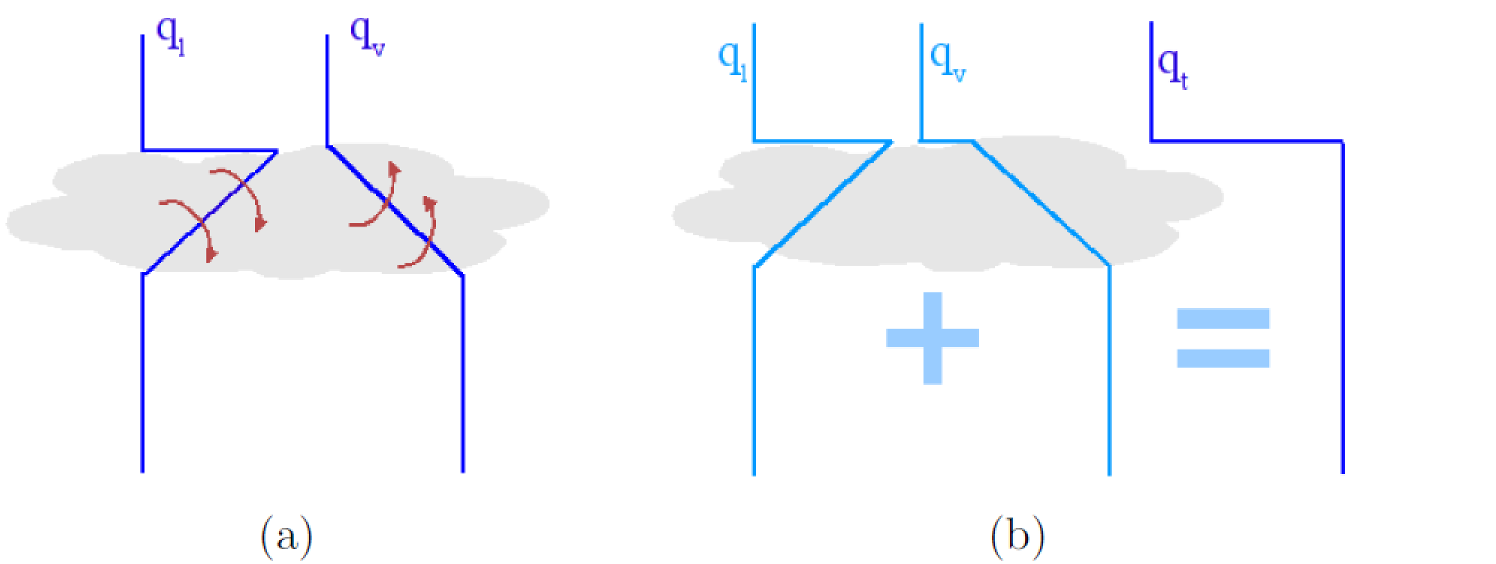

Figure from Siegenthaler-Le Drian, 2010

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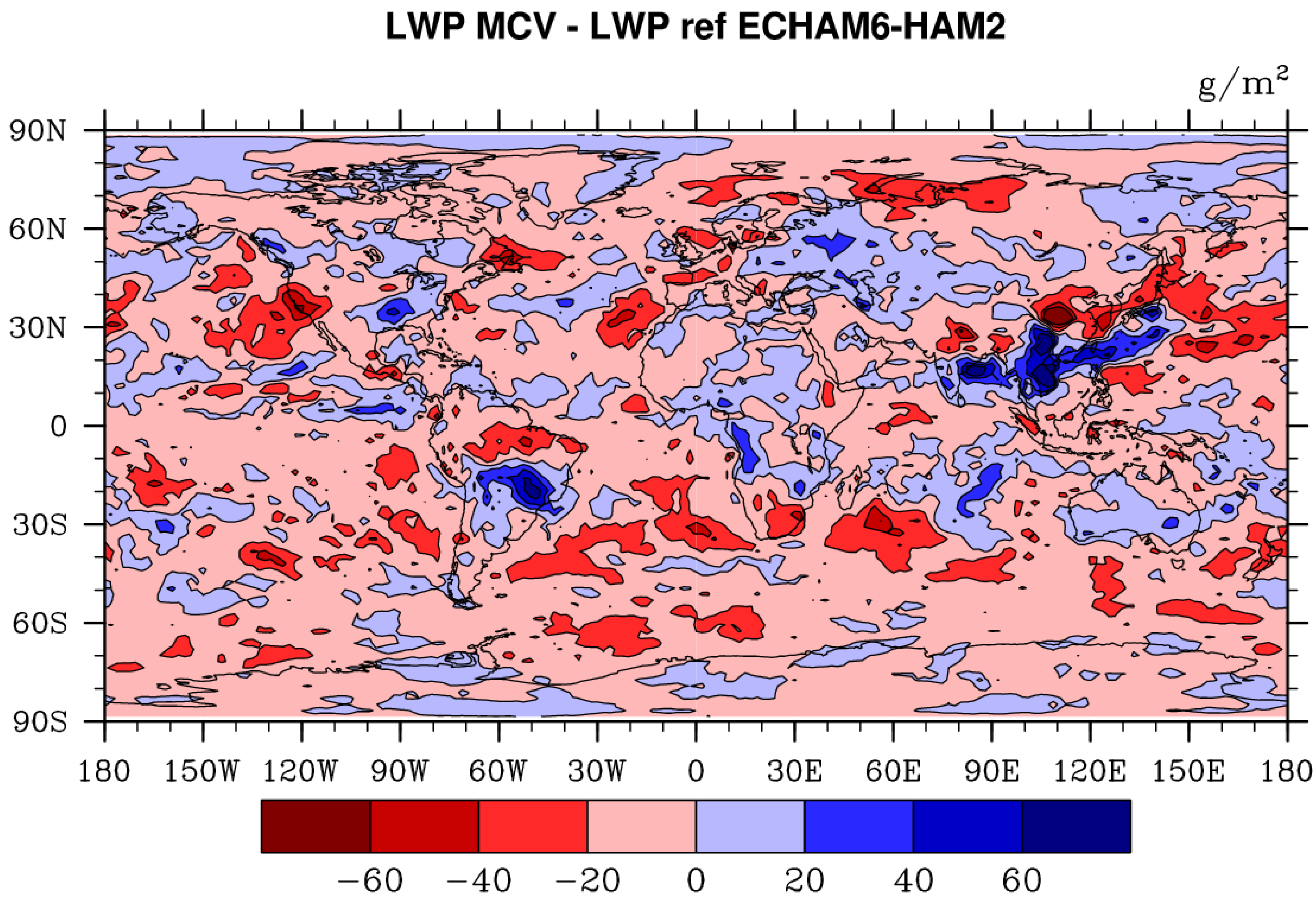
Moist conserved variables



Grid refinement

- ECHAM-turbulence scheme is principally capable to reproduce mixing and entrainment at high resolution but fails at coarse resolution (Lenderink and Holtslag, 2000)
- ‘numerical entrainment’ at coarse resolution keeps the cloud top ‘locked in’ (Lenderink and Holtslag, 2000; Lock, 2001)

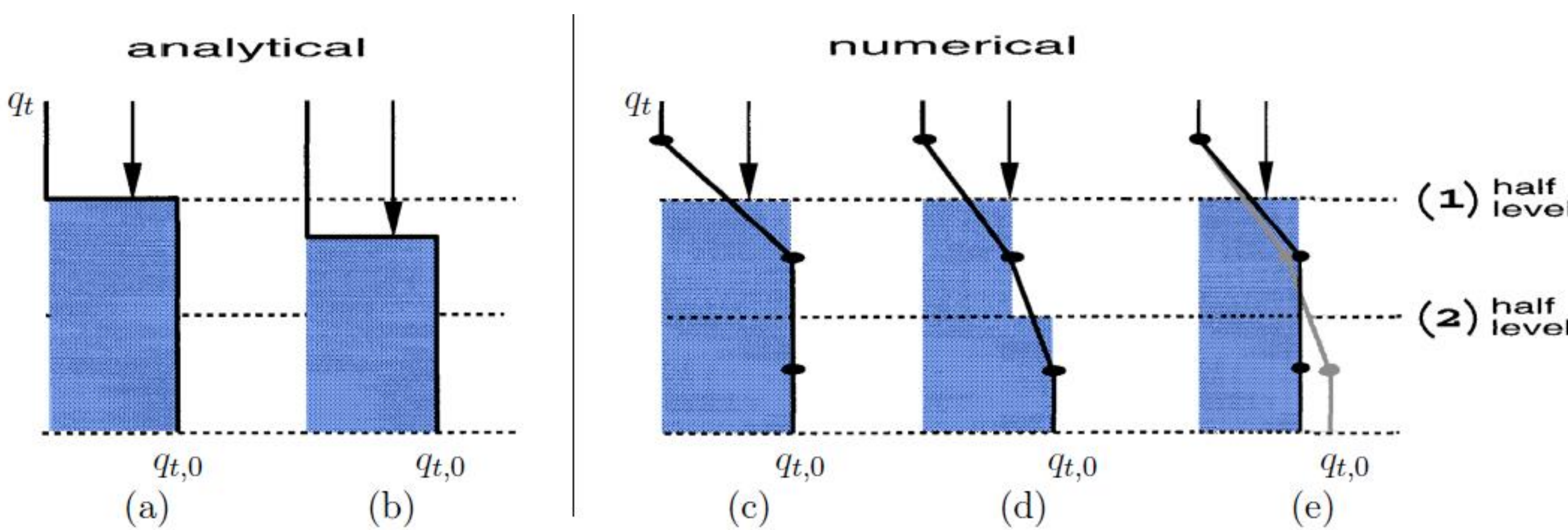
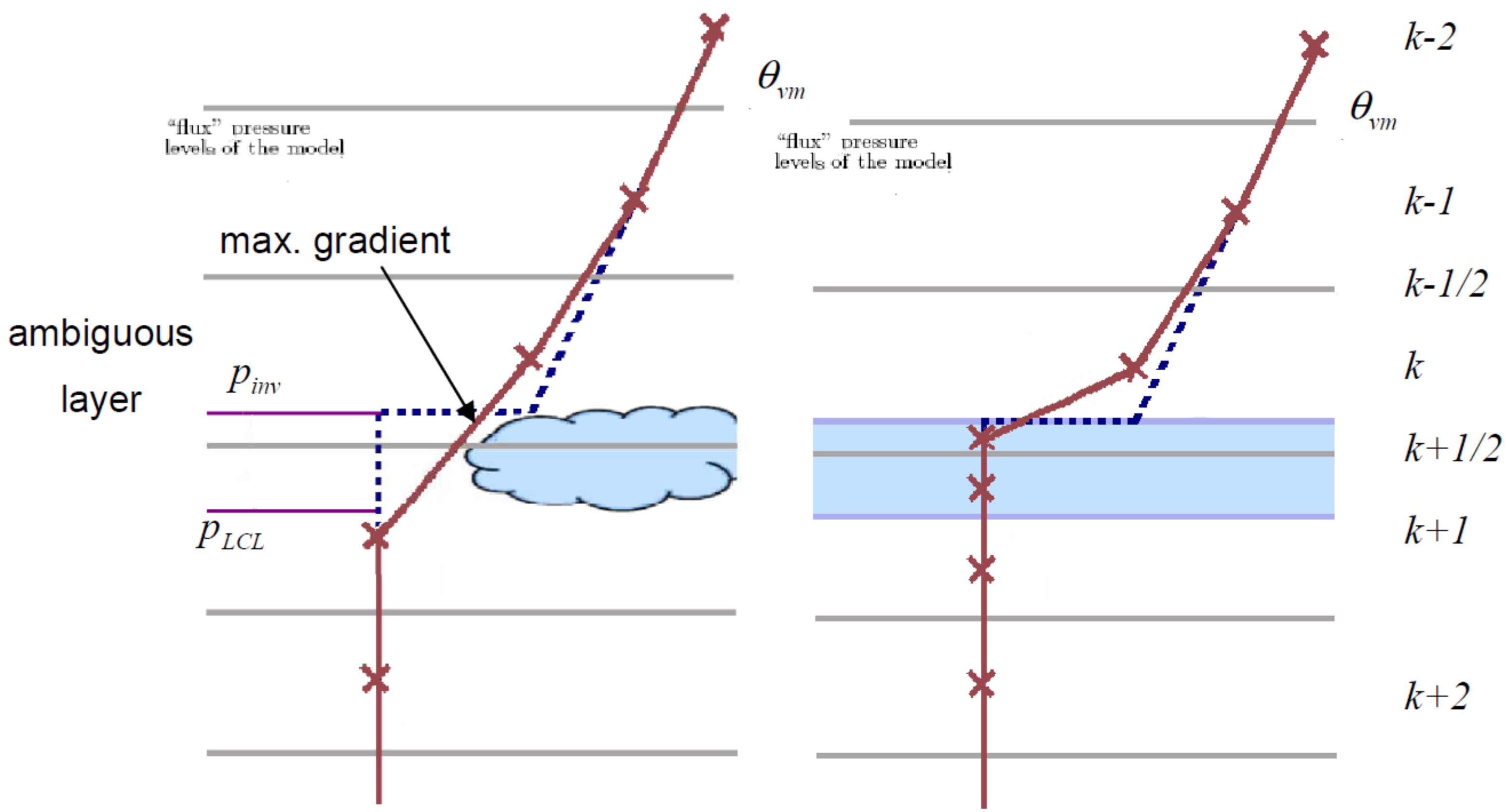


Figure from Siegenthaler-Le Drian, 2010

Grid refinement

- Based on reconstruction/restricted method by Grenier and Bretherton (2001), Siegenthaler-Le Drian (2010)



Adapted from Siegenthaler-Le Drian, 2010

Grid refinement

- Prognostic and reconstruction method by Grenier and Bretherton (2001) provide good SCM simulations of cloud-topped and dry PBLs at coarse GCM resolution
- Chlond et al., 2004 find significant improvements when using an explicit entrainment parameterization and an inversion following coordinate level in the ECHAM4-SCM
- Cloud top radiative cooling depends on model resolution (Stevens et al., 1999)