Atmospheric Spectroscopy Applications (ASA) Working Group

Dr. Iouli Gordon - Harvard-Smithsonian Center for Astrophysics

Realise of HITRAN2016 database

Highlighted updates:

1. The uncertainties in the intensities of a majority of CO_2 lines have dropped below 1%.
2. The long-standing problem of the consistency between intensities of the 5 μm and 10 μm bands of ozone has been successfully resolved.
3. Addition of substantially more lines for the deuterated isotopologues of water vapor.
4. Major improvements of the methane spectroscopy in all spectral regions.
5. Experimental absorption cross section for over 300 molecules

Article describing the HITRAN2016 database accepted for publication to the Journal of Quantitative Spectroscopy and Radiative Transfer (JQSRT) in a special issue dedicated to the new edition of HITRAN.

Other updates

New structure and interface of HITRAN online (http://www.hitran.org/) and the HITRAN Application Programming Interface;

Increased amount of parameters such as:

- non-Voigt line profiles;
- broadening by gases other than air and “self”;
- line mixing. A very important novelty that needs to be properly introduced in the radiative-transfer codes in order to advance accurate interpretation of atmospheric remote-sensing retrievals.

Last HITRAN Advisory Committee meeting

Goals:

- discuss remaining deficiencies in the HITRAN database,
- draw a roadmap for the future improvements that can aid terrestrial atmospheric remote sensing

Future

The next ASA/HITRAN meeting will be held in Cambridge, MA 12-15 June 2018.

Recent publications

I.E. Gordon et al., J. Quant. Spectrosc. Radiat. Transf. (2017) doi:10.1016/j.jqsrt.2017.06.038.

C. Hill et al., J. Quant. Spectrosc. Radiat. Transf. 177 (2016) 4–14. doi:10.1016/j.jqsrt.2015.12.012

R.V. Kochanovet al., J. Quant. Spectrosc. Radiat. Transf. 177 (2016) 15–30. doi:10.1016/j.jqsrt.2016.03.005

P. Wcisło et al., J. Quant. Spectrosc. Radiat. Transf. 177 (2016) 75–91. doi:10.1016/j.jqsrt.2016.01.024

J.S. Wilzewski et al., J. Quant. Spectrosc. Radiat. Transf. 168 (2016) 193–206. doi:10.1016/j.jqsrt.2015.09.003

Global Energy Balance (GEB) Working Group

Martin Wild and Norman Loeb

Activities

- Scientific meetings in 2016:

✓ IRS 2016: Session "Radiation Budget and Forcing", was organized by Co-chair M. Wild with Peter Pilewskie, Arturo Sanchez-Lorenzo, and Stefan Kinne, with more than 70 submissions;

✓ EGU 2016 General Assembly: Session "Earth radiation budget, radiative forcing and climate change";

✓ Earth Radiation Budget Workshop held at ECMWF on October 18-21, 2016, organized by Co-Chair Norman Loeb and colleagues. Presentations by CERES, GERB and ScaRaB science teams and other scientists from Europe, USA and China available online at: https://ceres.larc.nasa.gov/science-team-meetings2.php?date=2016-10;

✓ AGU fall meeting: Session "Improved Understanding of the Surface Energy Balance and the spatio-temporal Variation of its Components", was held for the time, with Martin Wild and WG-GEB member Chuck Long amongst the organizers. WG-GEB Co-Chair Norman Loeb gave an invited talk in the session.

Activities

- At ETH Zurich, a project funded by the Swiss National Science Foundation has successfully started.

✓ Objective: to estimate variations in solar absorption in the atmospheric column.

✓ Collocated observational data taken from the surface (GEBA/BSRN) with observations taken from space (CERES EBAF, MODIS)

✓ The period after 2000 is focused, when adequate satellite observations started to become available, and which states a period covering the global warming hiatus.

(SNF Project: “Towards an improved understanding of the Global Energy Balance: Temporal variation of solar radiation”).

Selected Research Results

- Letter published in Nature Climate Change (Von Schuckmann et al. 2016) suggests the Earth Energy Imbalance (EEI) as the most fundamental metric defining the status of global climate change, being more useful than global surface temperature;

✓ EEI can best be estimated from changes in ocean heat content, complemented by radiation measurements from space.

✓ Observations from the Argo array of autonomous profiling floats and further development of the ocean observing system to sample the deep ocean, marginal seas and sea ice regions are crucial to refining future estimates of EEI.

✓ Combining multiple measurements in an optimal way holds considerable promise for estimating EEI and thus assessing the status of global climate change, improving climate syntheses and models, and testing the effectiveness of mitigation actions.

Selected Research Results

- Report published in Current Climate Change under the topic "Global Energy Budget" (Wild, 2017):

✓ Satellites allowed global observational estimates of energy fluxes of the climate system at the top of atmosphere (TOA) with considerable accuracy;

✓ Recent independent global estimates of the surface radiation components from an increasing surface measurement network and satellite assessments have converged to within a few Wm^{-2}.

✓ Reaching stage of high confidence in the magnitudes of the global energy balance components at the TOA

✓ Confidence increasing also at the surface;

✓ Remaining challenges:

✓ *accurate determination of surface albedos and skin temperatures to calculate surface shortwave absorption and upward longwave emission, respectively,*

✓ *partitioning of surface net radiation into the non-radiative fluxes of sensible and latent heat.*

Recommendations

- For TOA radiation budget - governmental agencies building the next generation of Earth Radiation Budget instruments:
  - ✓ Onboard calibration;
  - ✓ Provide sufficient time for ground calibration activities. Shortening the length of the ground calibration period due to cost/schedule constraints adds uncertainty to the absolute calibration of the instrument;
  - ✓ Next generation of Earth Radiation Budget instruments built in collaborations with other international agencies specialized in calibration standards (e.g., NIST, NRL).
- For surface radiation budget:
  - ✓ Expansion of a well calibrated network of long term surface radiation stations, particularly in low latitude areas and the oceans;
  - ✓ Letters of support from the International Radiation Commission to National agencies funding BSRN stations may help to raise the recognition of the importance of such anchor sites for global energy budget studies.
  - ✓ Observed variables should include: direct and diffuse SW componentes; standard surface meteorological observations; atmospheric spectral optical depth to provide column abundance of aerosol, ozone water vapor and other trace constituents; surface albedo;

Recent Publications

Dallafior, T. N. et al., 2016, J. Geophys. Res. Atmos., 121, 49–66, doi:10.1002/2015JD024070.

Hakuba, M.Z., Folini, D., and Wild, M., 2016, J. Climate J. Climate, 29, 3423-3440, doi:10.1175/JCLI-D-15-0277.1.

Loeb, Norman G. et al., 2016, Remote Sensing, 8(3), 182. http://dx.doi.org/10.3390/rs8030182

Loeb, Norman G. et al., 2016, Climate Dynamics, 46(9-10), 3239-3257. http://dx.doi.org/10.1007/s00382-015-2766-

Loeb, Norman G. et al.,2017, International Journal of Climatology, 37(1), 159–168. http://dx.doi.org/10.1002/joc.4694

Raschke, E. et al., 2016: Comparison of Radiative Energy Flows in Observational Datasets and Climate Modeling, J. Applied Meteorol. Climatol., 55, 93-117, doi: 10.1175/JAMC-D-14-0281.1.

von Schuckmann, K. et al., 2016, Nature Climate Change online

Wild, M., 2016, Clim Change, 7, 91–107, doi: 10.1002/wcc.372.

Wild, M., 2017, Curr. Clim. Change Rep, DOI 10.1007/s40641-017-0058-x

Zhu, P. et al., 2016, J. Geophys. Res. Atmos., 121, doi:10.1002/2015JD024112

International Coordination-group on Laser Atmospheric Studies (ICLAS) Working Group

DR. UPENDRA SINGH AND PROF. ALEX PAPAYANNIS

International Laser Radar Conference

- New York, USA (2015): The 27th ILRC Conference - 267 participants from 27 countries (211 regular members and 56 students); 302 papers presented including 92 oral presentations and 210 posters.
  - ILRC Summer School organized by Prof. Gary Gimmestad of Georgia Institute of Technology (USA)
  - The conference provided a total of 40 students and scholars support to attend the ILRC and present their work
- Bucharest, Romania (2017): The 28th ILRC Conference - 353 participants from 31 countries (259 regular members and 94 students); 299 papers presented including 93 oral presentations and 206 posters
  - ILRC Summer School organized by Prof. Gary Gimmestad of Georgia Institute of Technology (USA)
  - The conference provided a total of 62 students and scholars support to attend the ILRC and present their work
- As part of the conference: awards to Young scientist under 40 years and 2 outstanding scientists

Elections

- 2017 new ICLAS members:
  - Dr. Georgios Tzeremes (ESA),
  - Dr. Dave Donovan (KNMI),
  - Prof. Shoken Ishii (Japan),
  - Prof. Fred Moshari (USA)
  - Prof. Dong Liu (China)
- Presidential Election:
  - Three nominees were accepted: Andreas Behrendt (Germany), Christoph Senff (USA) and Alex Papayannis (Greece).
  - After voting of all ICLAS members, Prof. Dr. Alex Papayannis was elected the new ICLAS President for a 6 year term (2015-2021).

IPRT - International working group on polarized radiative transfer

Claudia Emde and Bernhard Mayer

Meteorological Institute
Ludwig-Maximilians-University Munich
Germany

IRC business meeting, Cape Town, 30 August 2017

International Working Group on Polarized Radiative Transfer

Aims of working group IPRT:

- bring the community together (workshops)
- **compare and improve models**
- **provide benchmark results**
- provide information about free codes
- develop new and faster, publically available codes
- provide input data (scattering matrices, BPDFs – bidirectional polarization distribution functions, ...)

Project website:
www.meteo.physik.uni-muenchen.de/~iprt

Working group activities 2016/2017

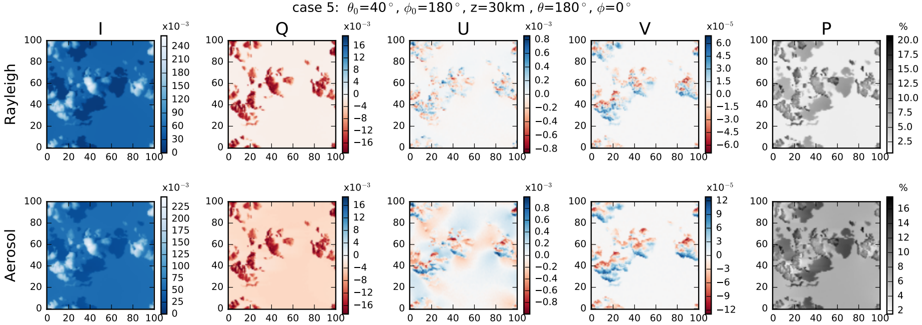
- 3D model intercomparison study for polarized radiative transfer
  - Full Stokes vector (linear and circular polarization)
  - Test cases with various degrees of complexity
  - Contribution of results from 5 vector radiative transfer codes
  - Intercomparison shows generally a good agreement (RMSE $<$ 1% for total intensity, RMSE $<$ 5% for linear polarization, this is within the noise level of Monte Carlo calculations.)
  - Results available on website `www.meteo.physik.uni-muenchen.de/~iprt`
  - Publication currently in preparation

Model intercomparison studies
Participating vector radiative transfer models

model name	method	geometry	references
3DMCPOL	Monte Carlo	1D/3D	Cornet et al. (2010), Fauchez et al. (2014)
MSCART	Monte Carlo	1D/3D	Wang
IPOL	discrete ordinate	1D	Korkin
MYSTIC	Monte Carlo	1D/3D[(a)]	Emde et al. (2010), Mayer (2009)
Pstar	discrete ordinate	1D	Ota et al. 2010
SHDOM	spherical harmonics discrete ordinate	1D/3D	Evans (1998)
SPARTA	Monte Carlo	1D/3D	Barlakas (2014)

[(a)] MYSTIC includes fully spherical geometry for 1D and 3D.

Example for nadir geometry, 3D LES cloud field



Stokes vector (I,Q,U,V) and degree of polarization P.

3D LES cloud field in pure Rayleigh atmosphere (top) and atmosphere including aerosol (bottom).

Summary of 3D intercomparison

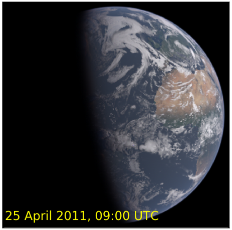
- Comprehensive test cases in 3D for:
  - Step cloud
  - Cubic cloud
  - LES cloud scene
- Results:
  - Models agree mostly within expected accuracy (i.e. standard deviation for Monte Carlo codes)
  - Differences at cloud boundaries due to definitions of model grids
  - Comparison of Monte Carlo forward and backward tracing method
  - Evaluation of variance reduction techniques

Previous work – Summary of 1D intercomparison

- Comprehensive test cases in 1D for:
  - Rayleigh scattering (with non-zero depolarization factor)
  - Surface reflection (Lambertian, reflectance matrix)
  - Spherical and non-spherical particles
  - Large size parameter
  - Coupling of layers with different optical properties
- Achieved very good agreement on high accuracy level (mostly better 0.1–1%)
- Benchmark data available on IPRT website
  `www.meteo.physik.uni-muenchen.de/~iprt`
- Publication:
  C. Emde, V. Barlakas, C. Cornet, F. Evans, S. Korkin, Y. Ota, L. C.-Labonnote, A. Lyapustin, A. Macke, B. Mayer, and M. Wendisch.
  IPRT polarized radiative transfer model intercomparison project – phase A.
  J. Quant. Spectrosc. Radiat. Transfer, 164(0):8-36, 2015.

Future plans – Polarized radiative transfer in fully spherical geometry

- Model intercomparison study in fully spherical geometry
- Particularly challenging for vector radiative transfer models using explicit methods (e.g. discrete ordinate or doubling-and-adding)
- Investigate accuracy of approximations
- So far no benchmark results exist!



Earth as seen by the moon, simulated with MYSTIC in fully spherical geometry.

UV@INNSBRUCK

MEDIZINISCHE UNIVERSITÄT
INNSBRUCK

Working Group-Ultraviolet Radiation

Co-chairs: Mario Blumthaler and Julian Gröbner

pmod wrc

Overview of Activities 2016/2017

- UV Session at IRS-2016, Auckland
- Quality assurance of spectral UV measurements
- Quality assurance of broadband UV measurements
- International Project ATMOZ: 2014-2017
- 2 recent Publications
- Future

UV Session at IRS-2016, Auckland

Presentations:

- 13 oral
- 11 posters

Proceedings: 12 contributions

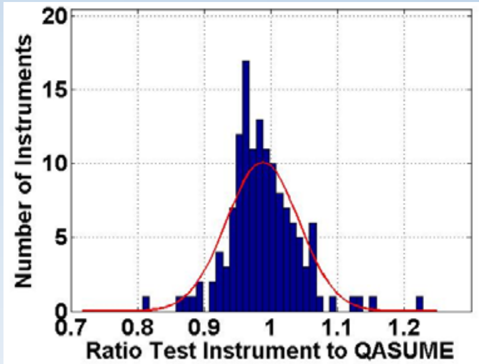
Several papers in peer reviewed journals

Solar UV Quality Assurance Program

QASUME: original – EU funded project called
“**Quality Assurance of Spectral Ultraviolet Measurements in Europe**“
➔ On site comparison with the portable QASUME reference spectroradiometer

Status 2002 - 2017

- **70 site visits**
- **36 sites**



$$\frac{Test}{QASUME} = 1 \pm 14\%$$

http://www.pmodwrc.ch/wcc_uv/?topic=qasume_audit

pmod wrc

Quality assurance of broadband erythemal UV measurements

Intercomparison campaign at WRC in Davos, 2017, supported by WMO for national calibration laboratories and for individual users

- 67 instruments: 25 K&Z , 24 SL, 10 YES, +…
- 55 participants
- From 36 countries (22 from Europe)
- Results: under preparation, paper planned

European Metrology Research Programme:

ATMOZ: Traceability of atmospheric total column ozone (2014-2017)

Radiometric characterization (slit function, stray light) of UV spectroradiometers used for determination of total column ozone.

Result: uncertainty budget for the UV measurement and for the ozone determination.

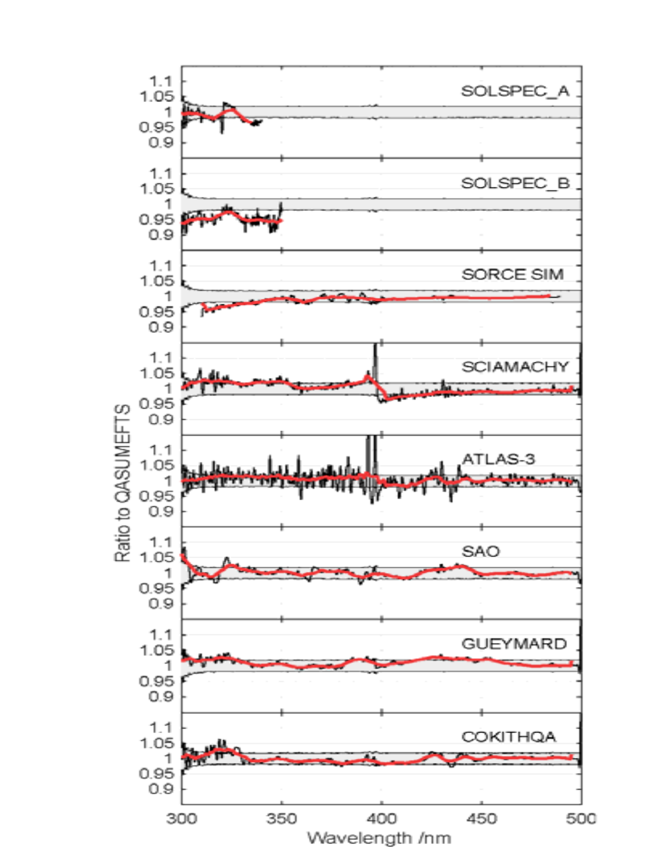
Publication:

'**A high resolution extra-terrestrial solar spectrum determined from ground-based solar irradiance measurements**' by J. Gröbner et al., A*MT*, 2017, (accepted)

Byproduct of ATMOZ field campaign 2016 in Izana, Tenerife.
From direct solar irradiance, 300-500 nm.

Combination of absolute medium resolution (0.86 nm) measurements of the QASUME spectroradiometer and relative high resolution measurements (0.025 nm) from a fourier transform spectroradiometer.

Expanded uncertainty: 2% 310 - 500 nm
4% at 300 nm



Publication:

‘UV-index monitoring in Europe’ by A. Schmalwieser et al.,

Photochem. Photobiol. Sci., 2017, DOI: 10.1039/C7PP00178A (accepted)

160 stations in 25 European countries deliver online values via the Internet.

Instruments, QAQC procedures and websites are described.

57% of the European population are supplied with high quality information, enabling them to adapt their behavior

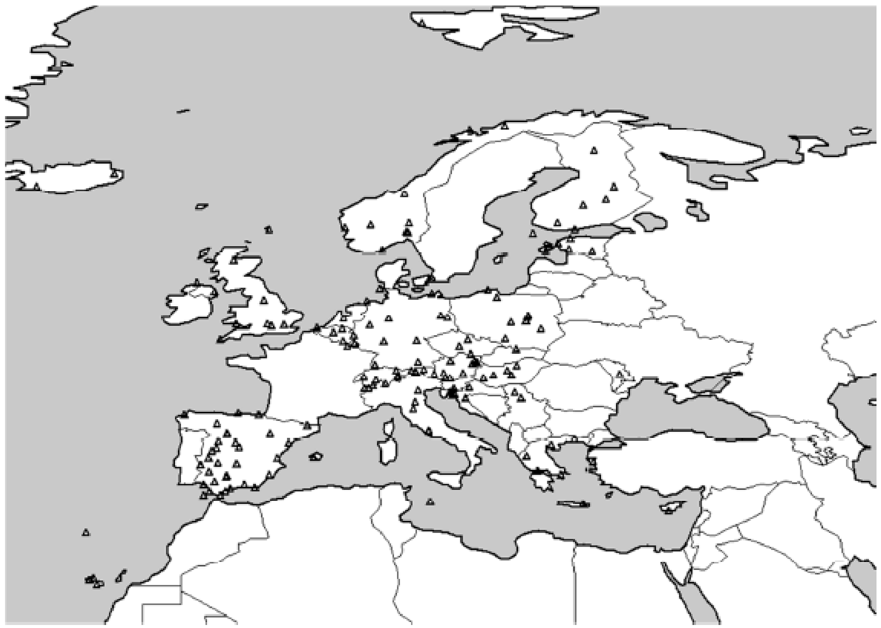


Figure 1: UV Index monitoring sites in Europe which deliver online values.

Working Group-Ultraviolet Radiation

Co-chairs: Mario Blumthaler and Julian Gröbner

Working Group-Ultraviolet Radiation

Co-chairs: and Julian Gröbner

Working Group-Ultraviolet Radiation

Co-chairs: Ann Webb and Julian Gröbner

Baseline Surface Radiation Network (BSRN)

Dr. Amelie Driemel and Dr. Chuck Long

Updates

- After Dr. Gert König-Langlo retirement in mid 2017, Dr. Amelie Driemel - the former BSRN data curator - is the new director of the World Radiation Monitoring Center;
- Up to now, 59 stations in contrasting climatic zones, covering a latitude range from 80°N to 90°S have provided data to the BSRN archive
- Data access via PANGAEA (https://dataportals.pangaea.de/bsrn/?q=LR0100) or via the ftp server (http://bsrn.awi.de/data/data-retrieval-via-ftp/)
- To gain access to the data (login info) contact Dr. Amelie Driemel (amelie.driemel@awi.de)
- The BSRN homepage was renewed (http://bsrn.awi.de/). Some of the links might have changed (e.g. the page http://www.bsrn.awi.de/en/data/conditions_of_data_release/ changed slightly to http://bsrn.awi.de/data/conditions-of-data-release/. So if you have links to the BSRN homepage please check if these are still valid.

Publications

- list of publications related to BSRN data: http://bsrn.awi.de/other/publications/.
- A paper describing the WRMC and BSRN data is under preparation by Amelie Driemel (co-authored by all station scientists) and will be submitted to Earth System Science Data at the end of this year.

Plans discussed during 2016 workshop

- Eight stations (1 in Russia, 1 in Australia, 2 in Taiwan and 4 in India) were declared to be BSRN candidates at the 14th BSRN Workshop in 2016. As soon as these start submitting data to the WRMC, they will be officially declared BSRN stations;
- Any station scientist whose data submission to the Archive lags by two years or more will be contacted by the BSRN Project Manager.
- One year after notification the situation will be reviewed, and if no sufficient progress has been made, the station scientist will be contacted again.
- Depending on the outcome of this second notice communication, the site may then be classified as "inactive" in the BSRN listing of sites.

Future

The 15th BSRN workshop will take place in 2018. The exact date and the venue are still to be determined

clouds and radiation

by Stefan Kinne, MPI, Hamburg
status Aug 2017

- summary of recent highlights
  - of recent presentations by

– Martin Wild	cloud radiative effects
– Tristan L'Ecuyer et al.	… now with (obs) detail
– Florent Malavelle	aerosol → clouds (obs)
– Chris Kummerow	GEWEX integrated data
– Hui Su	sat obs →feedback info?
– Mike Mishchenko	re-thinking radiative transfer theory

1. Clouds and Global Radiation

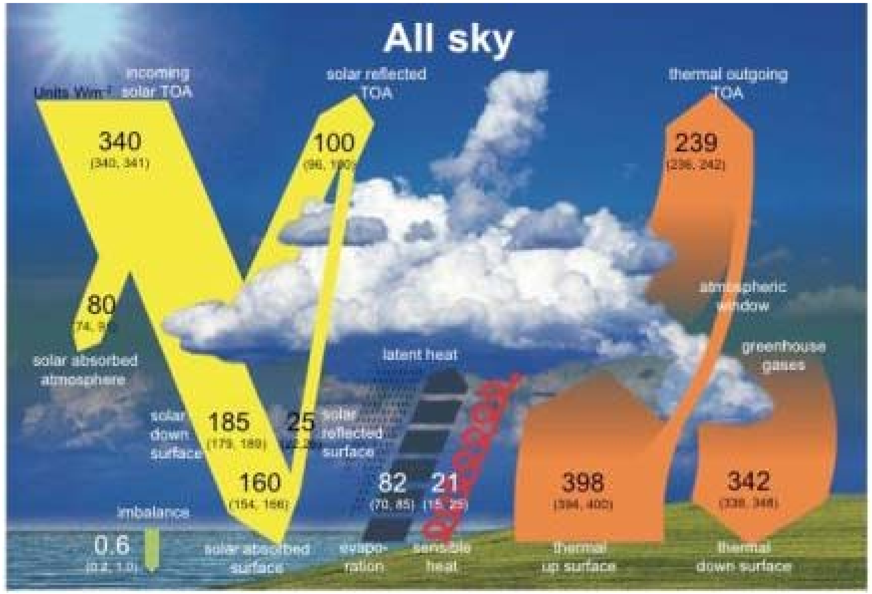
- cloud radiative effects (CRE)
  - how clouds modify clear-sky atmos. fluxes
    - CRE = all-sky flux *minus* clear-sky flux

- observational CRE constrains ?
  - Wild et al uses BSRN surface fluxes to scale global modeling (CMIP5) averages
  - L'Ecuyer et al combines 2008-11 global active and passive satellite products
    - active remote sensing permits phase and cloud type regional CRE allocations !

ETH Institute for Atmospheric and Climate Science

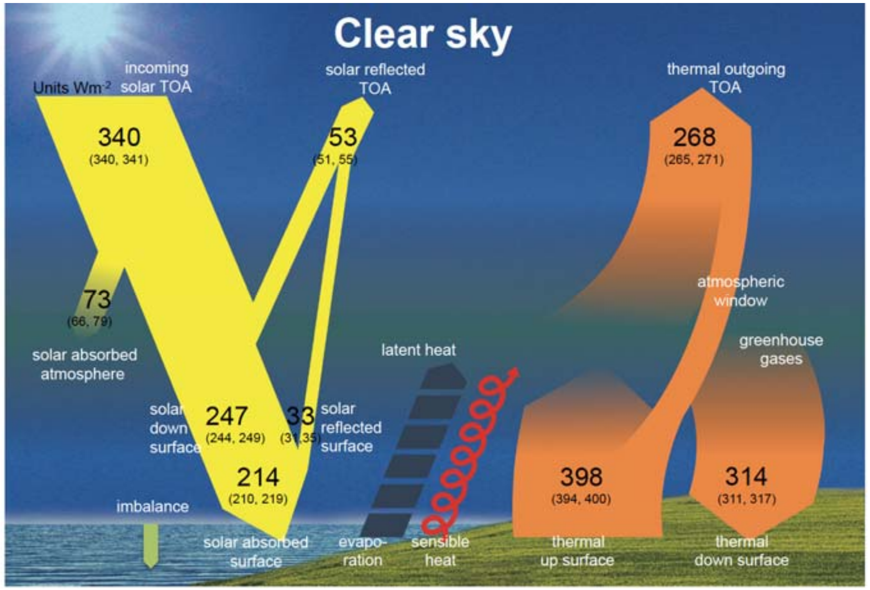
Cloud Radiative Effect (CRE) All-sky minus Clear-sky

All sky



Wild et al 2015 Clim. Dyn.

Clear sky



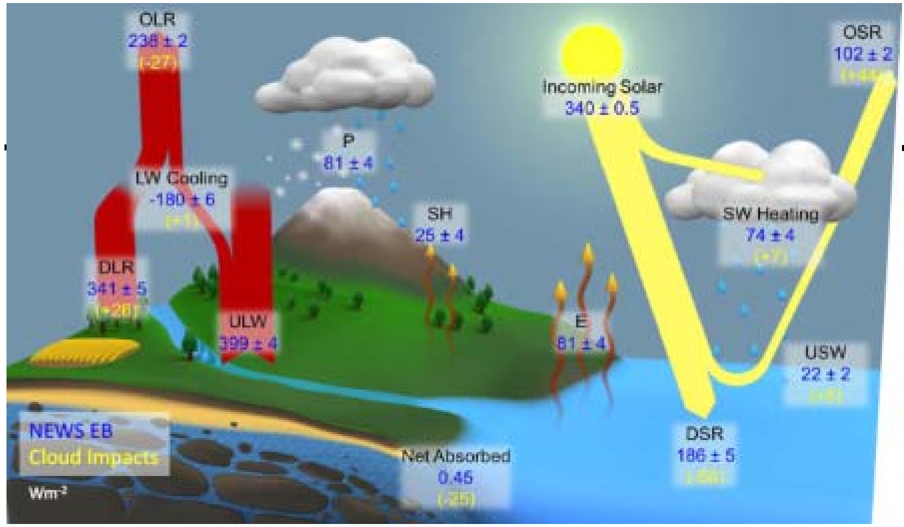
Wild et al in prep**.**

CRE Wm^{-2}	SW	LW	SW+LW
TOA	**-47**	**29**	**-18**
Atmosphere	**7**	**1**	**8**
Surface	**-54**	**28**	**-26**
Surf. CMIP5	*-53*	*25*	*-28*

… to remember

albedo > greenhouse
→ clouds cool climate

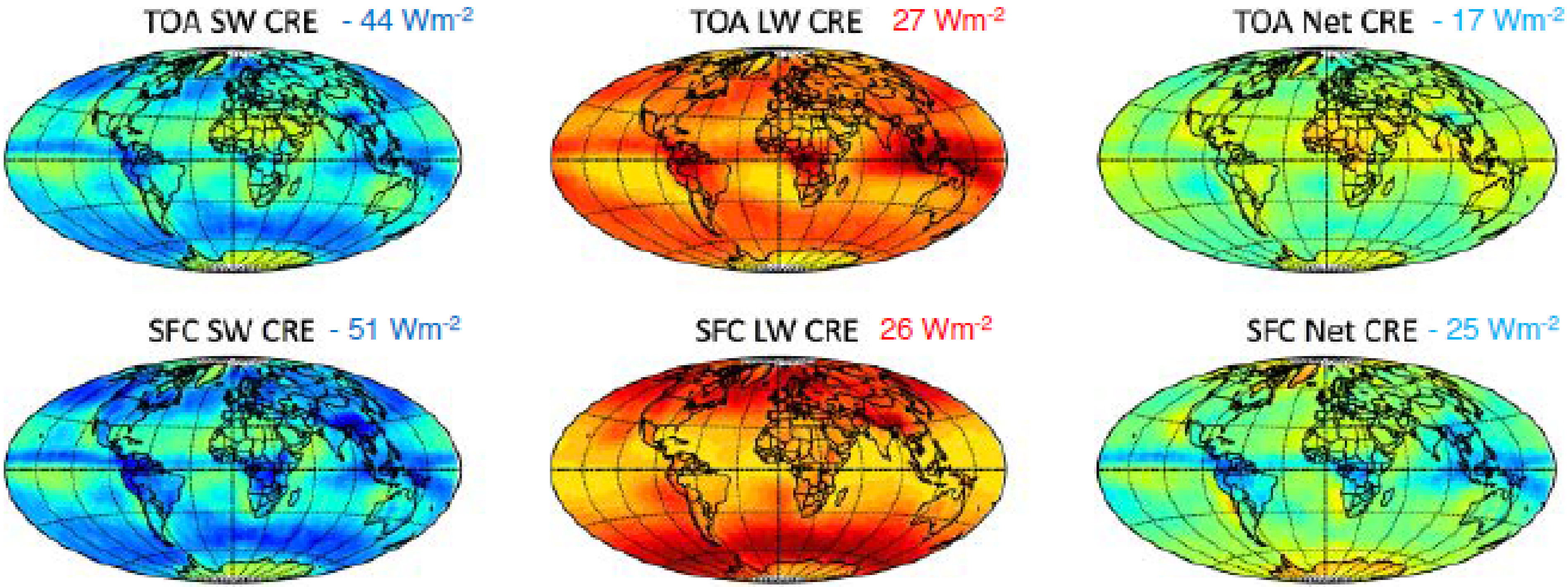
clouds increase solar heating in the atmosphere



CRE – now in patterns

CRE Wm^{-2}	SW	LW	SW+LW
TOA	-44	27	-17
Atmosphere	7	1	8
Surface	-51	26	-25

planetary albedo **greenhouse**

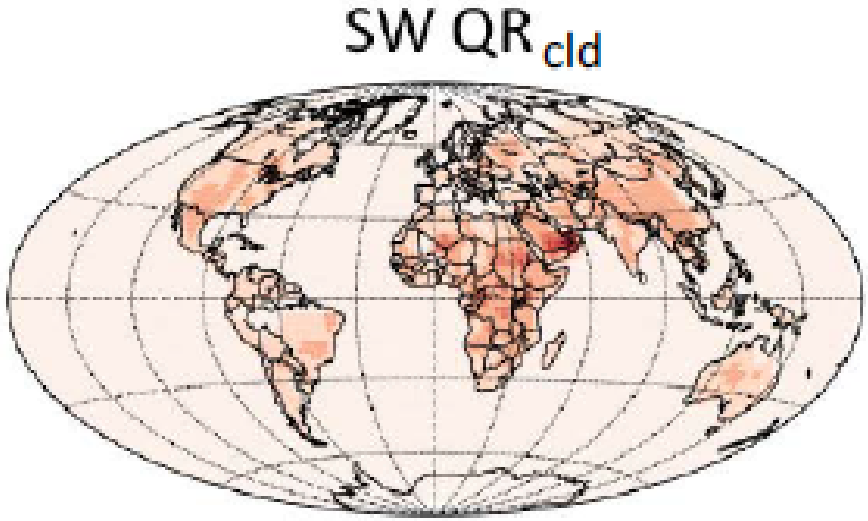


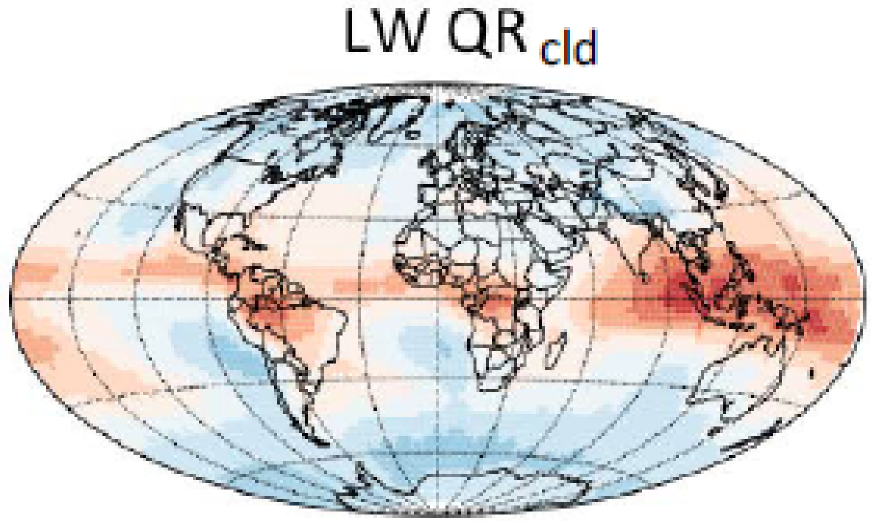
CloudSAT / CALIPSO.

Hang et al 2017 in prep.

atmospheric CRE: modified heating rates

L'Ecuyer et al 2017 in prep.

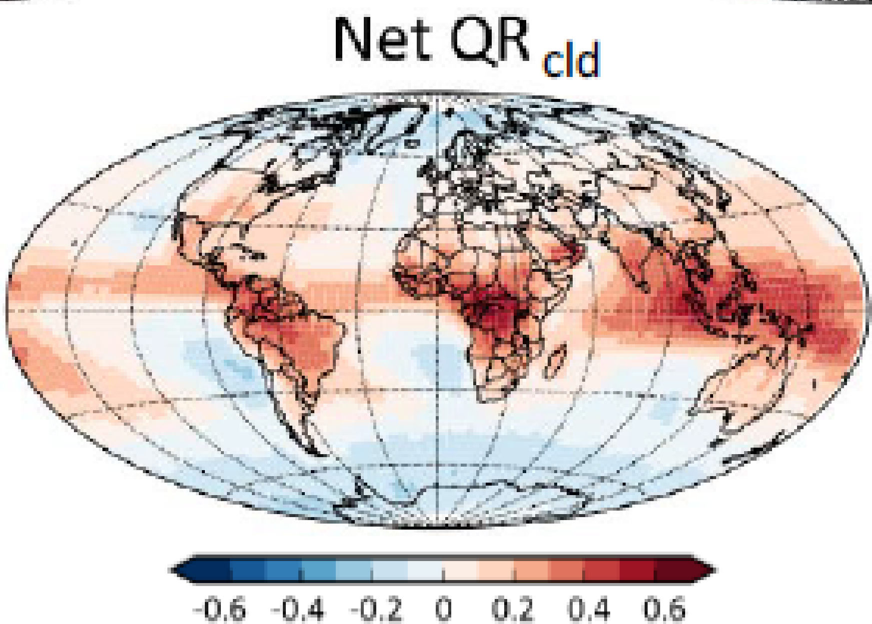




solar heating

longwave cooling

longwave heating



$$Q = \frac{dT}{dt} = -\frac{g}{c_p}\frac{\Delta F_{NET}}{\Delta p}$$

CRE, atm =
CRE, TOA
-CRE, surf

CRE summary

Manus and L'Ecuyeret al 2017 in prep.

- **cloud net (TOA) cooling of -17 W/m2 (+/-6)**
- **cloud net (surf) cooling of -26 W/m2 (+/-10)**

  - **ice-clouds: 20% of total cloud cover**

– **weak TOA warming / 11% of surface cooling**

  - **liquid clouds: 21% of total cloud cover**

– **50% of TOA cooling / 31% of surface cooling**

  - **mixed phase clouds: 8% of total cloud cover**

– **18% of TOA cooling / 19% of surface cooling**

  - **multi-layered clouds: 24% of total cloud cover**

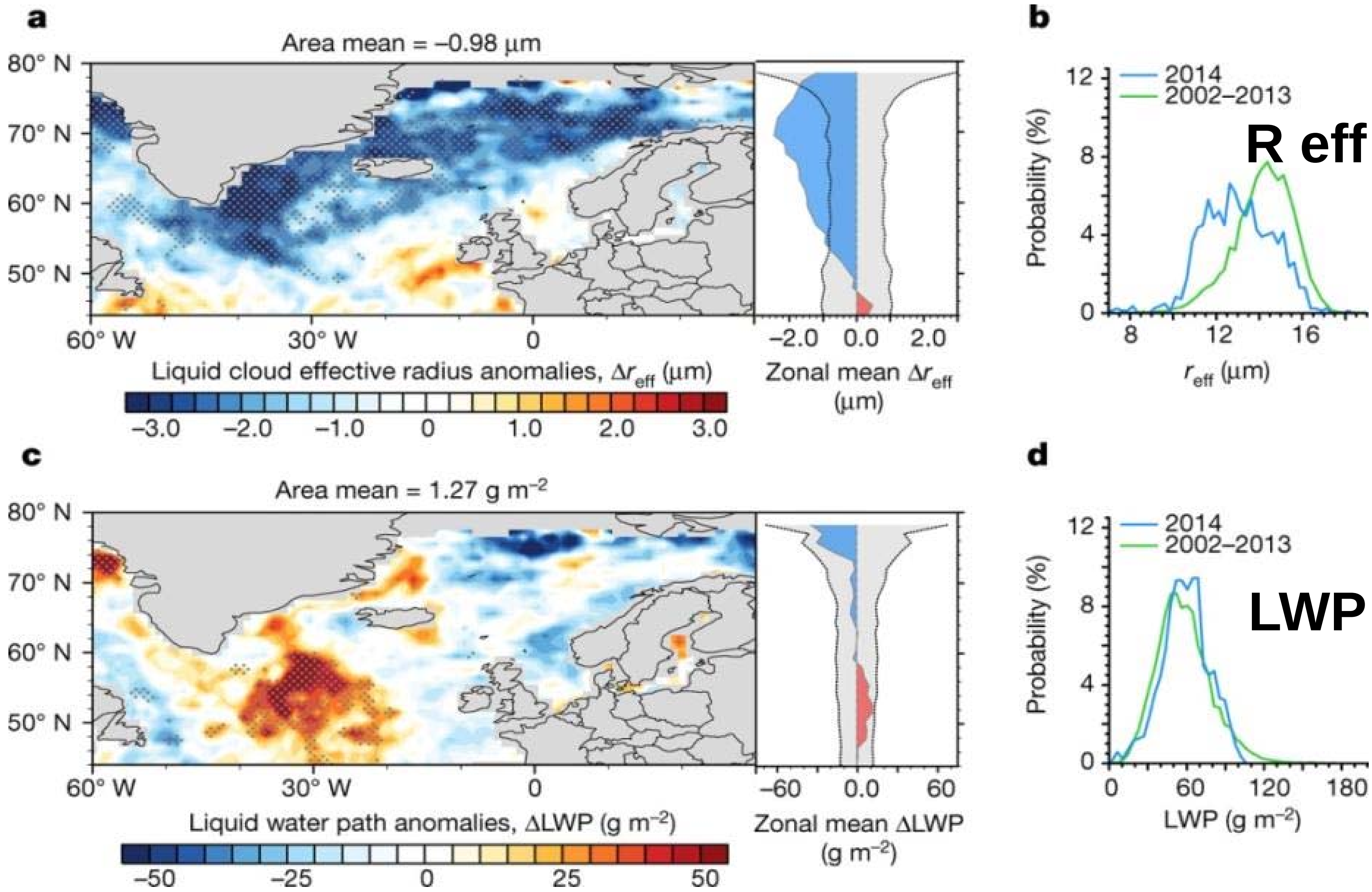
– **35% of TOA cooling / 39% of surface cooling**

2. cloud modifications by aerosol ?

- apparently smaller than often modeled
- sulfate eruptions off an Iceland volcano in 2014 caused cloud property anomalies
  - MODIS retrieval anomaly analysis:
    - smaller droplet radius
    - NO significant change to water-content
- effect on aerosol number on drop number
  - MODIS, ATSR retrieval analysis
    - relative weak CDNC increase with AODf increase
- observational plans

MODIS anomaly analysis

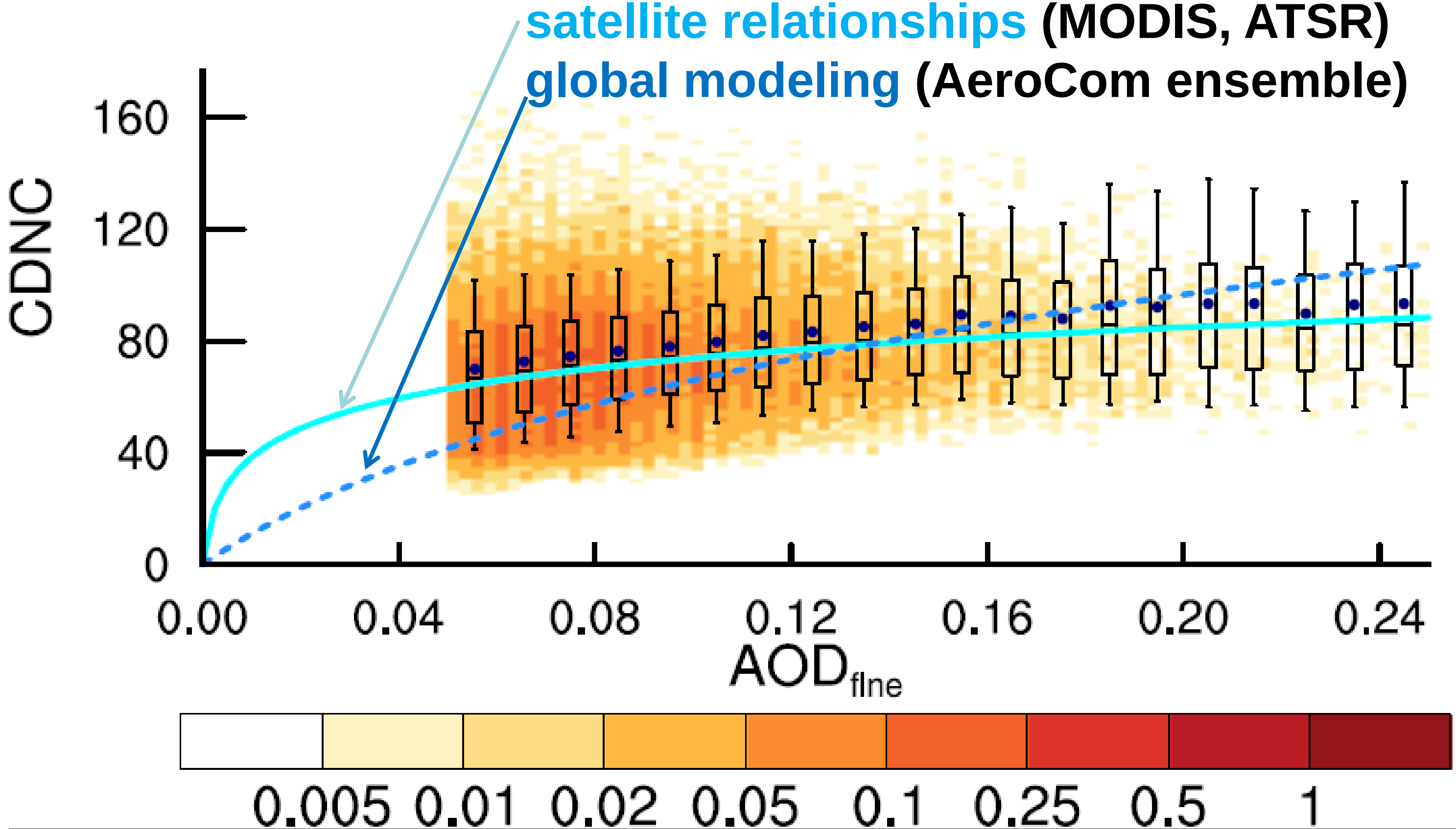
F F Malavelle et al. Nature 2017



concentrations: CDNC vs aerosol (via AODf)

B. Stevens et al. 2017

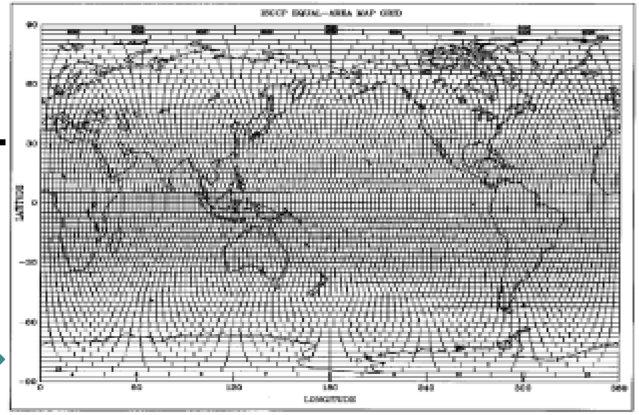
for oceanic retrieval co-locations



cloud modifications by aerosol ?

- **recent / on-going field experiments**
  - **ORACLES NH fall 2016 /2017/ 2018**
    - **SE - central Atlantic**
  - **CLARIFY NH summer 2016**
    - **E-central Atlantic**
  - **KAMP Kilauea Aerosol Microphysics Project NH sum 2018**
    - **Pacific off Hawaii**

3. GEWEX Integrated Product



- ‘consistent’ data
  - netcdf, 3hr, on equal area grid →
  - ftp://rain.atmos.colostate.edu/ftp/pub/GEWEX_IP/pbrown/GEWEX_IP/2007/
    - pbrown@atmos.colostate.edu
- elements
  - test period: 1 Jan 2007 – 31 Dec 2007
  - ISCCPClouds, MACv2Aerosols, SRBRadiation (TOA, Sfc)
  - Land / SeaFlux for sensible & latent heat flux
  - GPCP Precipitation
  - ERA-Interim for Water Vapor transport, CAPE, dynamical context

many variables

Cloud variables

- "Total number of pixels" (dividing other "number of pixels by this value gives cloud fractions)
- "Number of cloudy pixels"
- "Number of IR-marginally-cloudy pixels"
- "Number of IR cloudy pixels for IR cloud types" (low, middle, high)
- "Number of cloudy pixels for VIS/IR cloud types" (cumulus, etc)
- "Mean PC for cloudy pixels"
- "Mean TC for cloudy pixels"
- "Mean TAU for cloudy pixels"
- "Mean WP for cloudy pixels"
- "PC means for cloud types"
- "TC means for cloud types"
- "TAU means for cloud types"
- "WP means for cloud types"

- **try it out !**
  - **do NOT expect total consistency**
  - **learn about temporal and regional features**

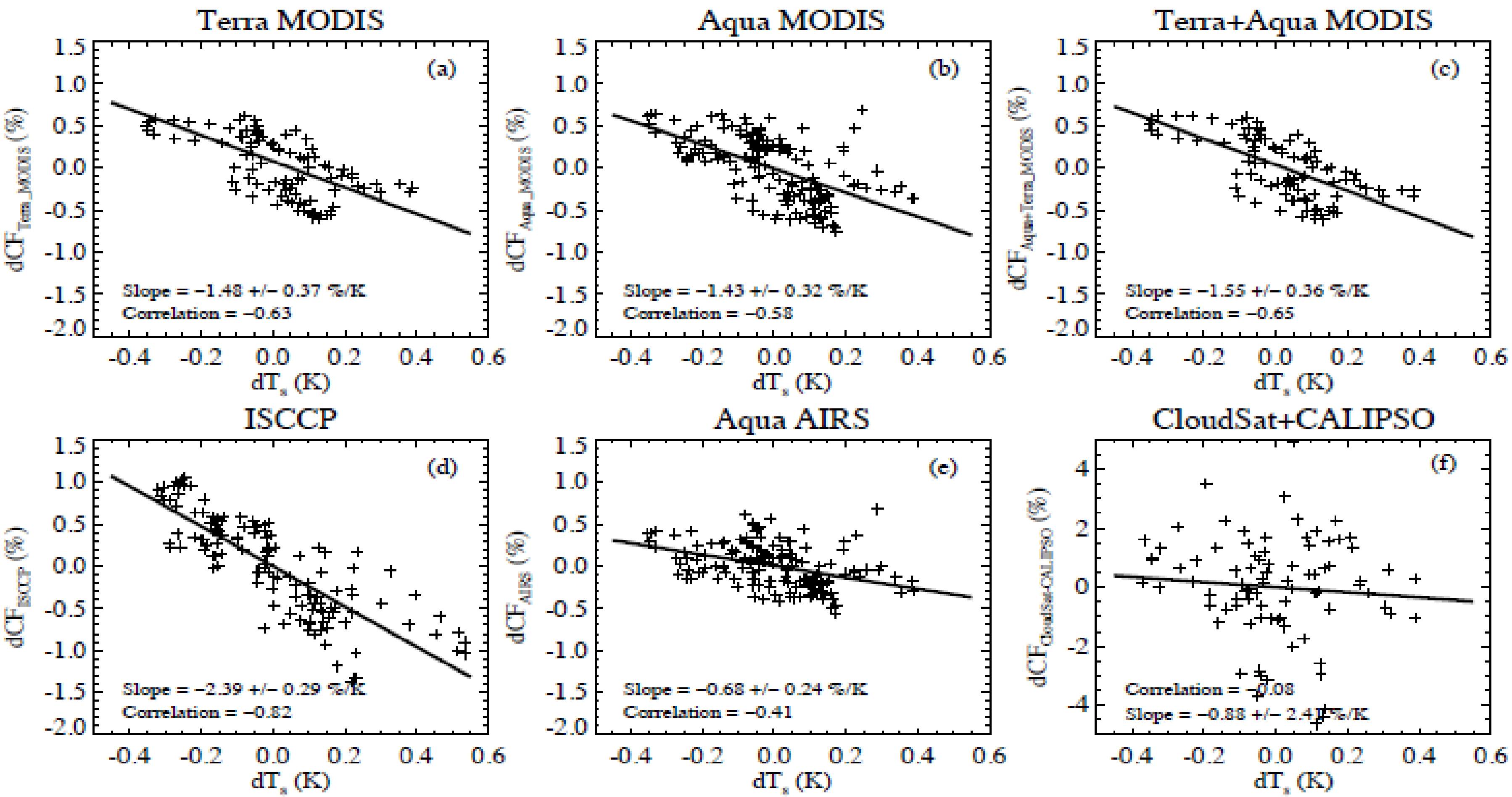
Surface and Atmosphere variables:

- "Snow/ice cover"
- "Mean TS from clear sky composite"
- "Mean RS from clear sky composite"
- "Pressure levels"
- "Near-surface air temperature (2 meters)"
- "Atmospheric temperature profile"
- "Maximum temperature"
- "Tropopause temperature"
- "Surface pressure"
- "Pressure at max temperature"
- "Pressure at tropopause"
- "Near-surface relative humidity"
- "Relative humidity profile"
- "Relative humidity at max temperature"
- "Relative humidity at tropopause"
- "Ozone abundance"

4. sat obs → cloud feedback constrains ?

Su et al. 2017

- **satellite observations**
  - **cirrus coverage decreases with warmer T**



“apparent IRIS” explanations

– **with warmer surface temperatures …**

… there is a reduced cirrus coverage because

- **convective aggregation**
  - **Mauritsen and Stevens 2015**
- **increased static stability**
  - **Bony 2016**
- **narrowing of the ITCZ**
  - **Su 2017**

(diverging opinions on its impact on climate sensitivity)

5. rethinking rad transfer (in clouds) ?

- **Fluctuational QED theory**
    - **Michael Mishchenko GISS**
- Quantum fluctuational electrodynamics provides a unified theoretical description of elastic scattering and thermal emission.
- The scattering and thermal-emission solutions are completely separated.
- The order-of-scattering expansion of the thermal-emission solution should pave the way to the fundamental derivation of the generalized RT theory.

impact of current 'simplifications' unclear at this point

first-principles approach to RTT

- The RT theory has been derived directly from the Maxwell equations in the case of elastic electromagnetic scattering (no thermal emission).
- Quantum fluctuational electrodynamics (Sergei Rytov) provides a unified theoretical description of elastic scattering and thermal emission by aerosol and cloud particles.
- Emission is modeled as the result of thermal fluctuations in positions and velocities of the elementary charges.

$$\nabla \times \mathbf{E}(\mathbf{r}, \omega) = \mathrm{i}\omega\mu_0 \mathbf{H}(\mathbf{r}, \omega)$$

$$\nabla \times \mathbf{H}(\mathbf{r}, \omega) = -\mathrm{i}\omega\varepsilon(\mathbf{r}, \omega)\mathbf{E}(\mathbf{r}, \omega) + \mathbf{J}^{\mathrm{f}}(\mathbf{r}, \omega)$$

This fluctuating electric current is the only addition to the classical Maxwell equations

current status and expectations

- The scattering and thermal-emission solutions of the modified Maxwell equations are completely separated.
- The order-of-scattering expansion of the thermal-emission solution is expected to pave the way to the fundamental derivation of the generalized RT theory.
- It is expected that the scattering and emission components of the RTE will also be completely separated.

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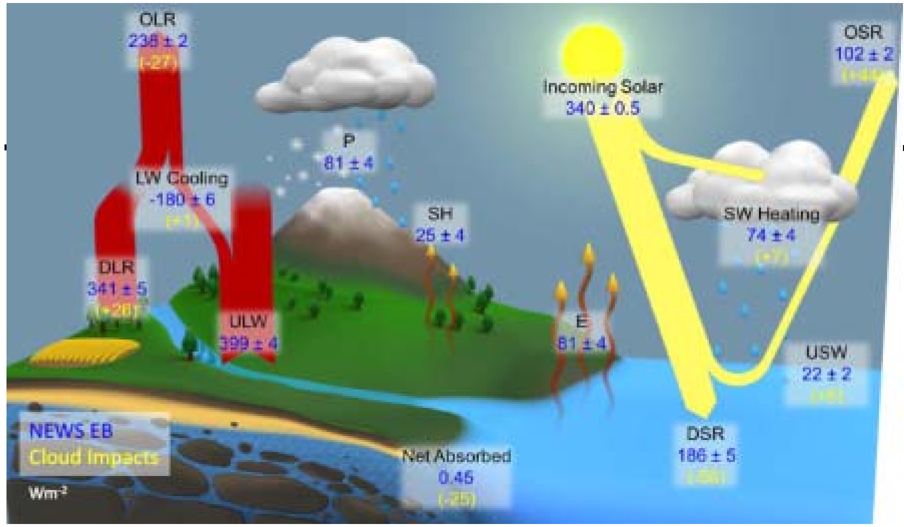
Electromagnetic scattering and emission by a fixed multi-particle object in local thermal equilibrium: General formalism

CrossMark

Michael I. Mishchenko

NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA

- **extras with more detail**

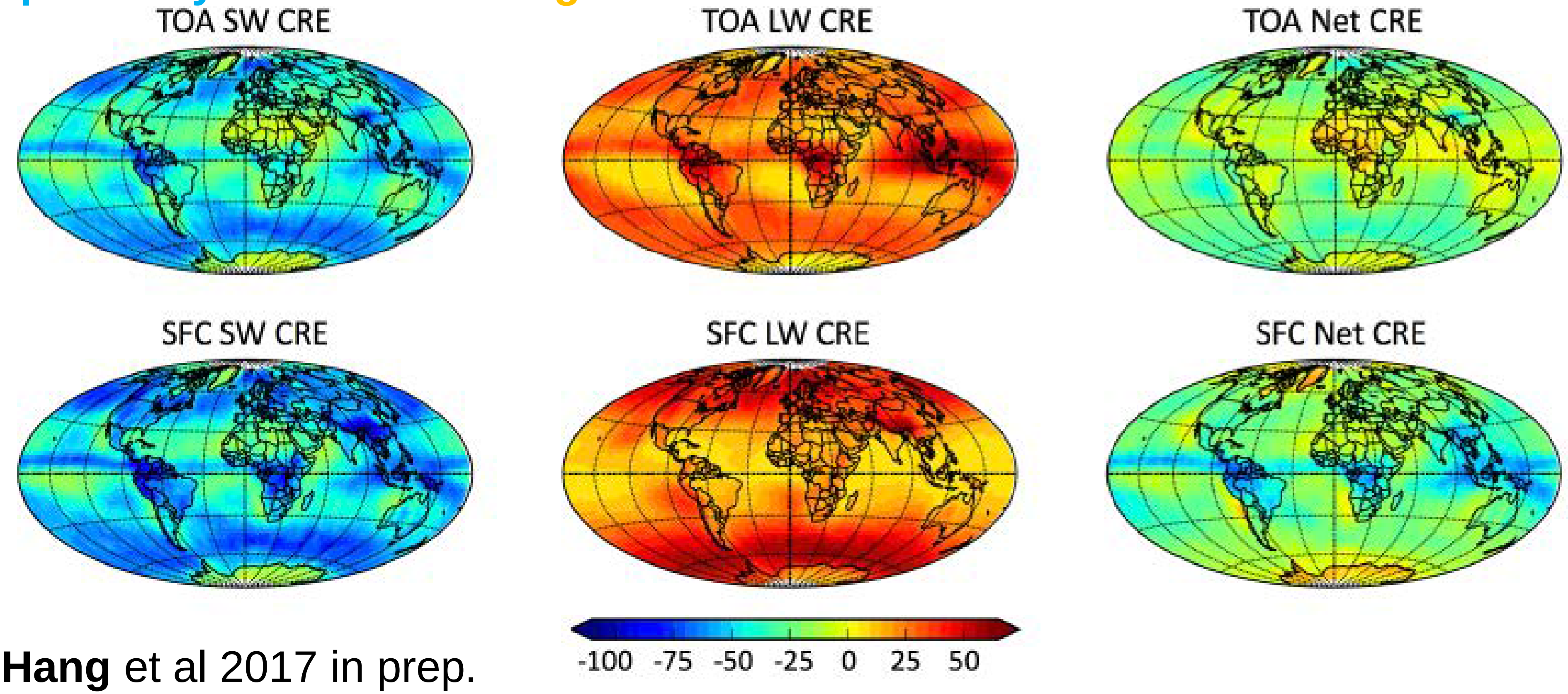


CRE – now in patterns

CRE Wm^{-2}	SW	LW	SW+LW
TOA	-44	27	-17
Atmosphere	7	1	8
Surface	-51	26	-25

planetary albedo

greenhouse

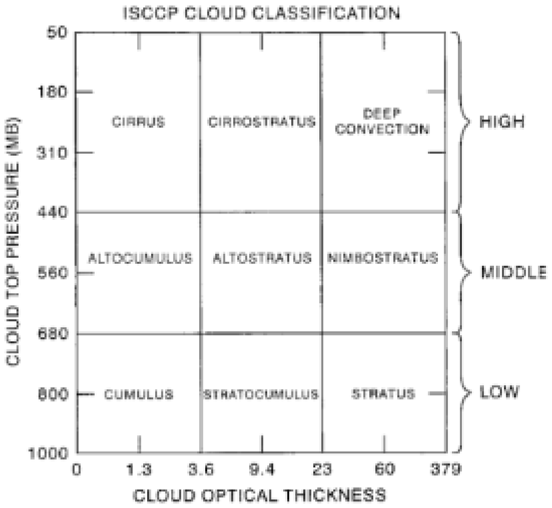


Hang et al 2017 in prep.

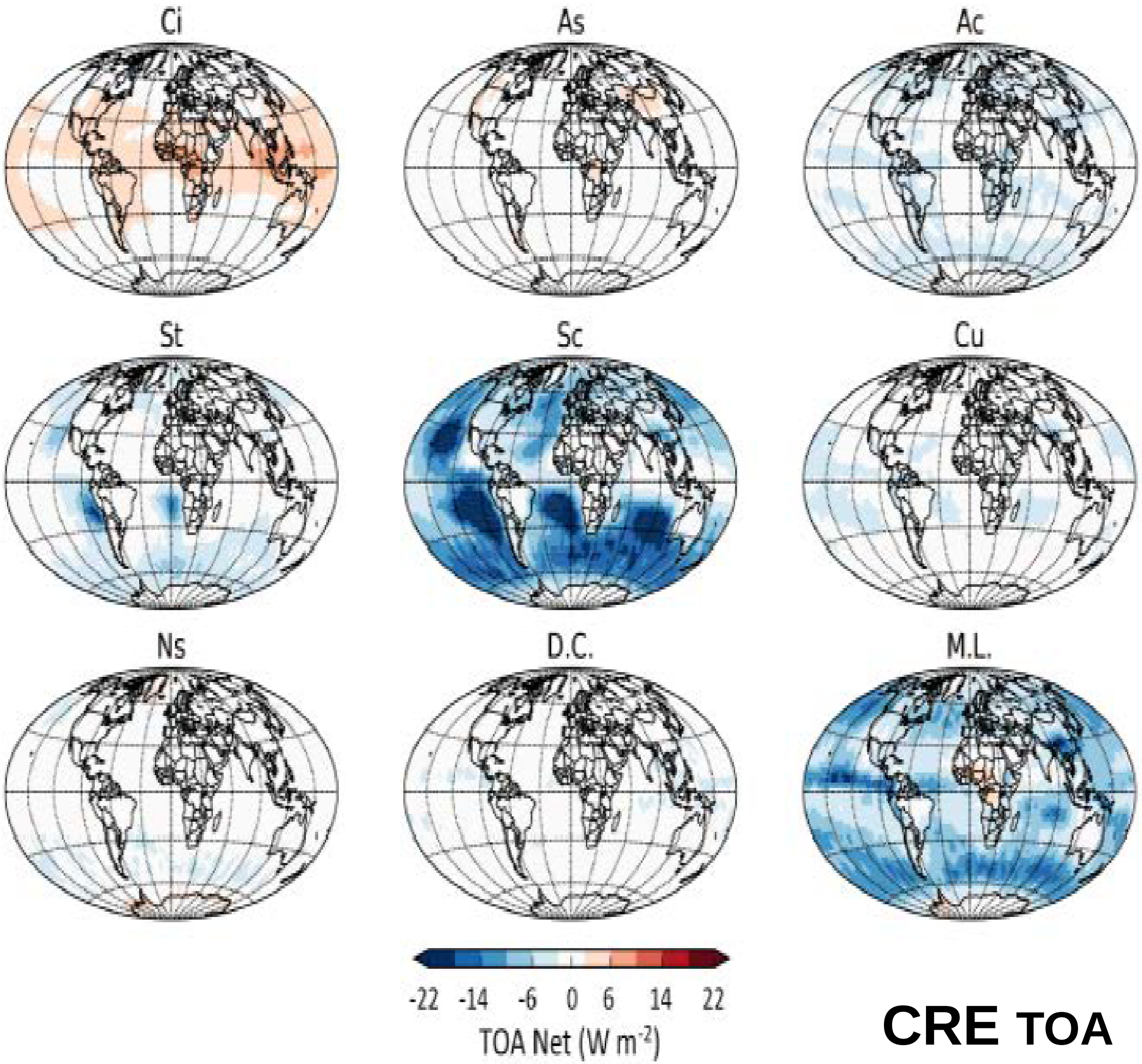
CRE – by cloud type

Manus and L'Ecuyer et al 2017 in prep.

Ci cirrus
As altostratus
Ac Altocumulus
St Stratus
Sc Stratocumulus
Cu Cumulus
Ns Nimbostratus
DC Deep Convection
ML Multi-Layer



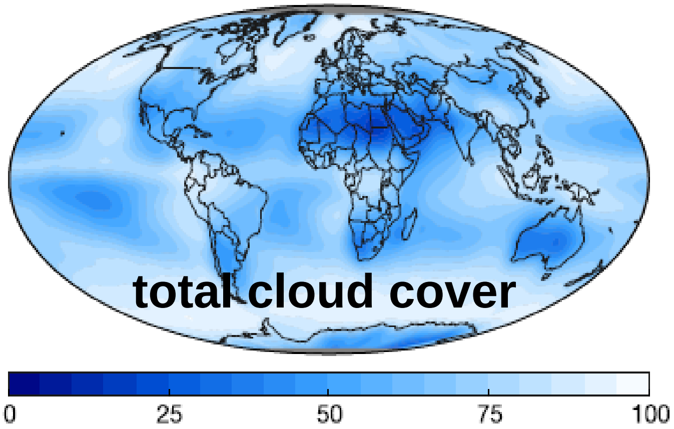
Rossow and Schiffer, *BAMS* (1999)

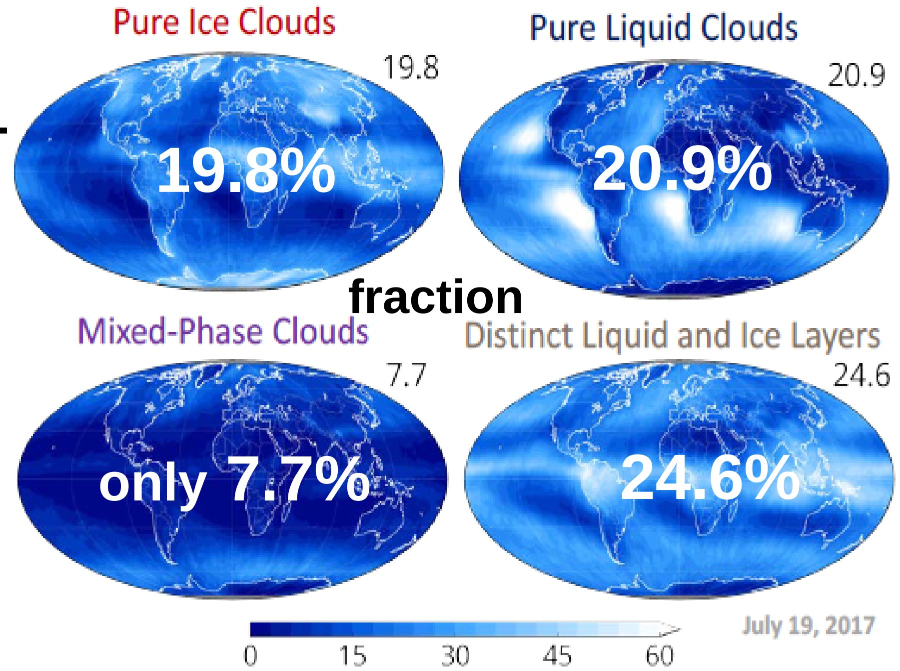


CRE TOA

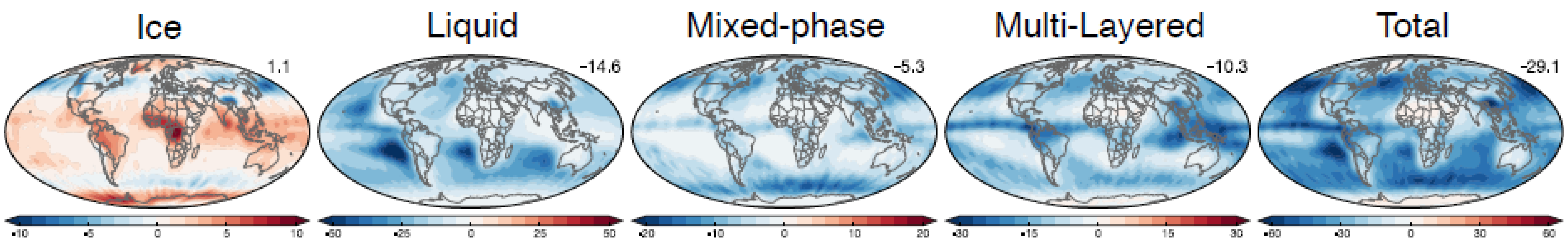
CRE – by cloud phase

Manus and L'Ecuyeret al 2017 in prep.

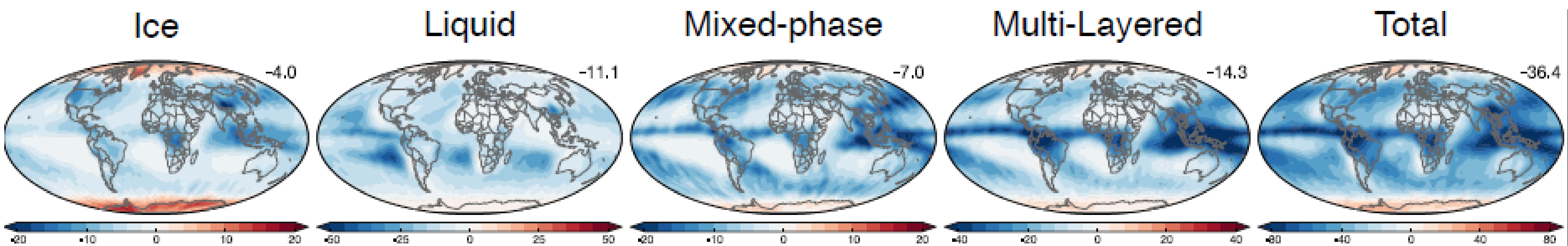




CRE at TOA



CRE at surface



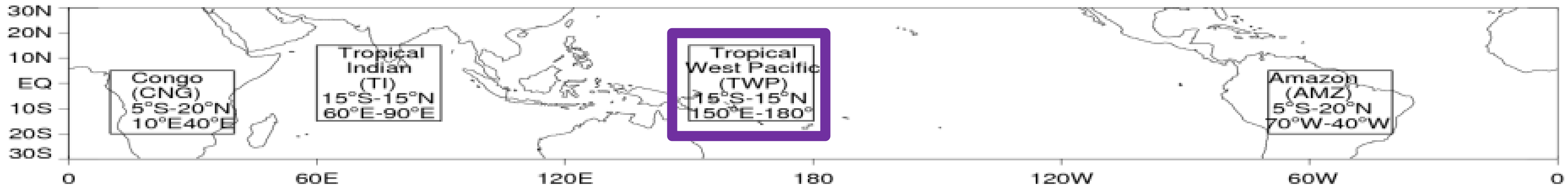
GEWEX integrated data-set (examples)

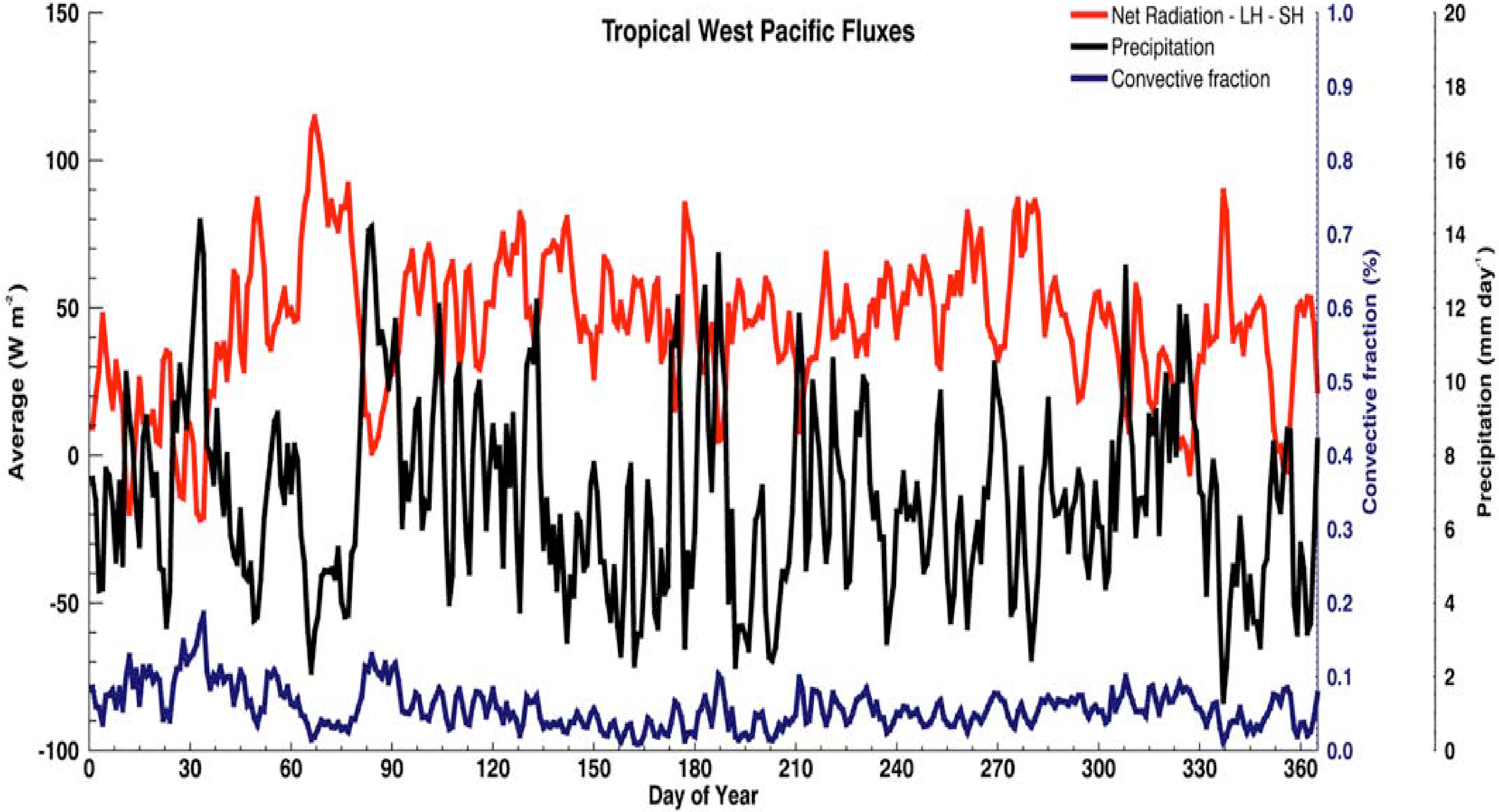
surface radiation budget analysis in 4 regions

- **Indian**
- **Pacific**
- **Congo**
- **Amazonas**

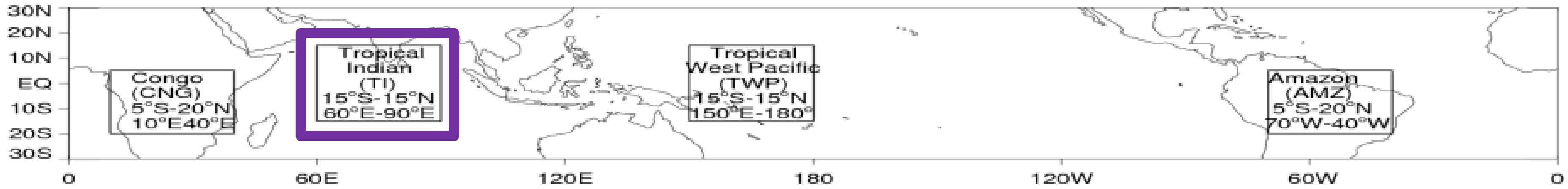
(still global 10W/m2 imbalance between ‘obs’ and modeling)

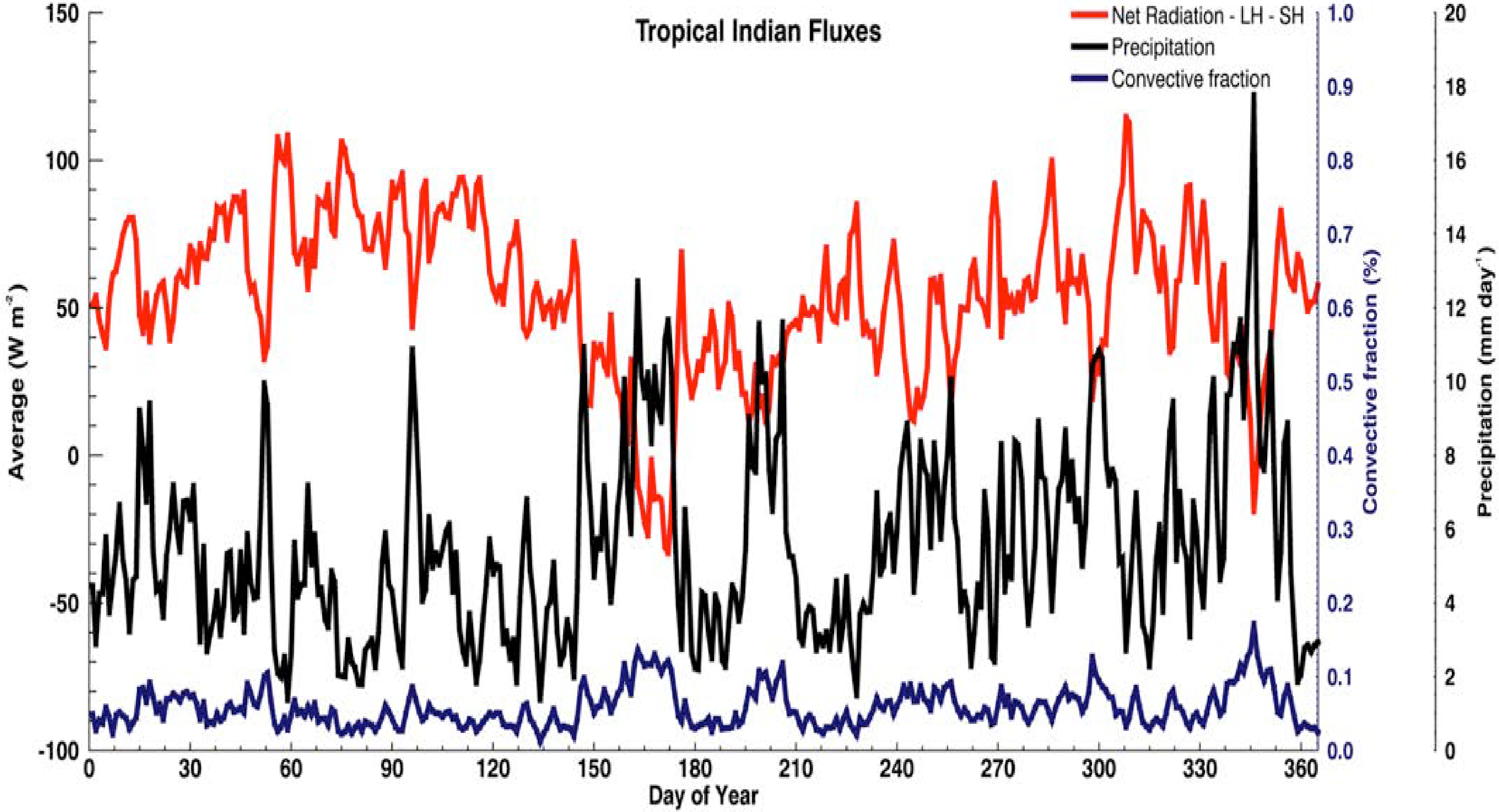
surface energy budget *(pacific ocean)*



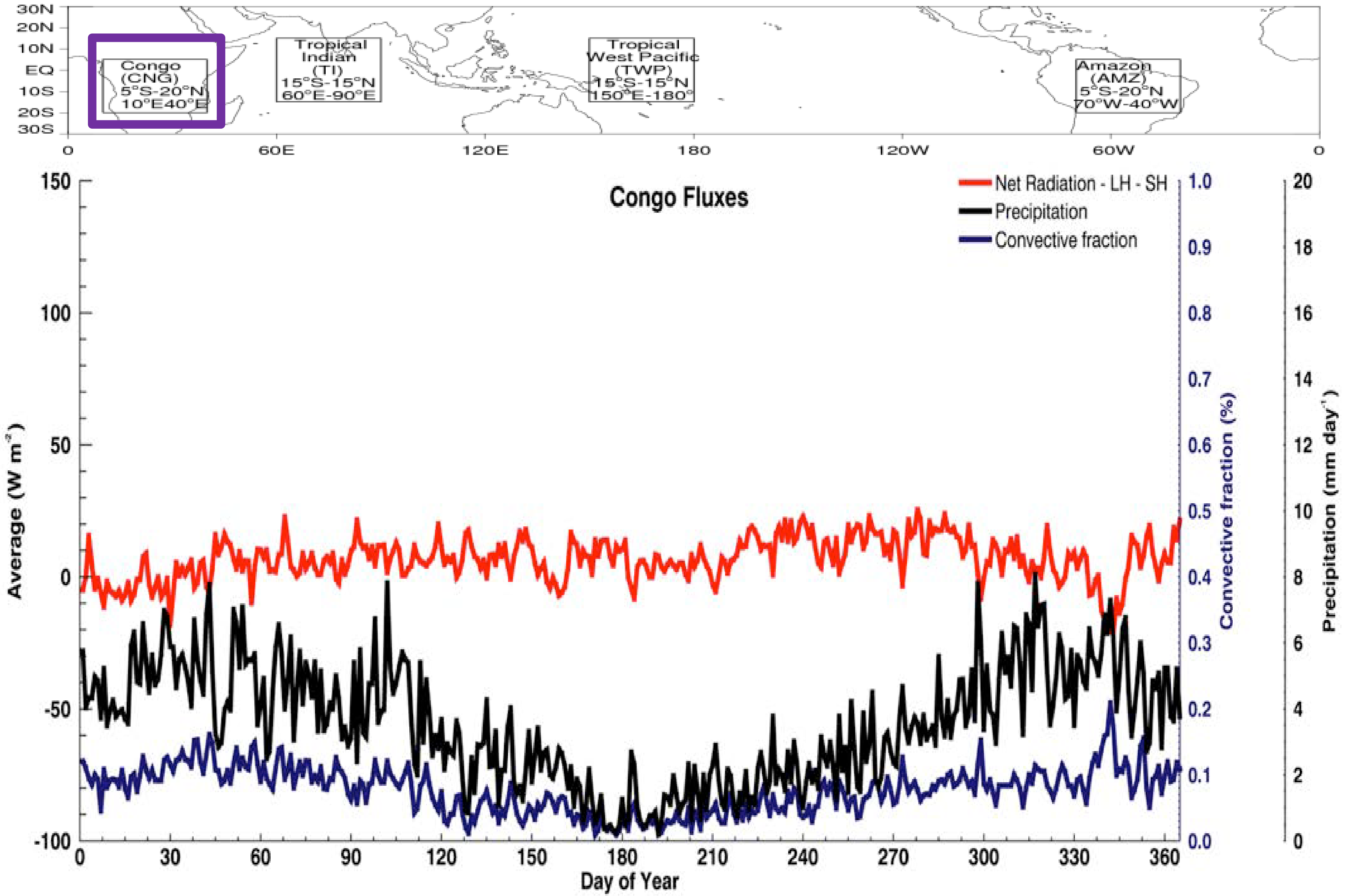


surface energy budget *(indian ocean)*





surface energy budget *(Congo region)*



surface energy budget *(Amazonas region)*