Cloud Radiative Effect Evaluation using CC4CL Broadband Flux Algorithm

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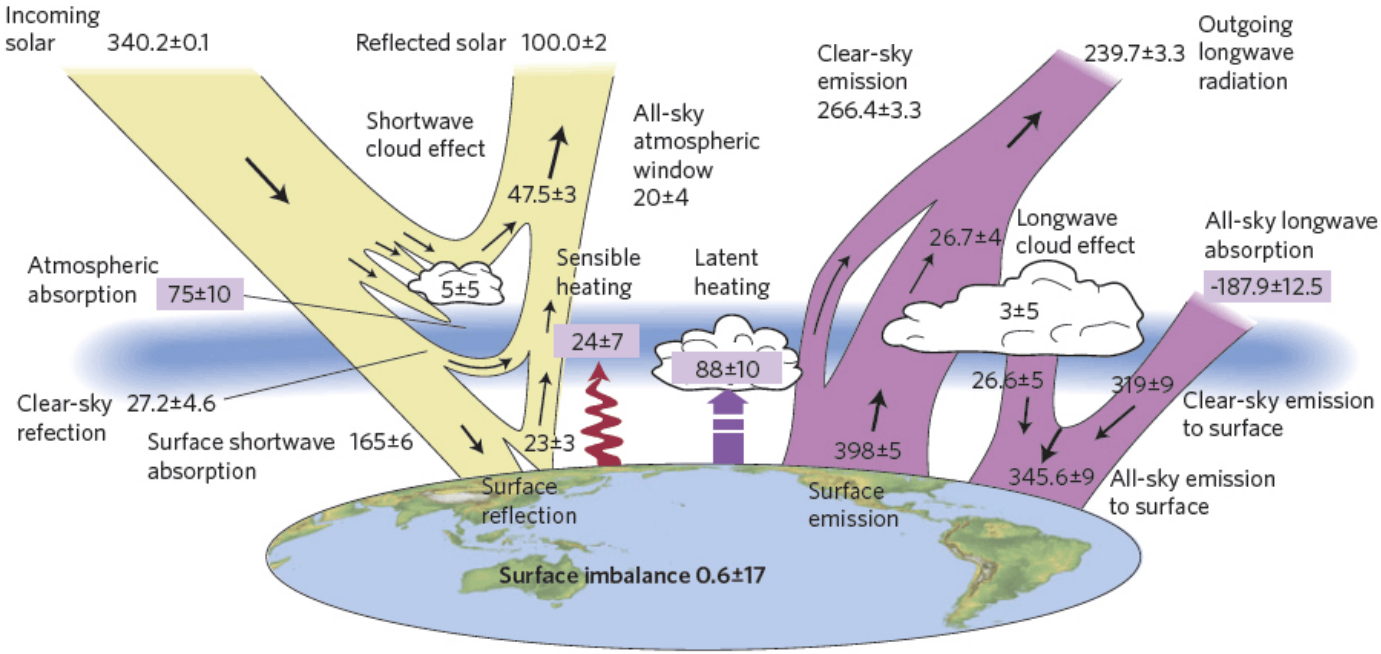
Global Radiation Budget

- Clouds globally cool the planet by –17 W m^{-2} (Loeb et al., 2009).
  - *cooling* in the shortwave is **-47.5 ± 3.0** W m^{-2}
  - *warming* in the longwave is **+26.7 ± 4.0** W m^{-2}
- Radiative impact from anthropogenic CO_2 since 1750 is **2.63 ± 0.26** W m^{-2}
- Uncertainties in the representation of clouds can have a considerable impact on the simulated climate.



Stephens et al. 2012, *Nat. GeoSci*.

CC4CL
(Community Code 4 CLimate)

- Algorithm used in the ESA CCI (Climate Change Initiative)

- **Aerosol-ORAC**
  - Optimal estimation algorithm
  - Similar forward model to cloud retrieval
  - Dual view algorithm
  - Visible channels only
  - NN cloud mask
  - 10km product
  - Thomas et al. 2010

- **Cloud-CC4CL**
  - Optimal estimation algorithm
  - Similar forward model to aerosol
  - Single view algorithm
  - Visible and IR
  - NN cloud mask
  - 1km retrievals
  - Poulsen et al 2012

http://proj.badc.rl.ac.uk/orac

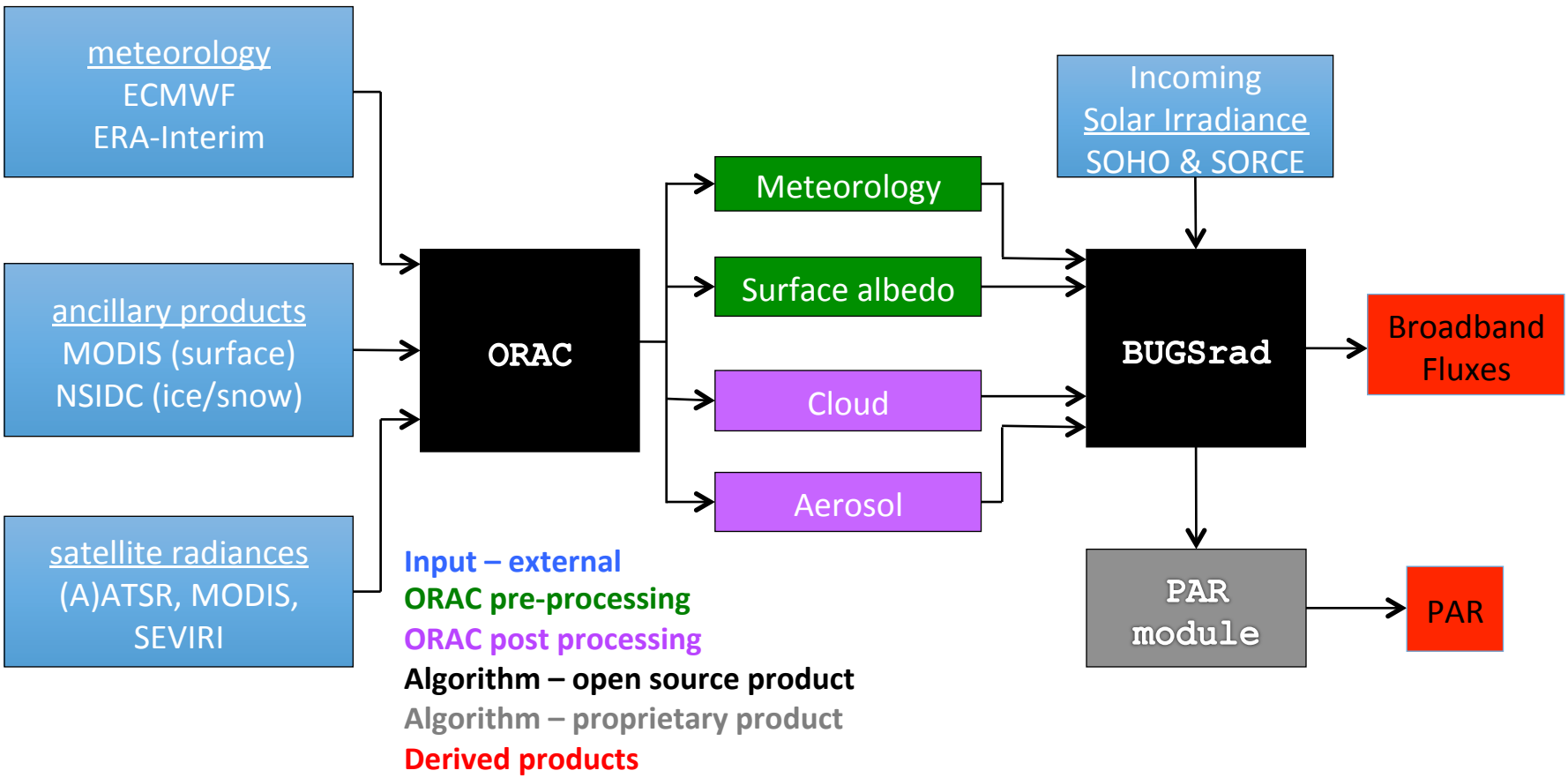
Retrieved Quantities

Variable	Aerosol CCI	Cloud CCI
Resolution	10km	1km
Time period	1995-2012	1995-2012
Aerosol Optical depth	x	
Aerosol effective radius	x	
Angstrom	x	
Cloud optical depth		x
Cloud effective radius		x
Cloud top height/pressure/ temperature		x
Cloud ice/water path		x
Cloud mask		x
Cloud phase and type		x
Cloud spectral albedo		x
Top and bottom longwave and shortwave radiative flux	x	x
Corrected cloud top height		x

Optimal Retrieval of Aerosol and Cloud (ORAC): Broadband Fluxes

ORAC is part of CC4CL (Community Code for CLimate) and applied to many satellite sensors.

- AVHRR, ATSR-2, AATSR, SEVIRI, & MODIS



Waveband	primary absorber
200 – 689 nm	O_3
689 – 1299 nm	H_2O
1299 – 1905 nm	H_2O
1299 – 2500 nm	H_2O
2500 – 3509 nm	H_2O
3509 – 4000 nm	H_2O

Longwave	
4.5 – 5.2 µm	H_2O
5.2 – 5.8 µm	H_2O
5.8 – 7.1 µm	H_2O
7.1 – 8.0 µm	H_2O, CH_4, N_2O
8.0 – 9.1 µm	H_2O, CH_4, N_2O
9.1 – 10.2 µm	O_3, H_2O
10.2 – 12.5 µm	H_2O
12.5 – 14.9 µm	H_2O, CO_2
14.9 – 18.5 µm	H_2O, CO_2
18.5 – 25 µm	H_2O
25 – 36 µm	H_2O
36 – ∞	H_2O

BUGSrad Radiative Flux Algorithm

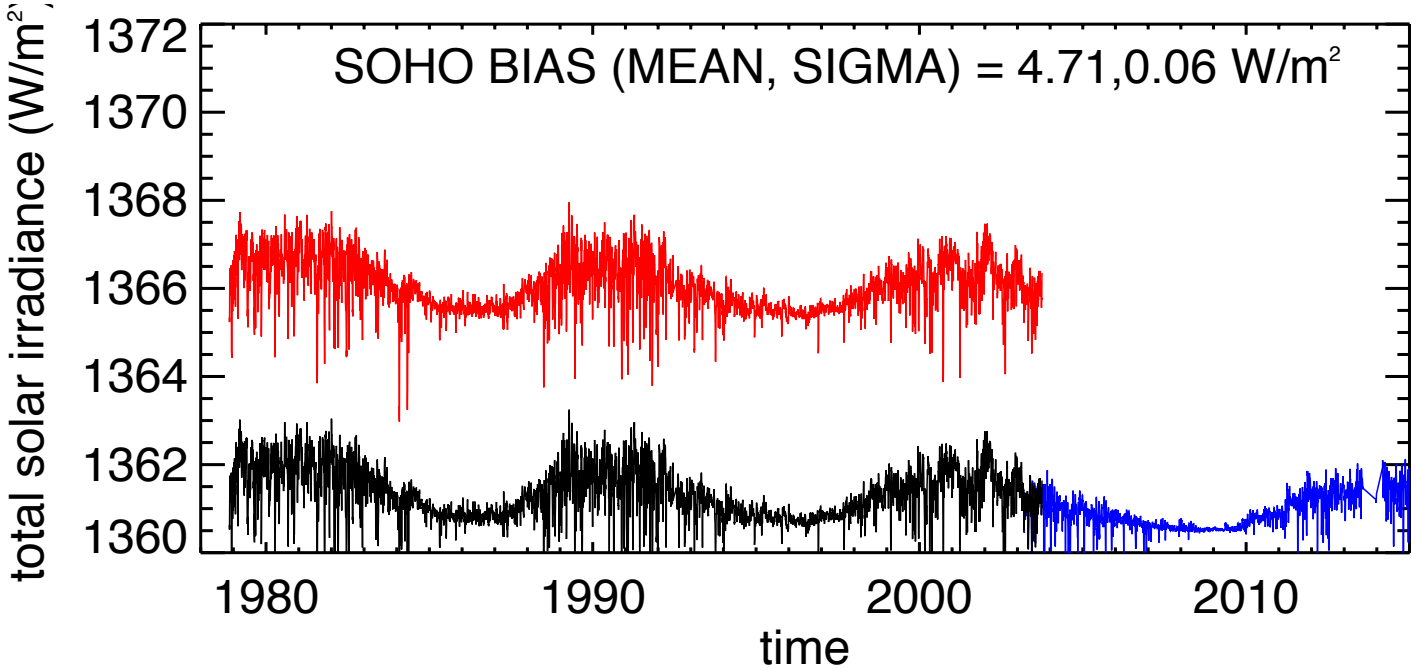
- Correlated-k distribution method.
  - based on Fu Liou (1992)
- Two-stream approximation.
- Plane-parallel cloud approximation.
- Developed for the Community Atmosphere Model (CAM) [Collens et al., 2004].
- Used to generate radiative fluxes and heating rate profiles using CloudSat observations.
- Excellent agreement between CloudSat/MODIS and CERES (Hendersen et al. 2013).
- Open source: http://biocycle.atmos.colostate.edu/shiny/BUGSrad/

Output

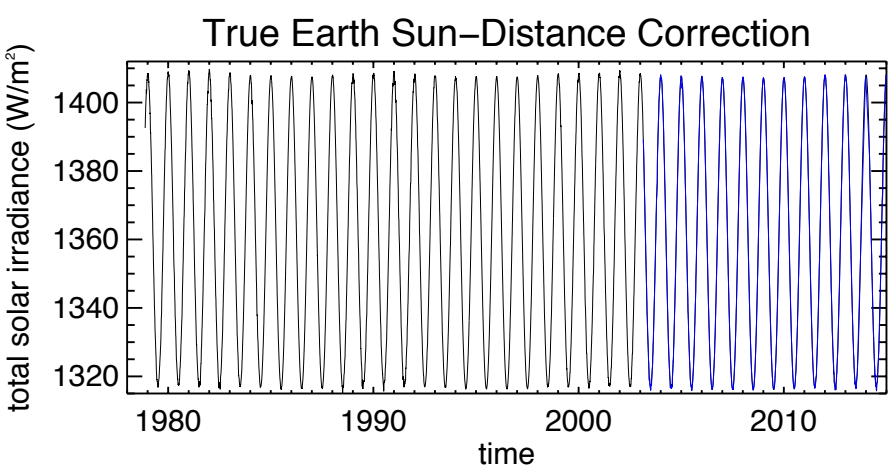
- **Top** and **bottom** of atmosphere longwave and shortwave fluxes.
  - Observed: With cloud and aerosol properties
  - CLEAR: Assuming no cloud and aerosol properties
- Diffuse and direct surface shortwave radiative fluxes
- Photosynthetic Active Radiation (PAR)

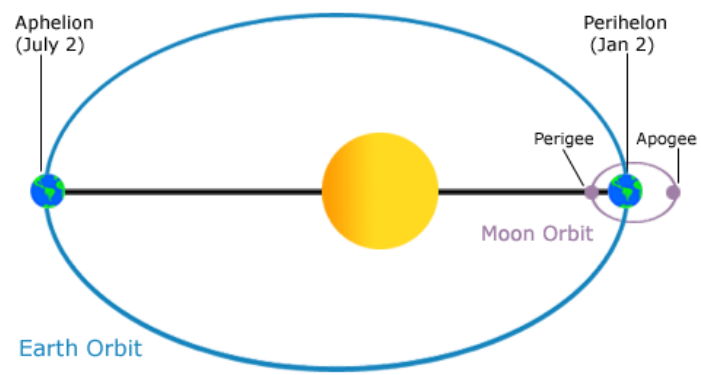
Fu-Liou model option is available for intercomparison. More accurate with more SW bands but 3 times slower.

Total Solar Irradiance



- SoHo and SORCE TSI observations are used to characterize top of atmosphere incoming shortwave radiative flux.
- Uncertainty estimates using this data 1361 ± 0.8 W/m² (Loeb et al. 2008).



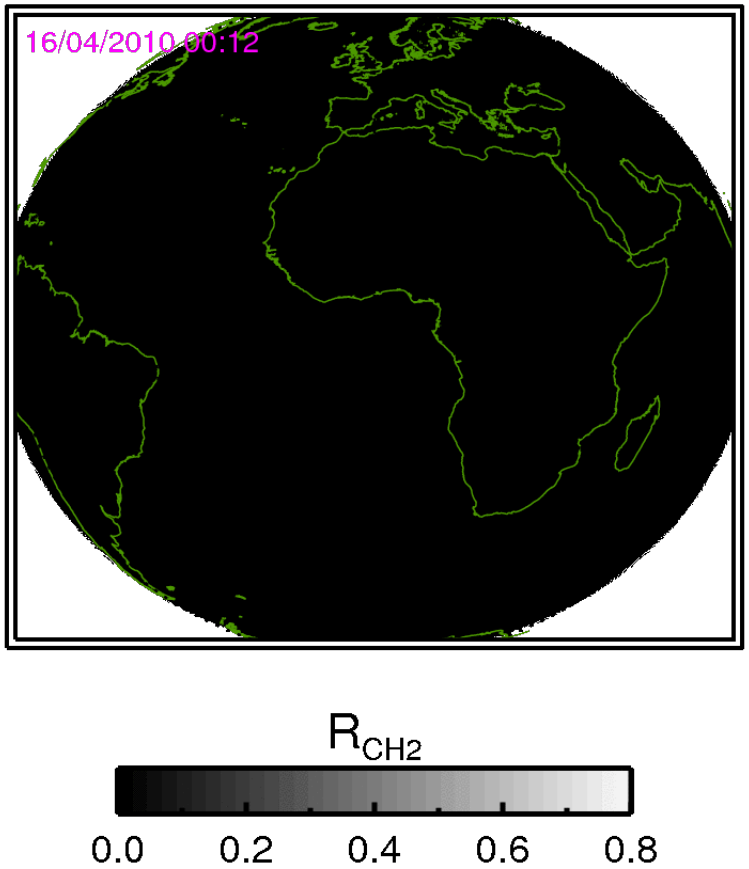


$$S_{fac}(t) = 1.0001 + 0.0334\cos(t) + 0.00128\sin(t) + 0.00071\cos(2t) + 0.000077\sin(2t)$$

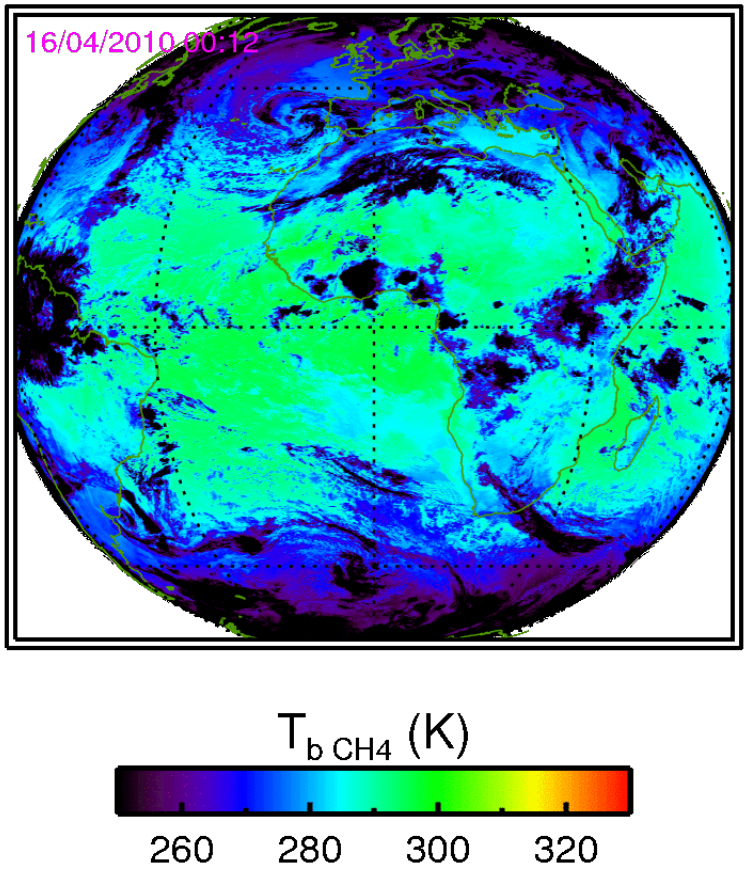
Image from NOAA

Application to SEVIRI Observations

0.55-µm Reflectance (ch 2)

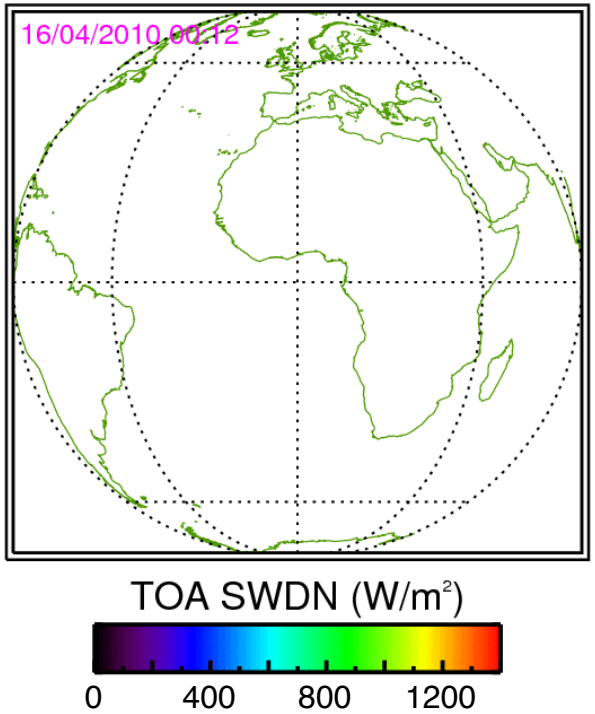


3.9-µm Brightness Temperature (ch 4)

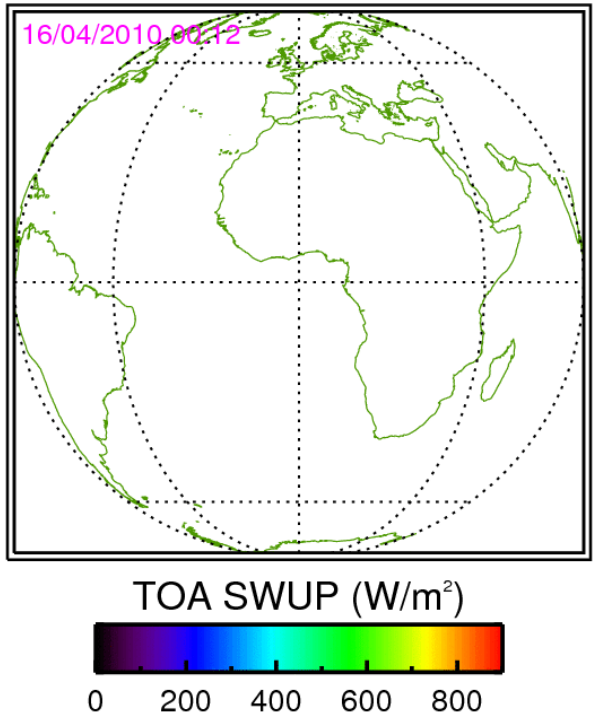


Application to SEVIRI Observations

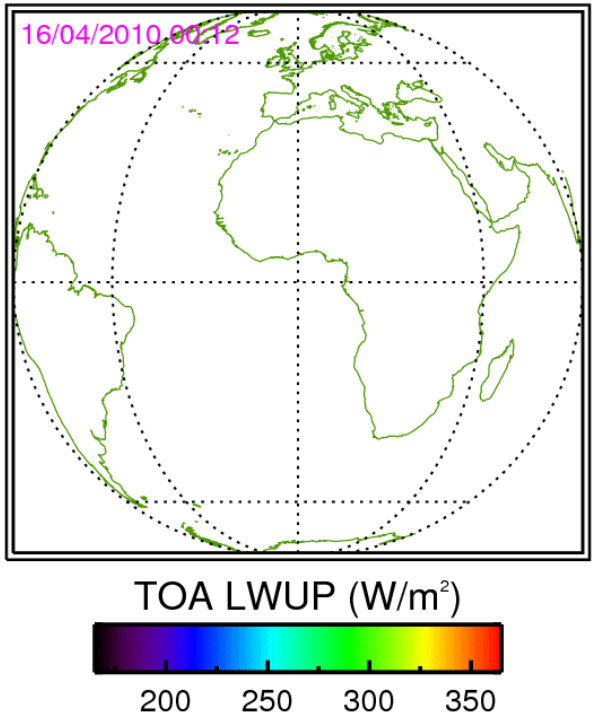
TOA incoming shortwave flux



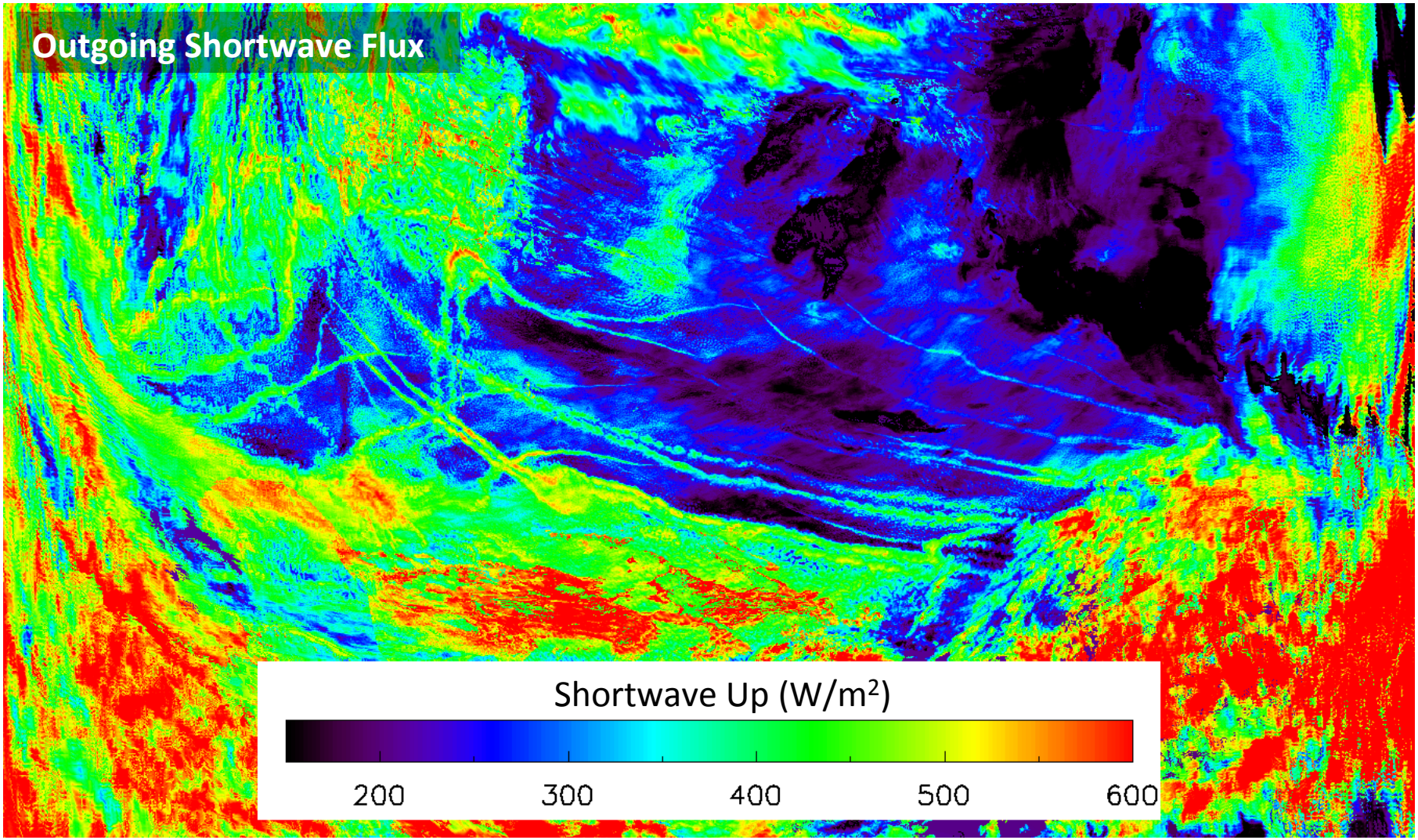
TOA outgoing shortwave flux



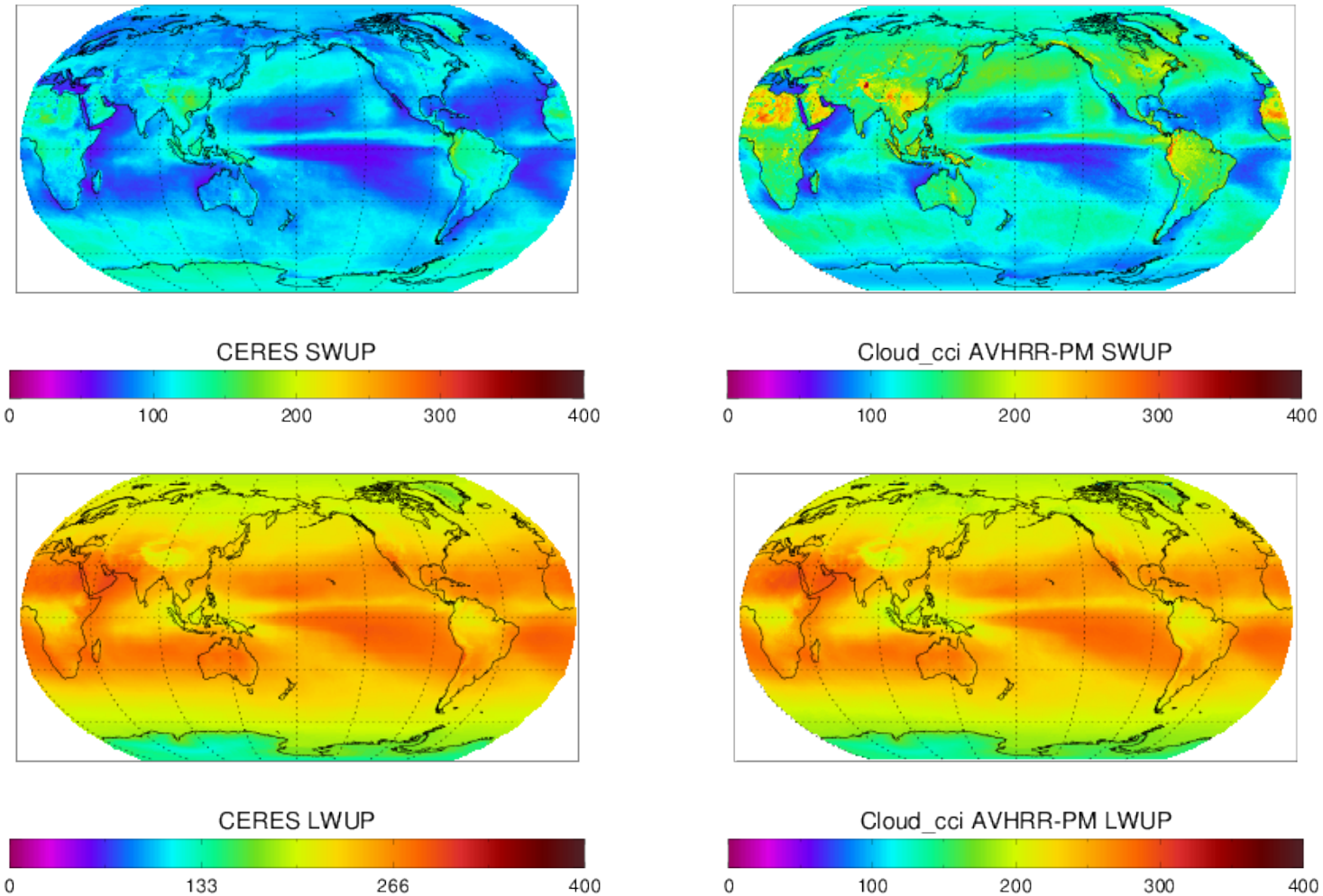
TOA outgoing longwave flux



Ship Tracks – ORAC applied to MODIS



Application to AVHRR Observations



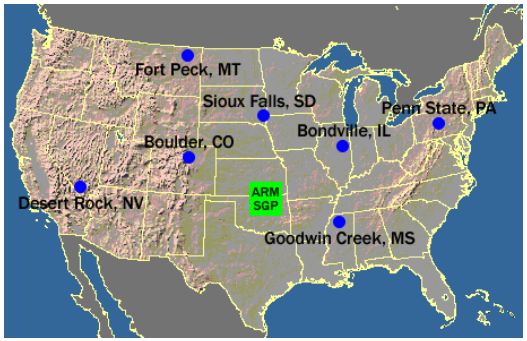
- CCI plans to process whole time-series 1982 – present.

Figures courtesy of Martin Stengle, DWD.

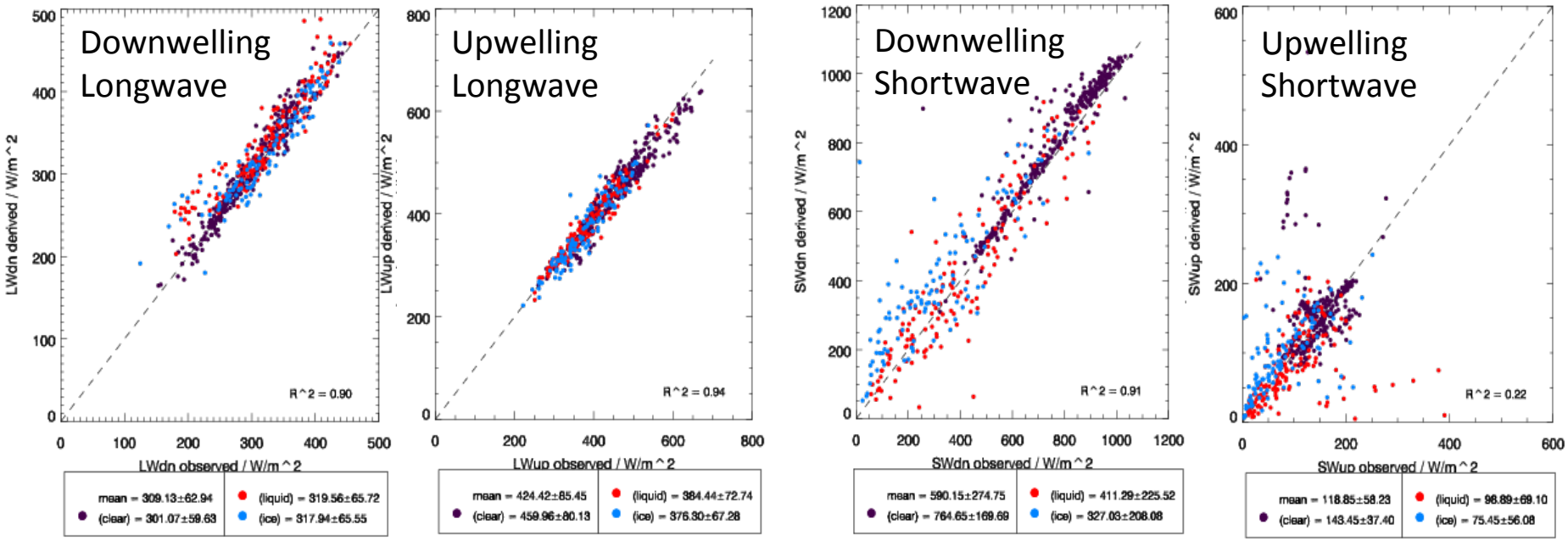
AVHRR annual mean: 2008

Ground-Based Validation

- Data: ORAC-MODIS & SURFRAD (ground sites)
- Period: 4-months (January, April, October) in 2008
- SURFRAD overpasses 727



Surface Fluxes – SURFRAD Validation



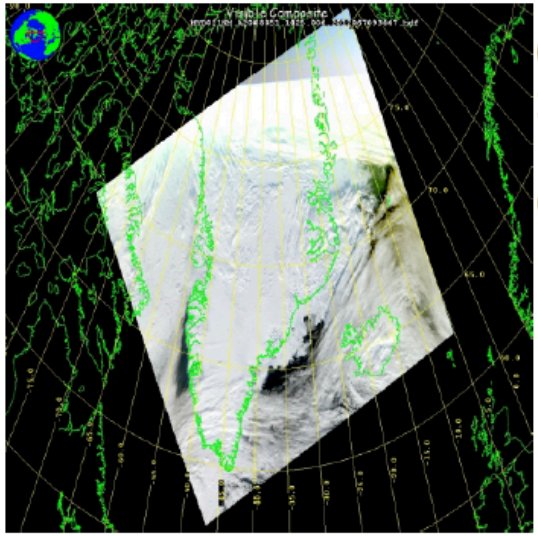
Relative biases

- Net Longwave ~ 1%
- Net Shortwave = 5%

CERES Comparison

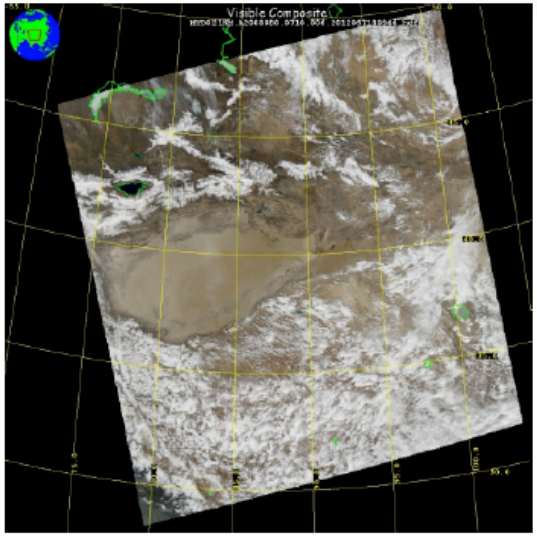
Test Scenes

Freie Universität Berlin



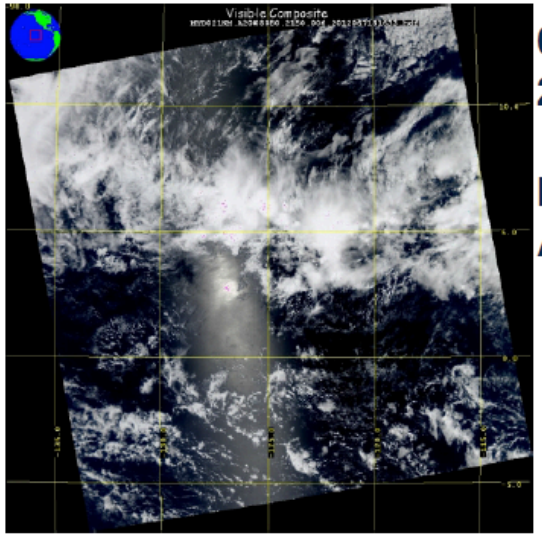
02/20/2008
14:25 UTC

Greenland



03/20/2008
07:10 UTC

Taklamakan desert



03/20/2008
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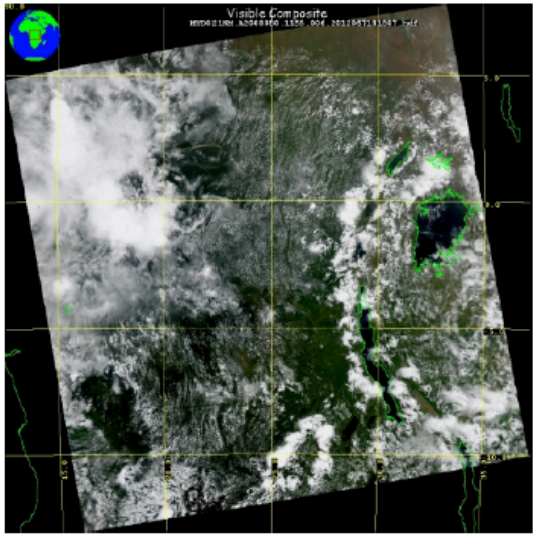
North Atlantic



02/20/2008
11:55 UTC

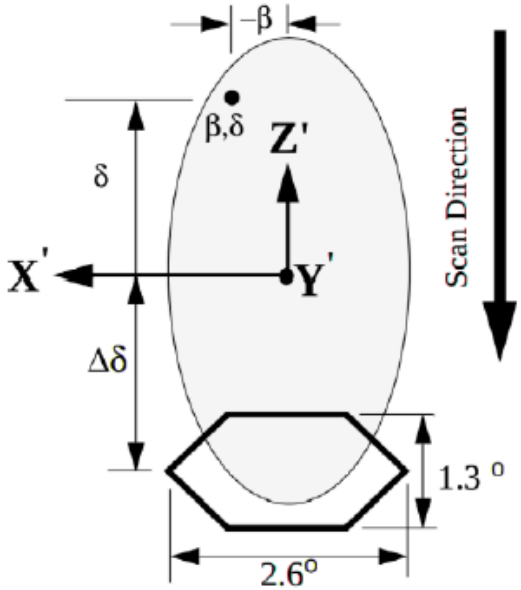
Central Africa

Slide courtesy of Sören Testorp, FUB.

Collocation

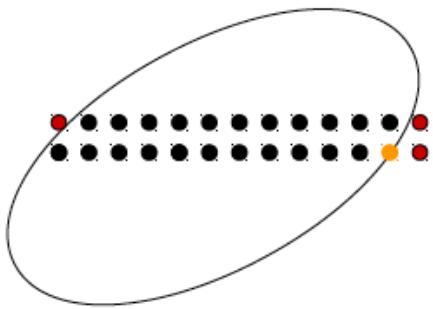
Freie Universität Berlin

CERES footprint

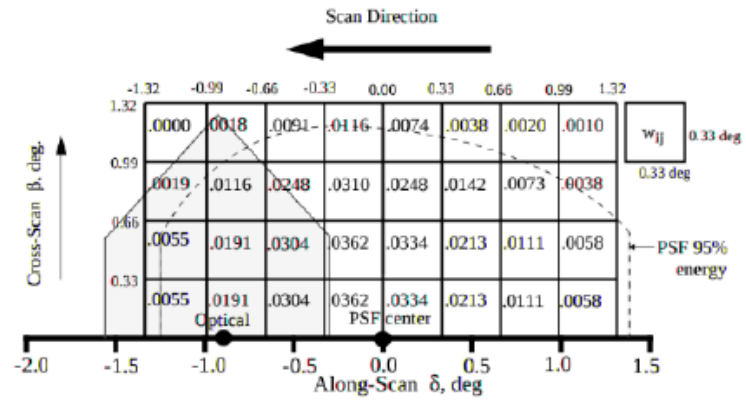


β – cross-scan angle
δ – along-scan angle

Collocation according to CERES: ATBD Subsystem 4.4 - Convolution



• – MODIS pixel



- Retrieve β_{img}, δ_{img} for each imager pixel
- Compare PSF: $P_{img} \geq PSF_{95\%}$
- Average imager pixel over footprint including PSF weights

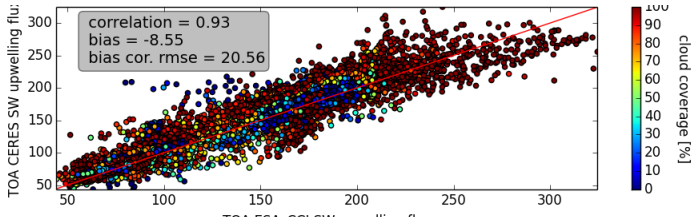
Slide courtesy of Sören Testorp, FUB.

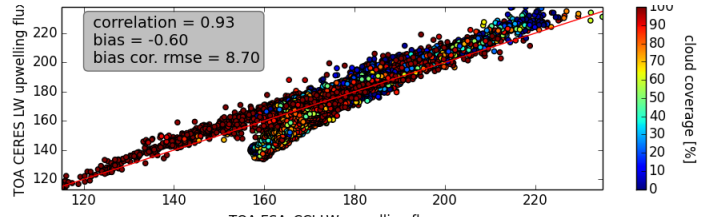
CERES Comparison

TOA Outgoing Shortwave

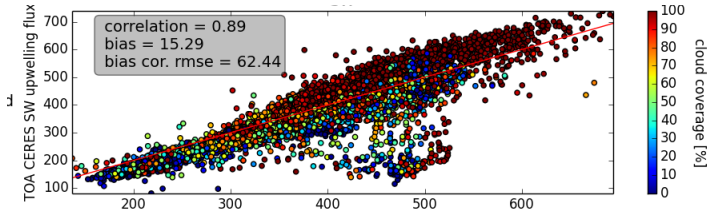
TOA Outgoing Longwave

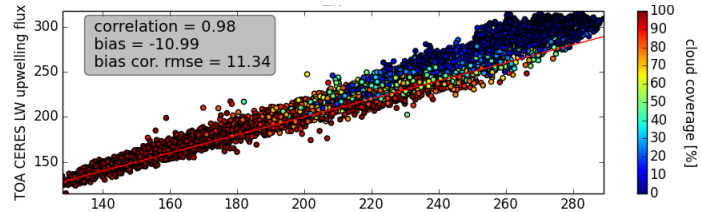
Greenland



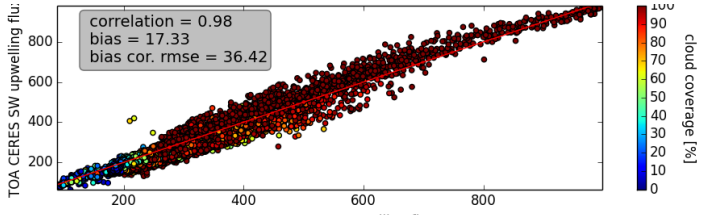


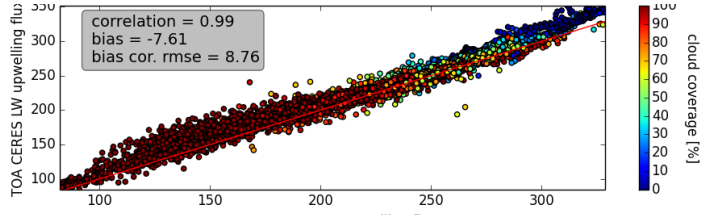
Taklamakan Desert



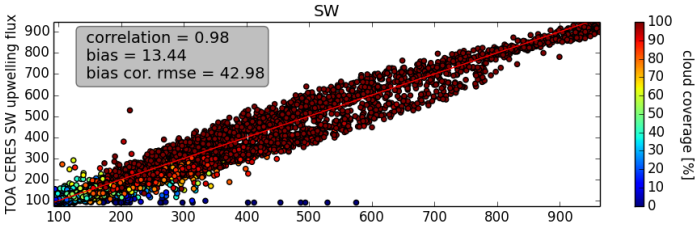


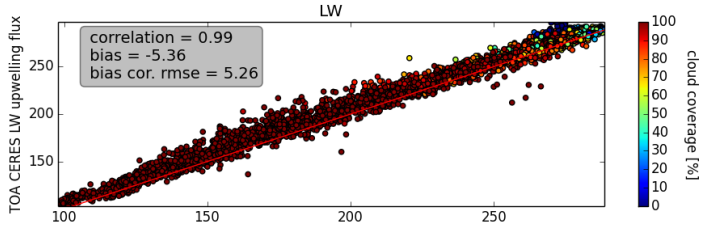
Central Africa





North Atlantic





ESA-ORAC TOA SW upwelling flux

ESA-ORAC TOA LW upwelling flux

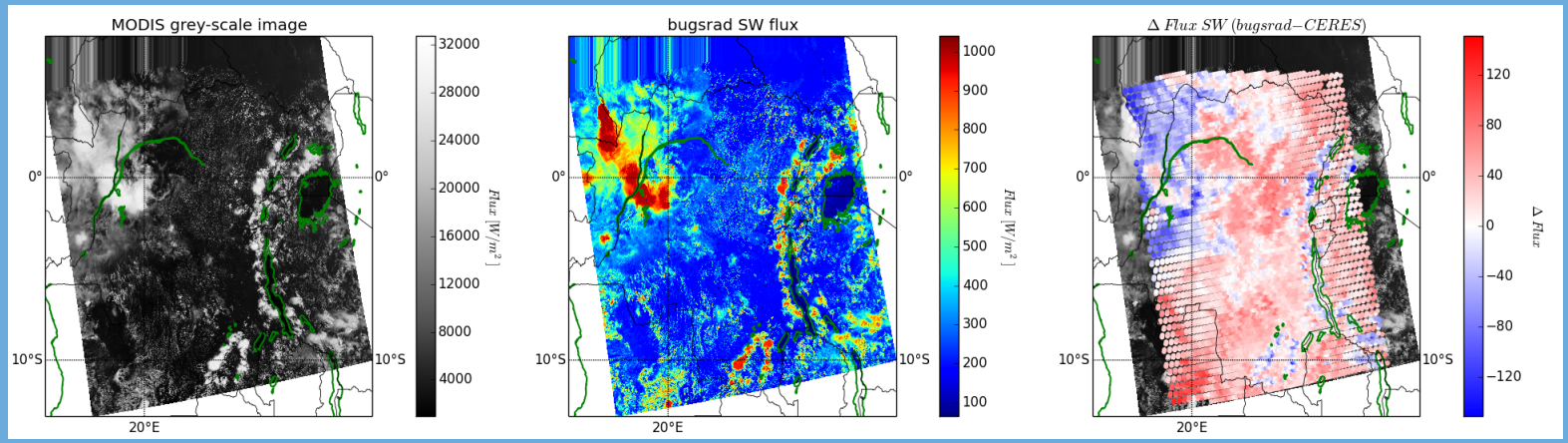
- Correlations are high and tend to be above 0.95.
- Still room to improve shortwave and longwave biases.

Figurescourtesy of Sören Testorp, FUB.

CERES Comparison

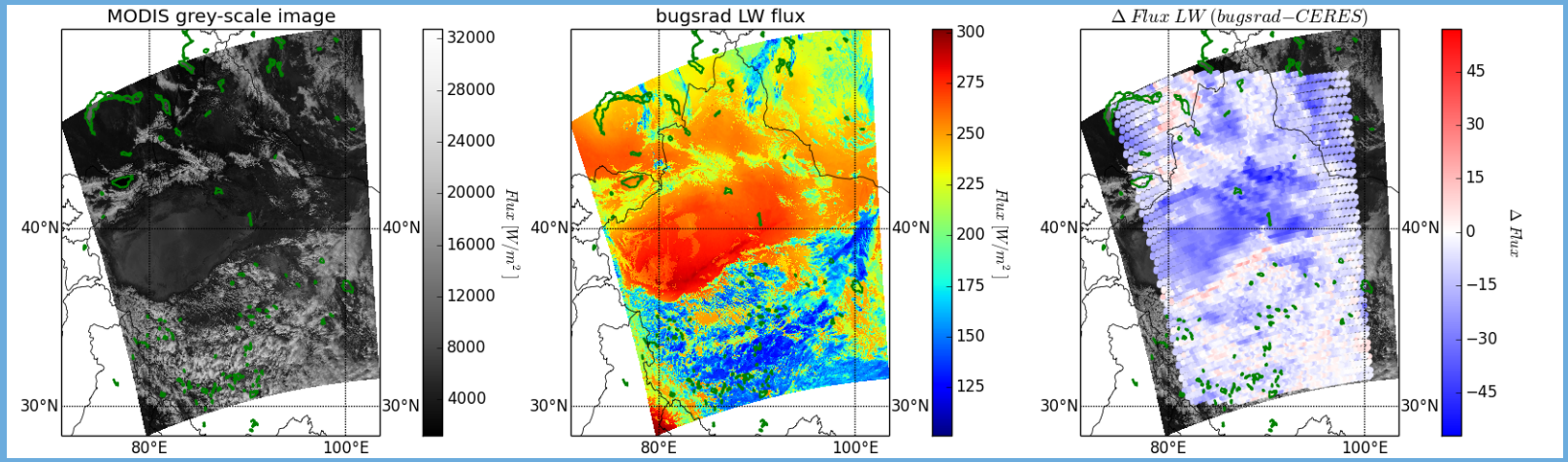
Central Africa

Short wave Fluxes



Taklamaken Desert

Long wave Fluxes

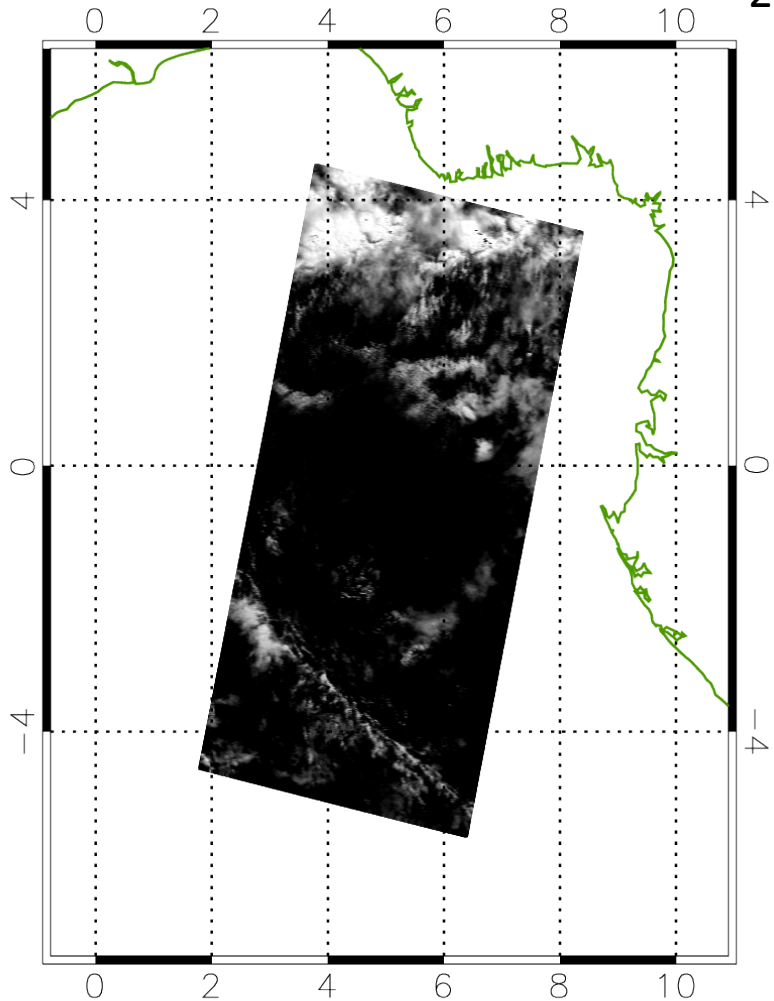


Areas of Improvement

- Negative shortwave bias retrieved for ice clouds. Test LUTs for Baum and Bauran.
- Negative longwave bias over clear-sky desert regions → use LST retrieval instead of ECMWF.

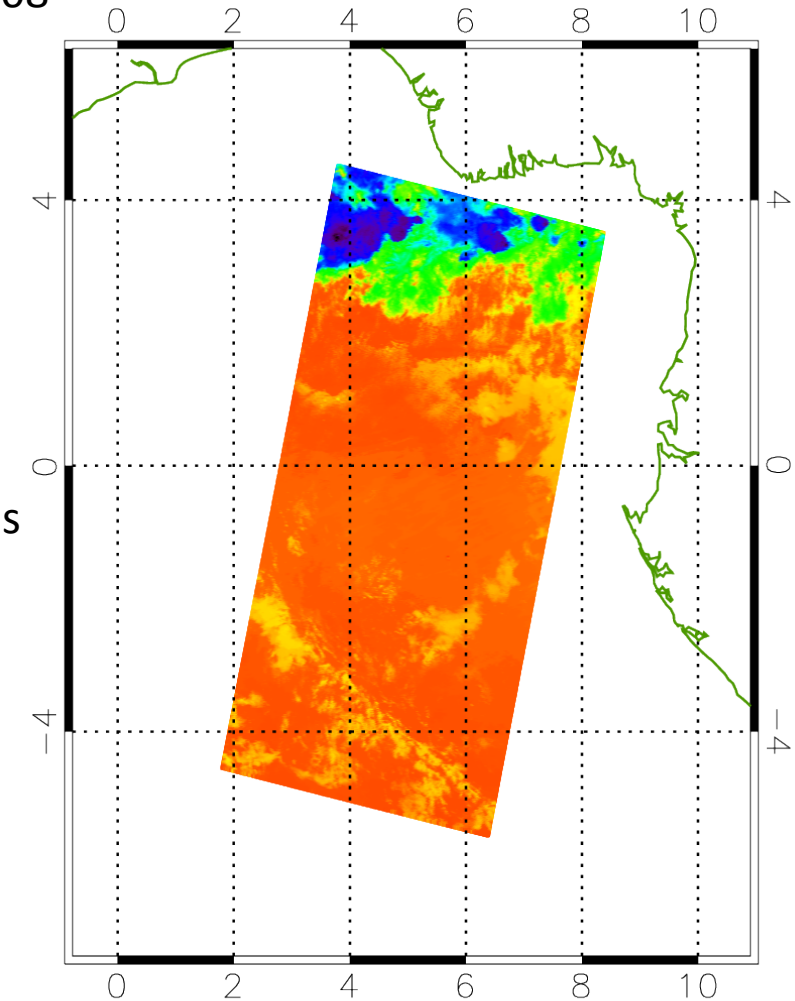
GERB Comparison

20th June 2008

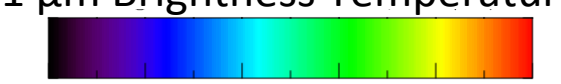


0.87 µm Reflectance

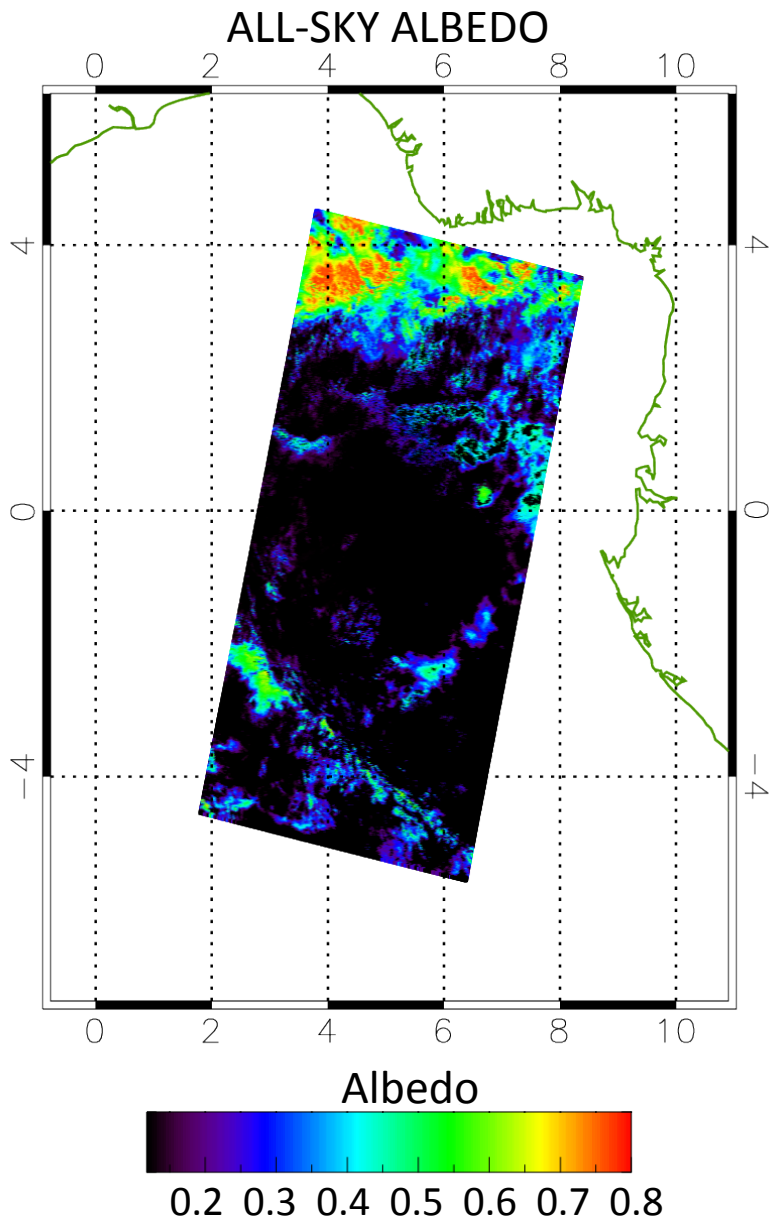
AATSR
1 km pixels



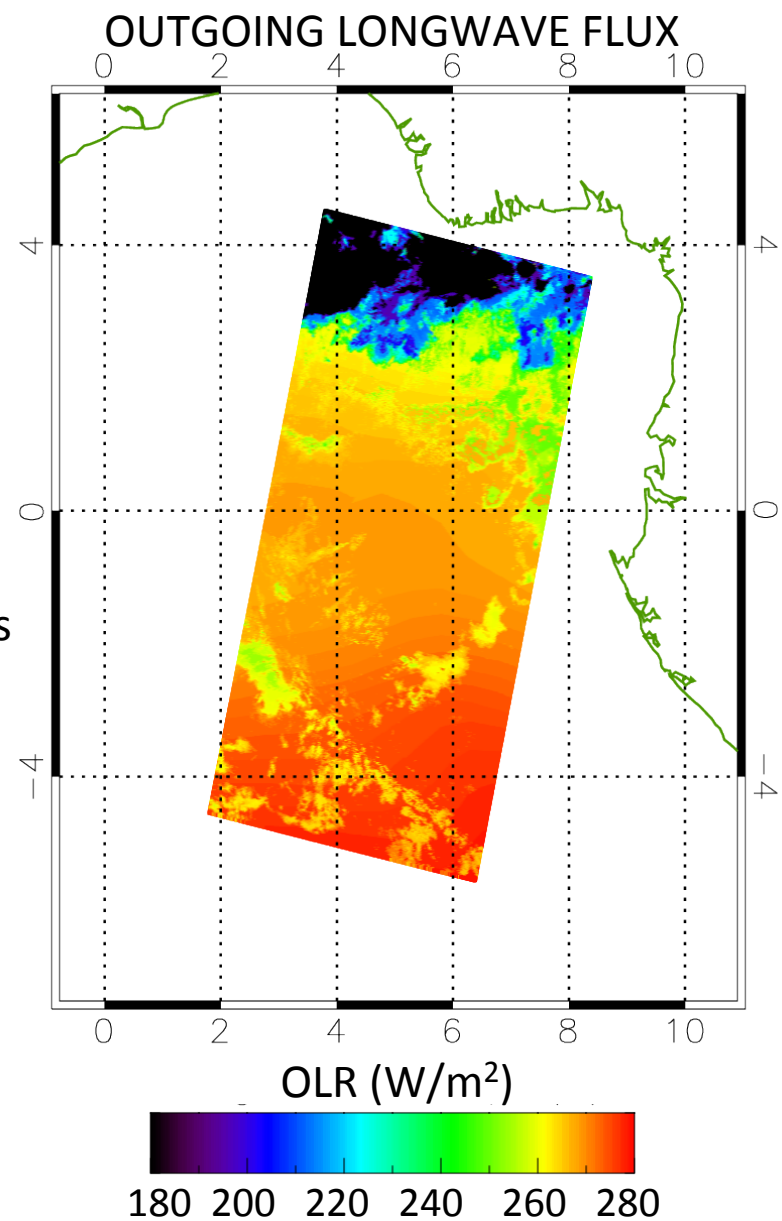
11 µm Brightness Temperature (K)



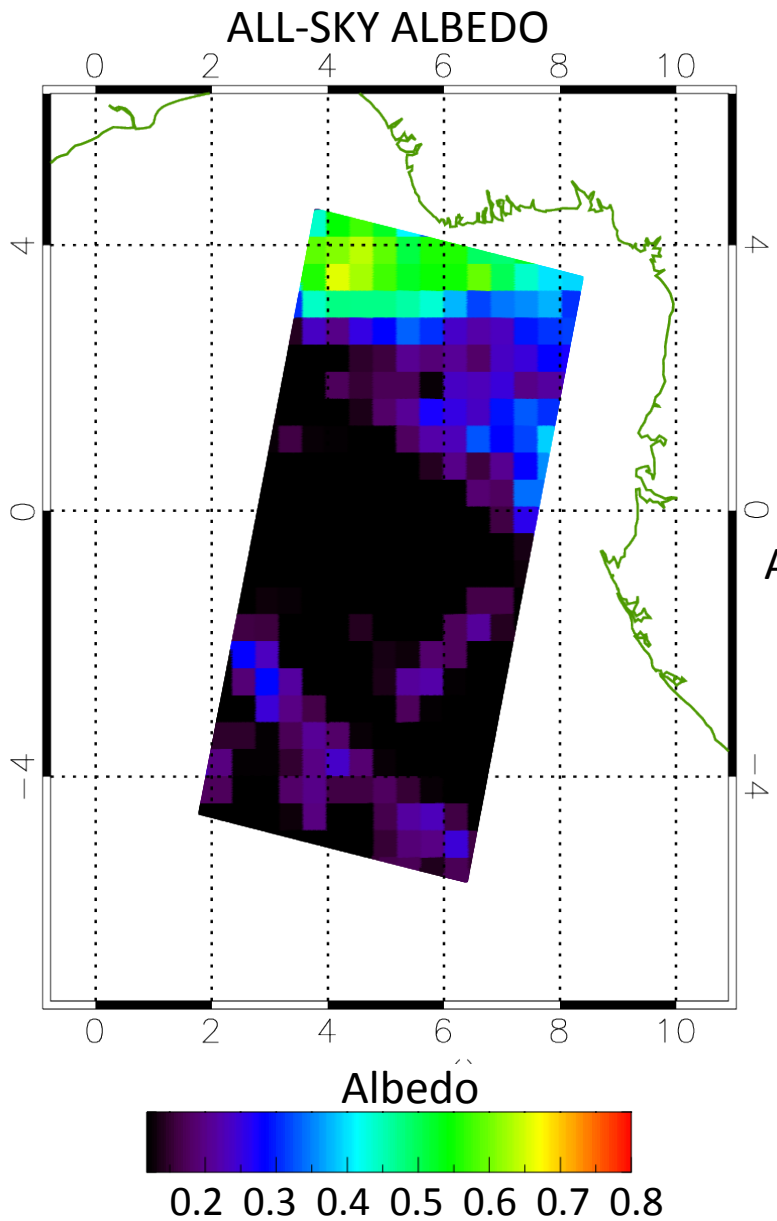
GERB Comparison



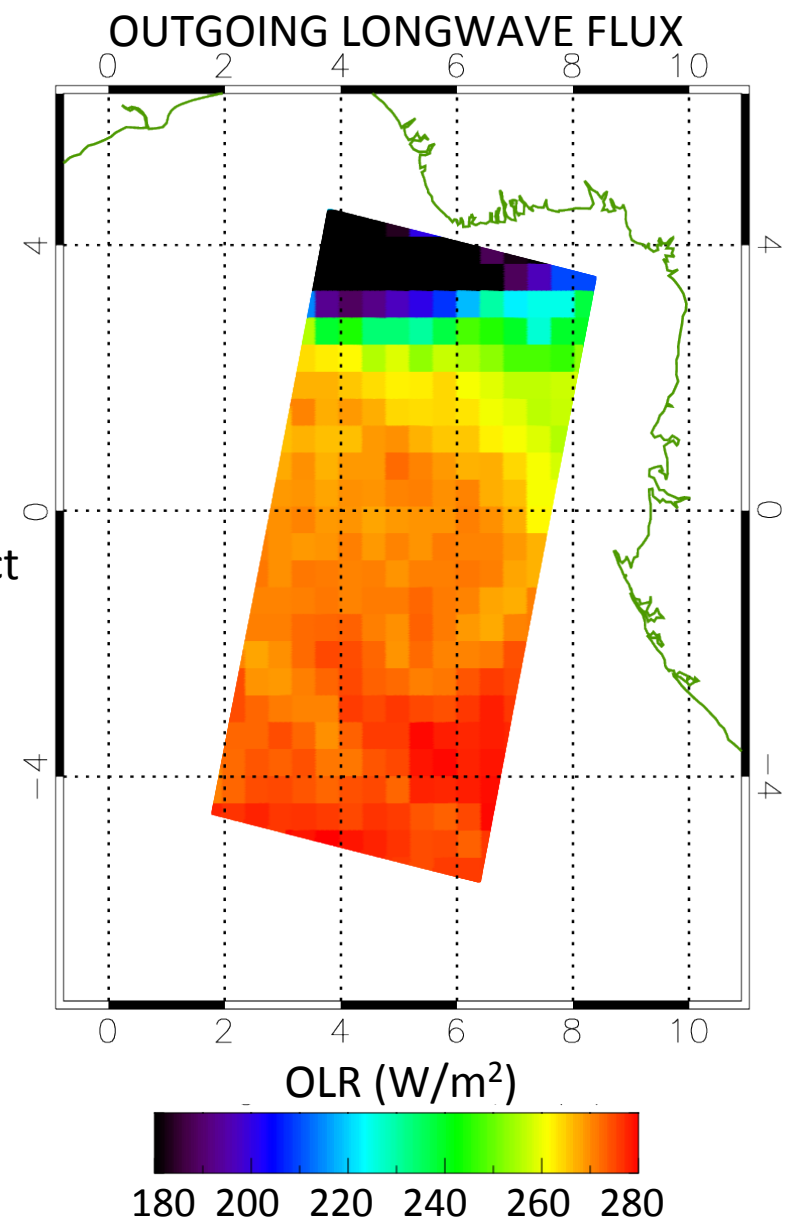
BUGSRAD
applied to
AATSR
1 km Pixels



GERB Comparison



GERB
ARG Product
44 x 39 km
Pixels



Cloud Radiative Effect

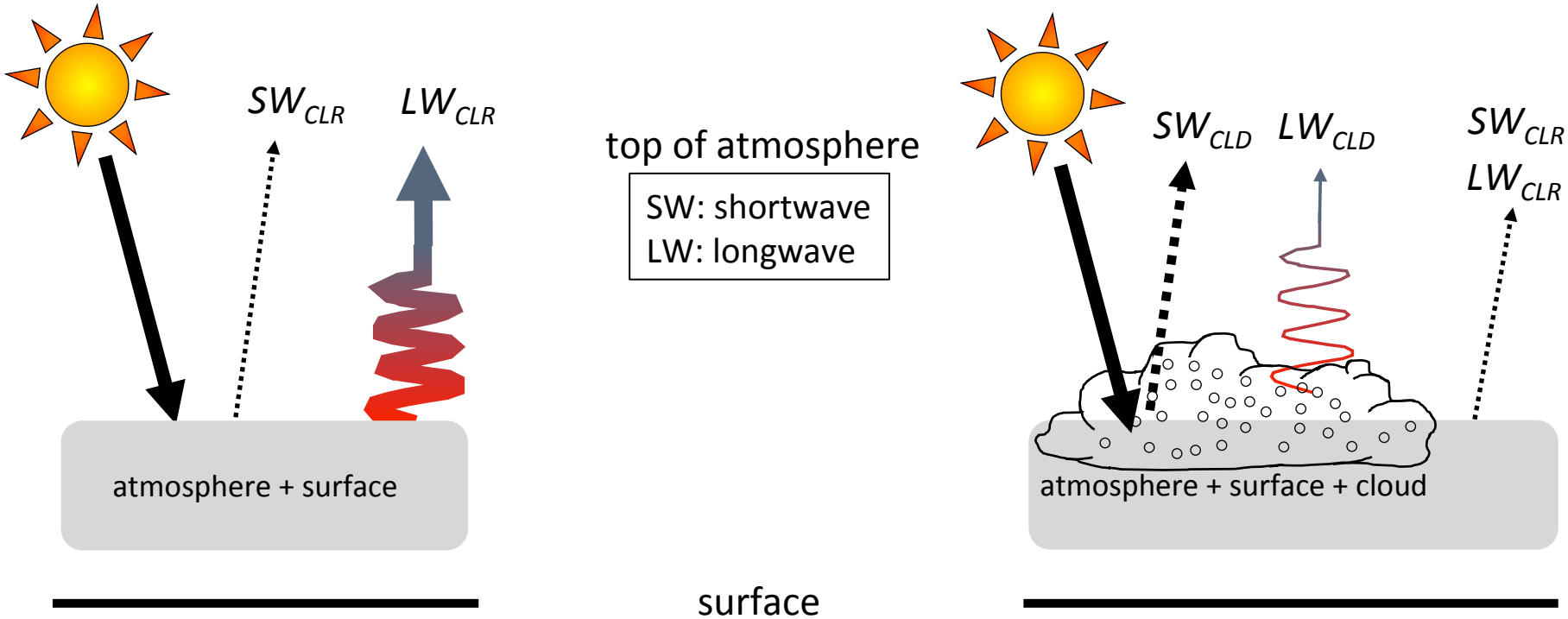
$CRE = F_{CLR} - F_{OBS}$ (1) Difference between clear-sky (F_{CLR}) and observed (F_{OBS}) flux.

$F_{OBS} = (1 - A_c)\, F_{CLR} + A_c F_{CLD}$ (2) Observed flux: decomposed into clear and cloud fluxes.

$\boldsymbol{CRE = A_c(F_{CLD} - F_{CLR})}$ (3) Combining (1) & (2)

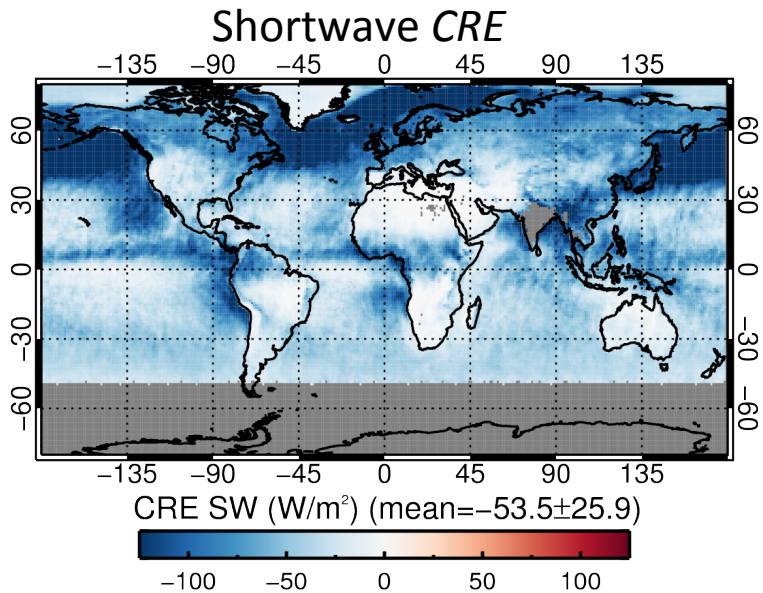
F_{CLR}: Flux *assuming no clouds*

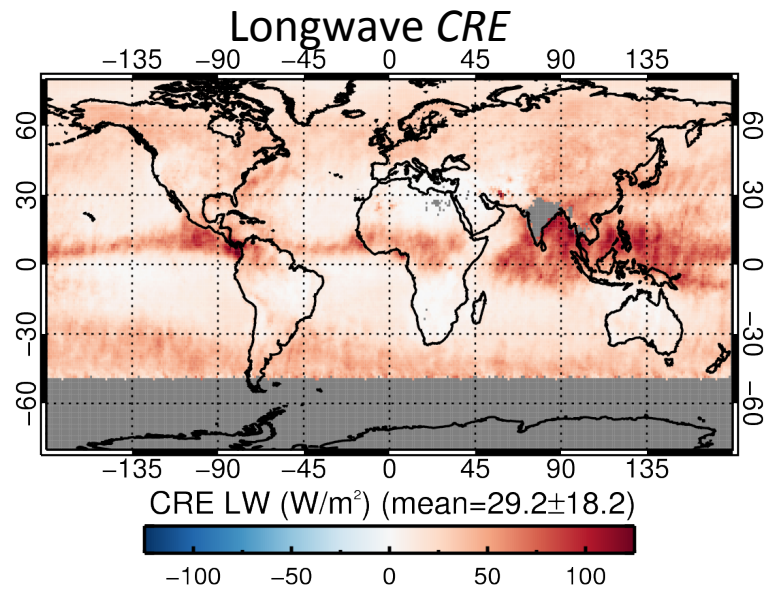
F_{OBS}: Observed flux (clear + cld)



CRE: Effect of clouds on the reflected solar and emitted flux relative to the clear-sky flux.

AATSR: Cloud Radiative Effect





NET = -24.7 ± 2.5 W/m²

In agreement with CERES (Loeb et al., 2009)

Instrument: AATSR
Spatial resolution: 1-km then aggregated onto a 1°×1° grid
Period: 10-Year July average for AATSR mission

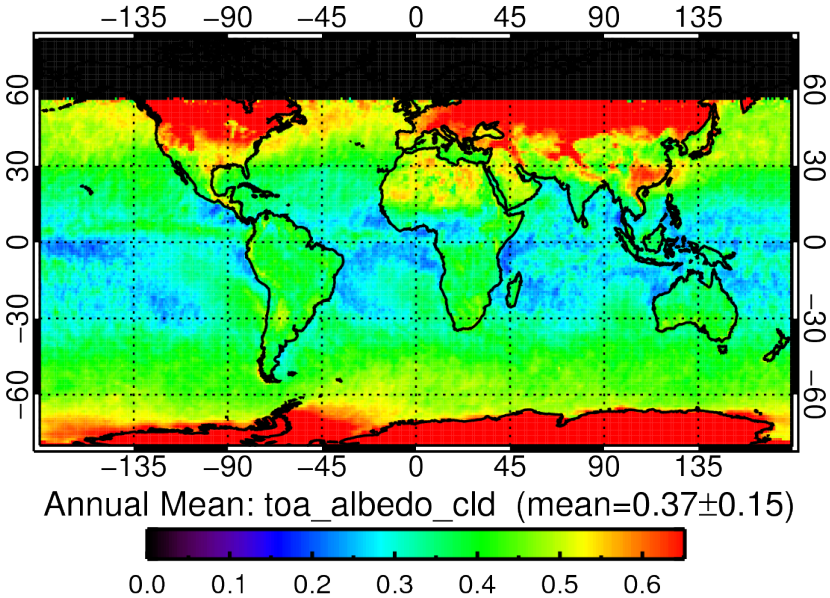
- Global mean values and standard deviations weighted by latitude are provided in brackets.
- *Instantaneous value* for shortwave *CRE* is converted to temporally interpolated fluxes based on monthly mean solar insolation (method described in Coakley et al., 1979, *JAS*, **36**).

Top of Atmosphere All-Sky Albedo

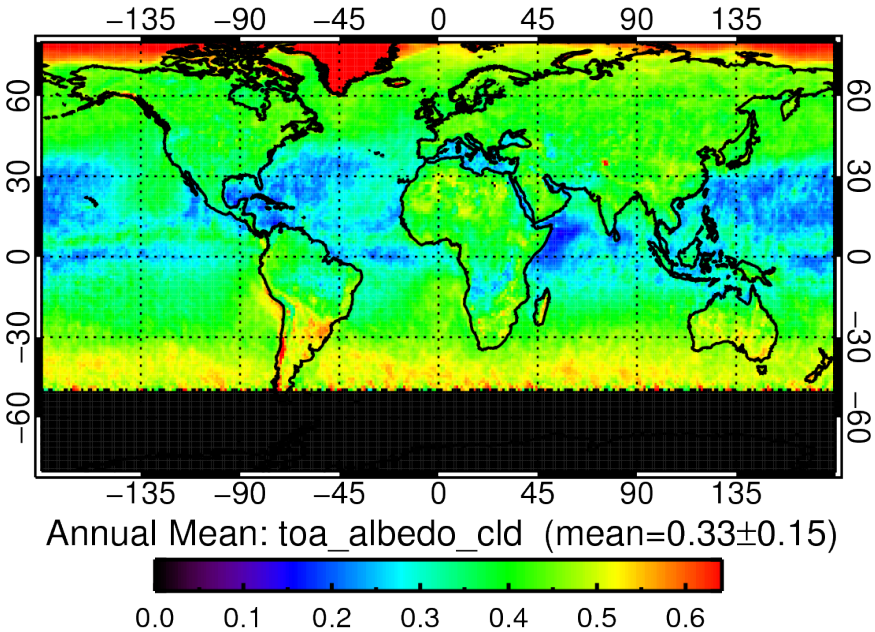
AATSR: 2002 – 2012 Monthly L3 Data

<u>Top of atmosphere all-sky albedo</u>

January long-term Mean



July long-term Mean



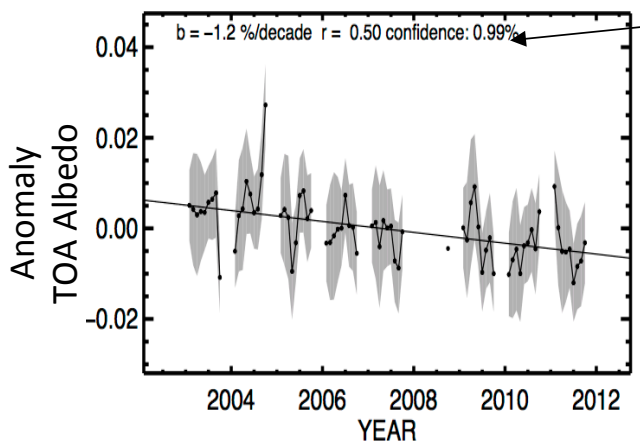
<u>Features</u>

- Sea Ice and Snow changes over Arctic, Antarctica, and Canada & Eurasia.
- Clouds: midlatitude storm tracks, ITCZ, and subtropical stratocumulus.

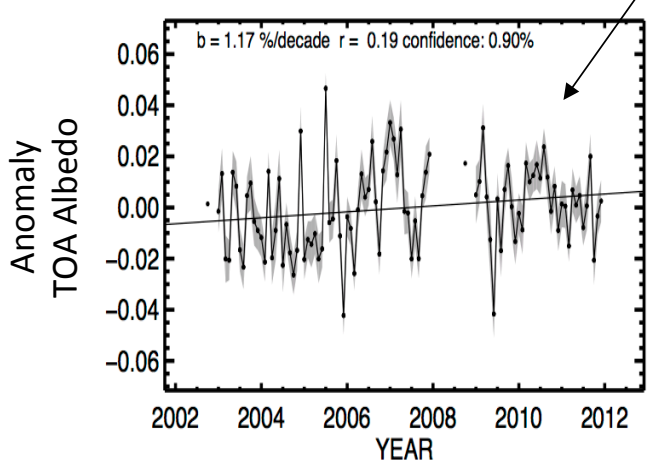
Trend: TOA All-Sky **Reflected Solar Flux**

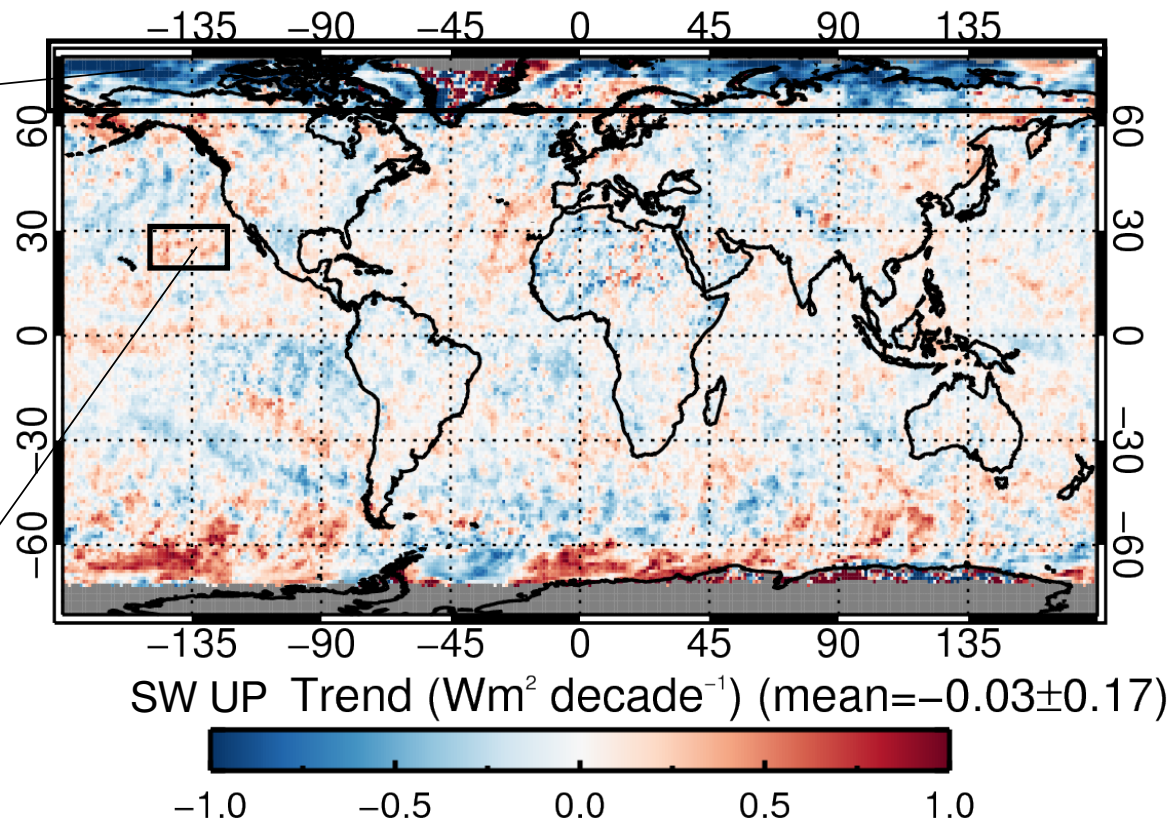
AATSR: 2002 – 2012

Arctic sea ice loss



marine cloud brightening





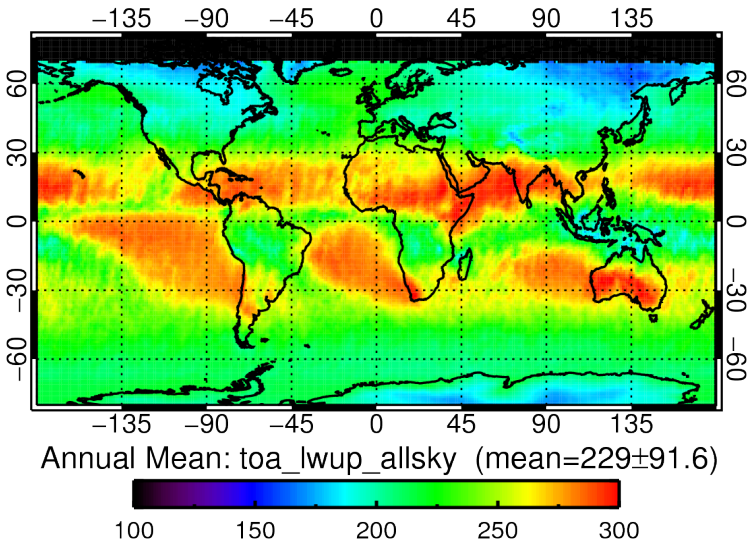
- Trends are consistent with CERES observations documented in (Hartmann and Ceppi, 2014, AMS)

Top of Atmosphere Emitted Longwave Flux

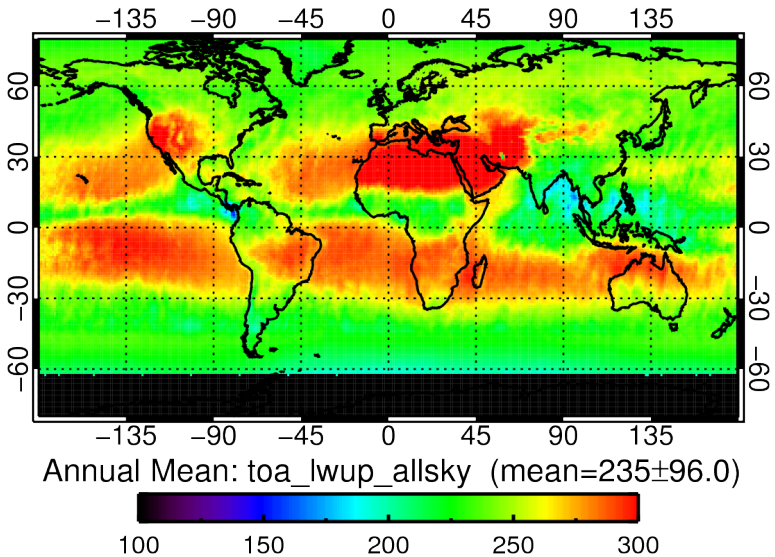
AATSR: 2002 – 2012 Monthly L3 Data

<u>Top of atmosphere longwave emission</u>

January long-term Mean



July long-term Mean

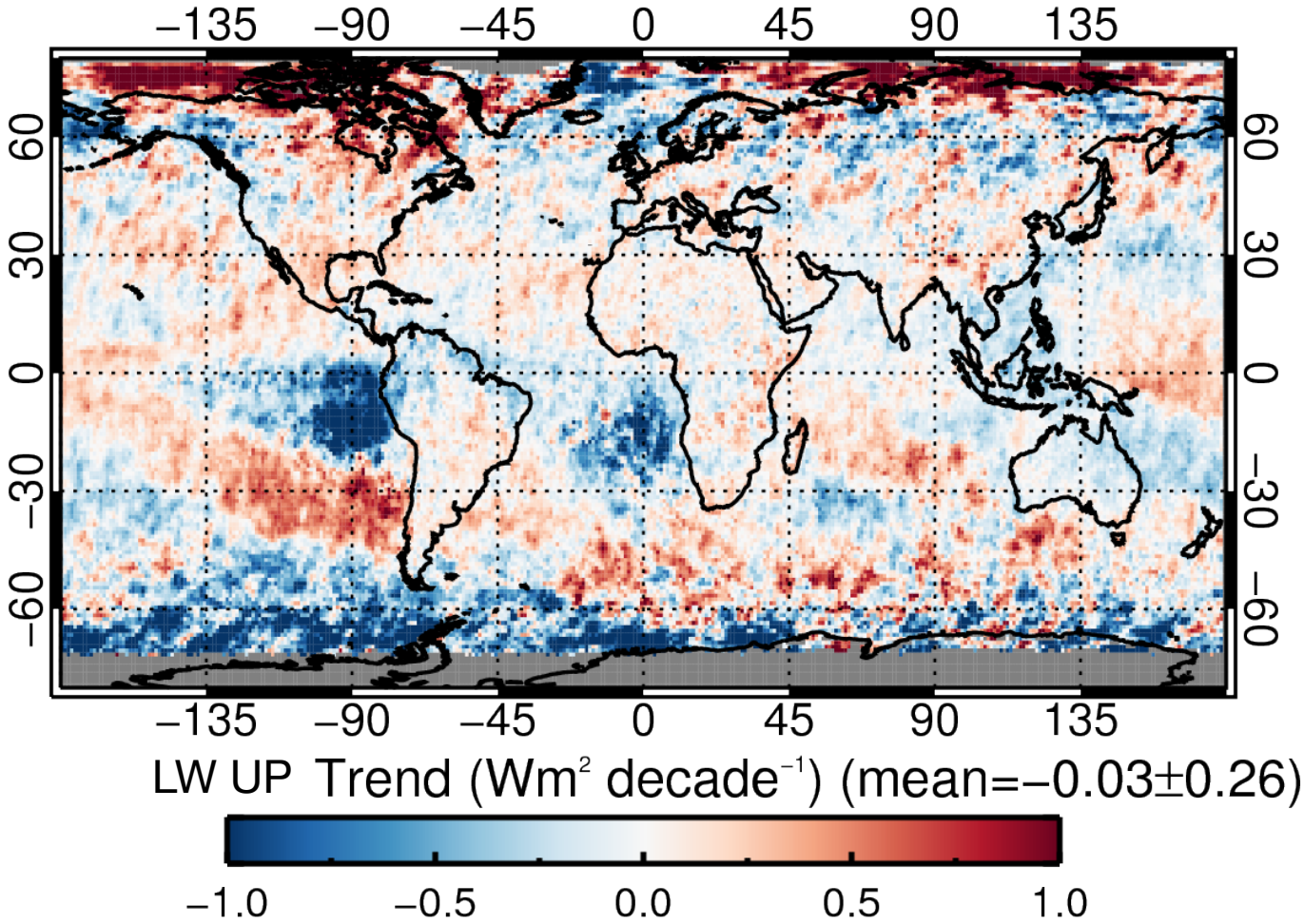


<u>Features</u>

- Large OLR over Subtropics and warm land areas (e.g., Saharan Desert)
- Clear northward shift in N.H. OLR between winter and summer.

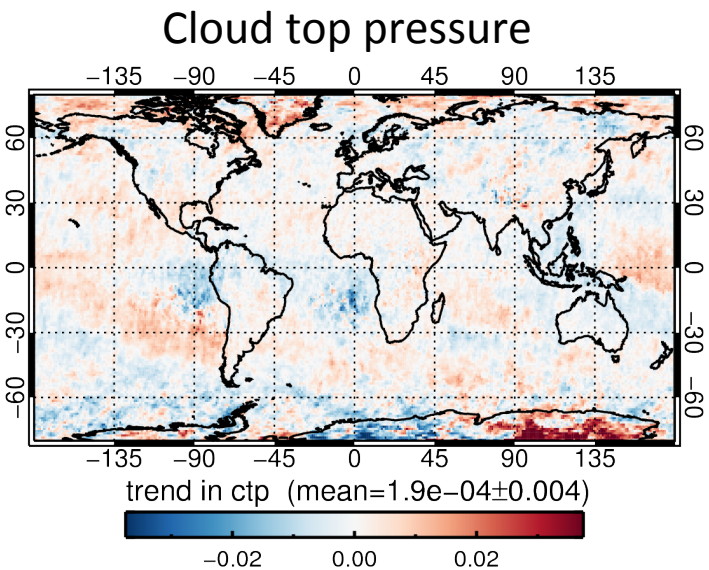
Trend: TOA All-Sky **Emitted Longwave Flux**

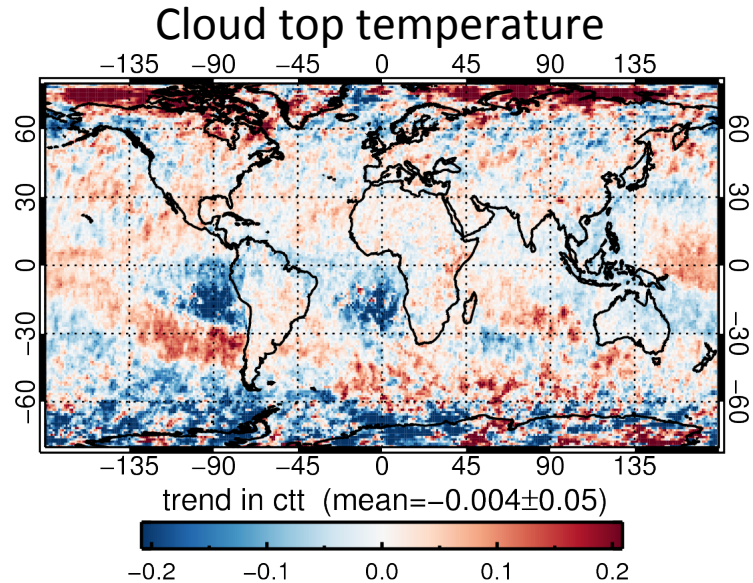
AATSR: 2002 – 2012 Monthly L3 Data

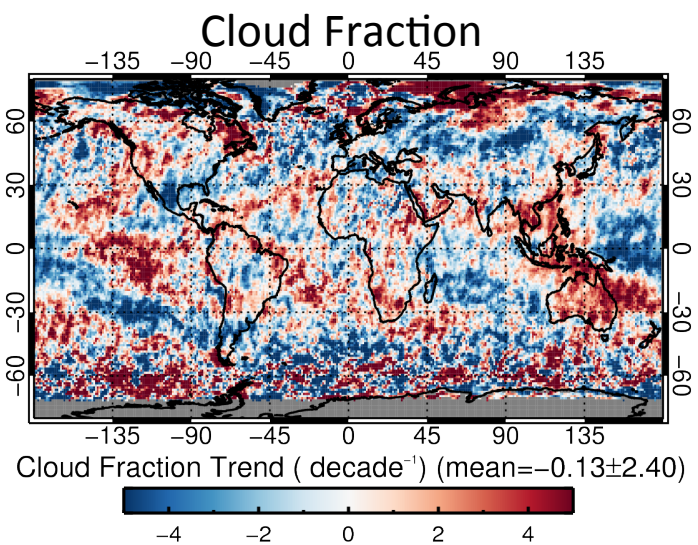


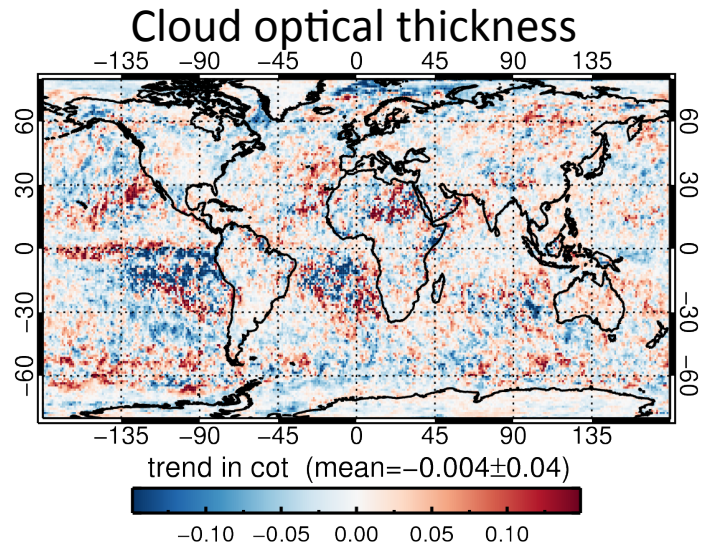
Trend: Cloud Properties

AATSR: 2002 – 2012 Monthly L3 Data









Summary

Main Findings

- New broadband radiation scheme can be applied to numerous satellite sensors at the pixel-scale resolution.
  - Trend analysis (AVHRR satellite series over 30 years of observations)
  - High spatial resolution application, e.g., ship tracks.
- Validation analysis shows strong agreement with high correlations and relative biases less than 10% relative error.
- AATSR trends show similar responses to CERES observations (Hartmann and Ceppi, 2014)

Further Work

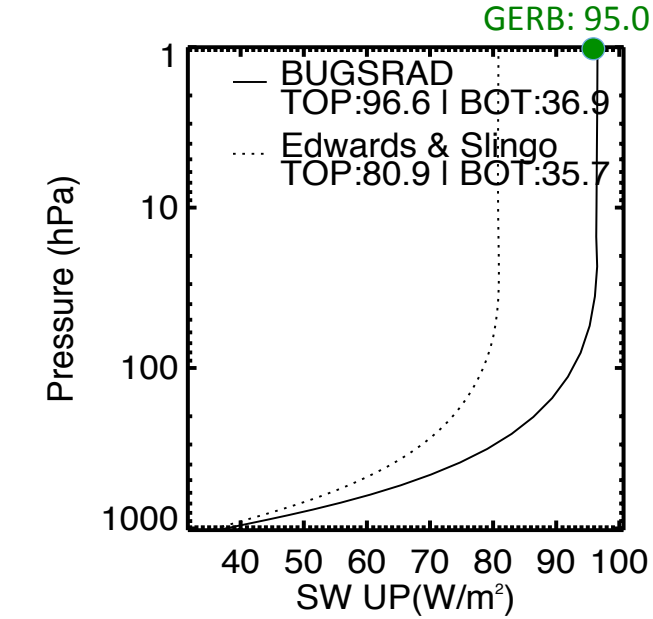
- Use overlap period between ATSR-2 (1995 – 2003) and AATSR (2002 – 2012) to constrain trend analysis for longer 17-year period.
- Improve ice cloud retrievals – comparison of look-up table properties.
- Apply data to the North Atlantic Climate System Integrated Study (ACSIS)

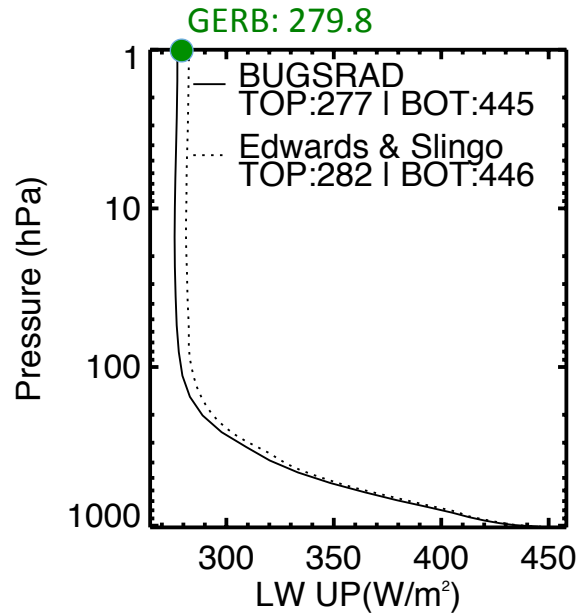
Acknowledgements

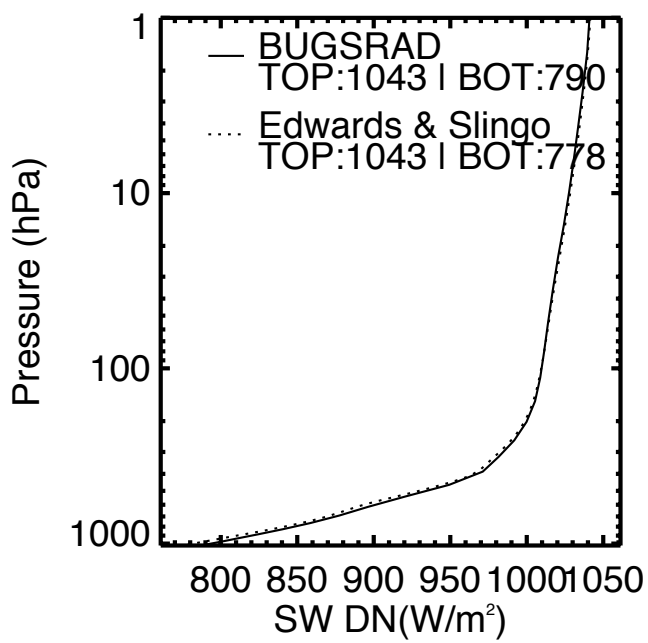
Support from the ESA-CCI programme

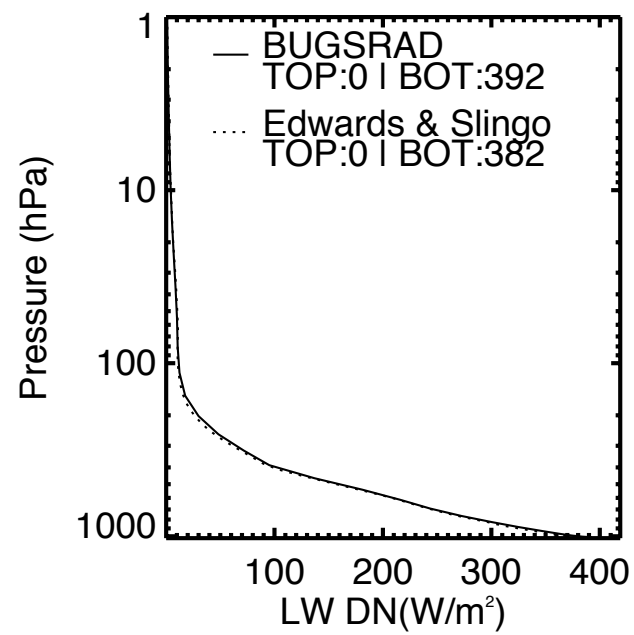
Production of data was carried out using CEDA JASMIN-CEMS.

Comparison with Edwards and Slingo







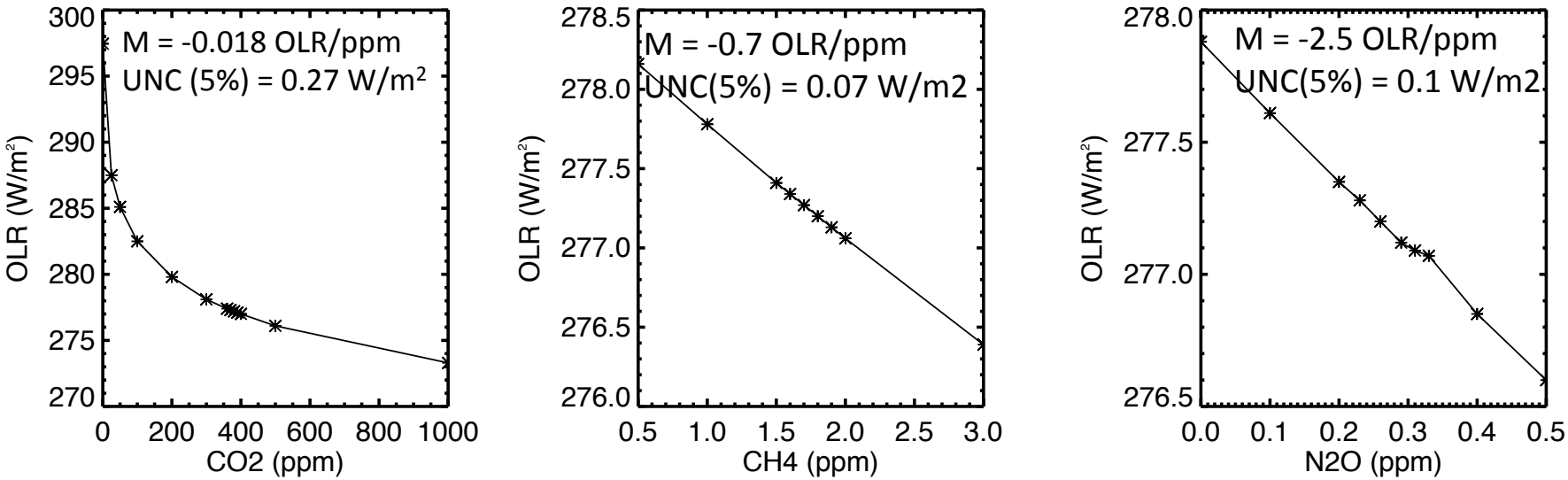


Clear-sky pixel over ocean coast of Africa
June 20th 2008
Latitude = -0.57°
Longitude = 5.74°

<u>TOA fluxes</u>

- Longwave differences between models are less than 5 W/m².
  - GERB result lies between models.
- Shortwave differences between models are less than 10 W/m².
  - BUGSrad closer agreement to GERB than Edwards Slingo.

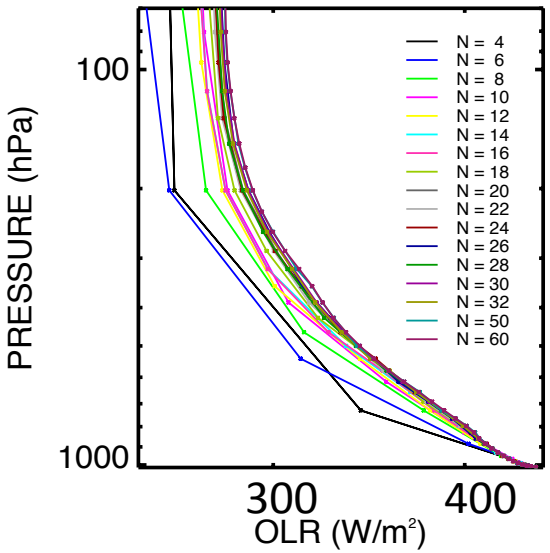
OLR Sensitivity to Gases

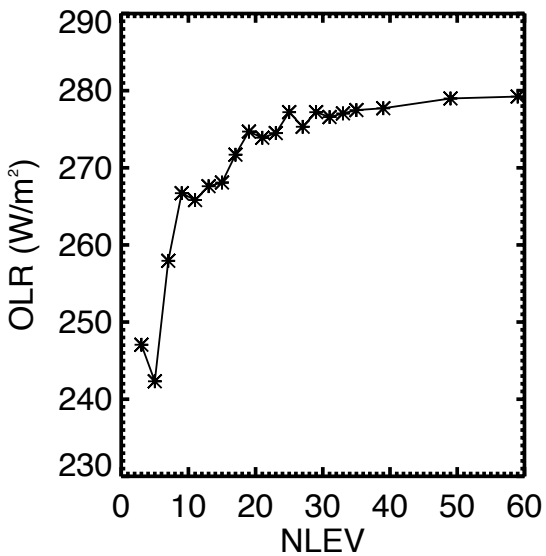


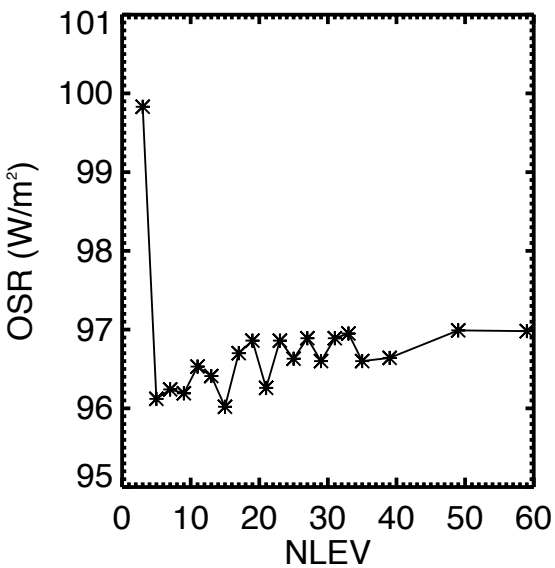
- Expected spatial variability (e.g., land VS ocean)
  - CO2 ±15 ppm
  - CH4 ±0.1 ppm
  - N2O ±0.2 ppm

Maximum uncertainty from 5% variance: ±0.3 W/m^2

Number of Vertical Levels



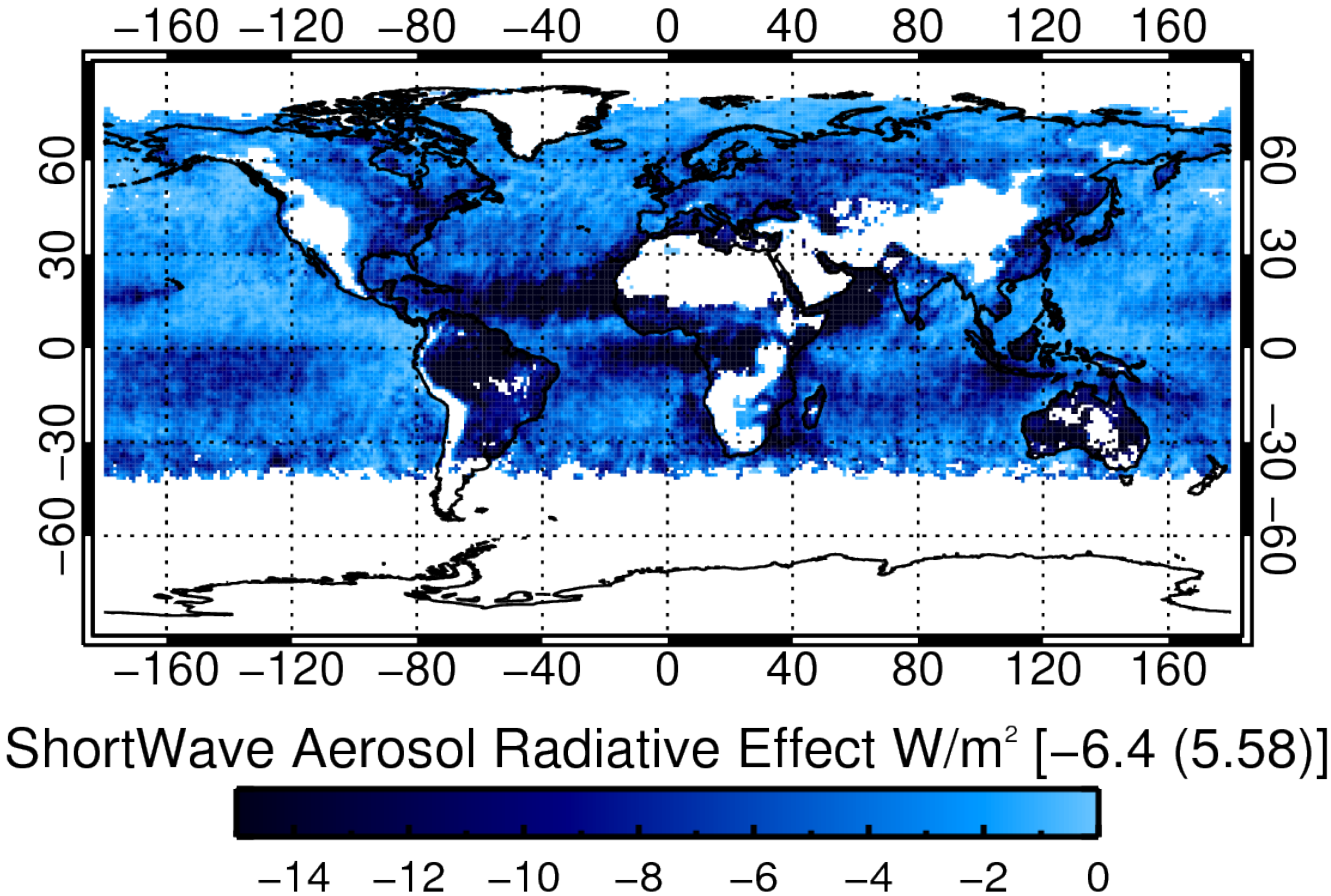




- Speed of algorithm *linearly* scales with # vertical levels in model.
  - Using 29 levels

- OLR at TOA is sensitivity to number of levels.
  - More levels increases OLR due to including more weight from lowest part of atmosphere.

Aerosol Radiative Effect



Aerosol direct effect: strong effects off coast of Africa and Hawaii.

Hartmann and Ceppi, 2014

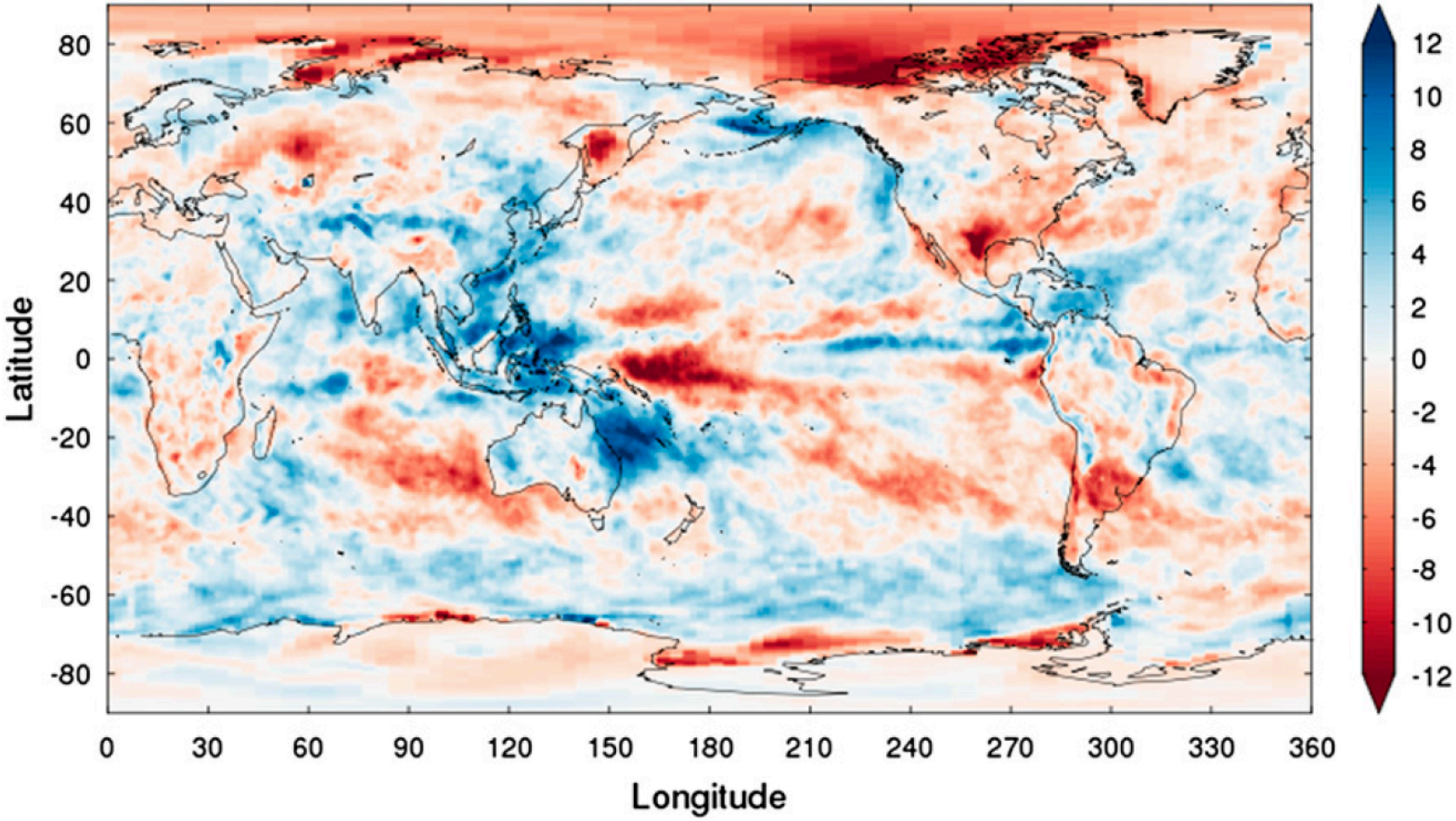


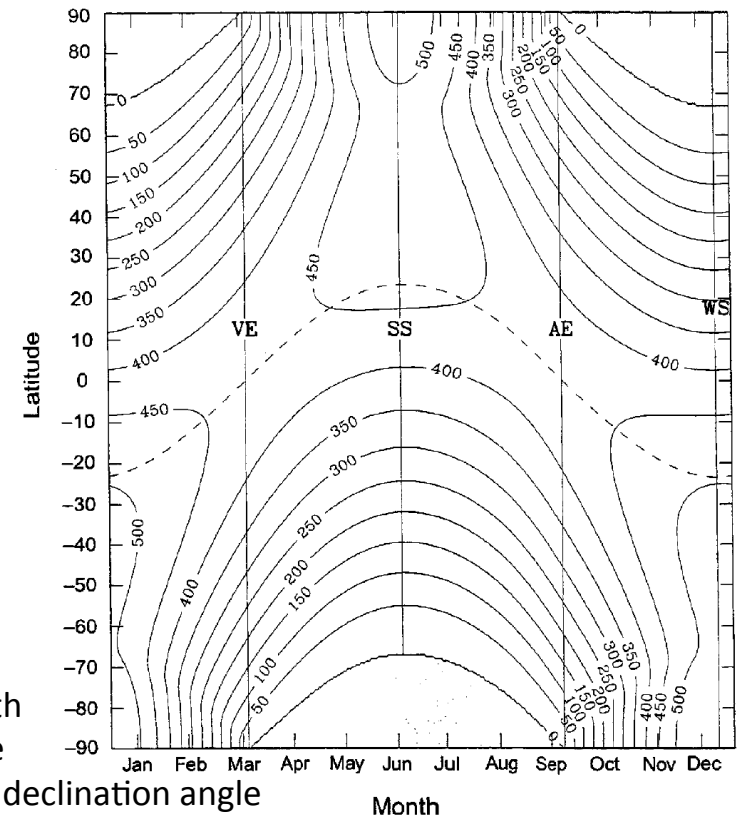
FIG. 3. Linear trend of CERES annual-mean reflected shortwave computed for each $1° \times 1°$ region of the globe ($\mathrm{W\,m^{-2}\,decade^{-1}}$).

Energy Balanced Fluxes

- Instantaneous fluxes at 10:30 am equator crossing need to be normalised by monthly mean solar insolation.
- Incoming shortwave fluxes are energy balanced according to the mean solar insolation for each month.

$$\bar{F} = S_0 \left(\frac{r_0}{r}\right)^2 \int_{-H}^{H} \cos\theta_0 \frac{dh}{2\pi}$$

$$\cos H = -\tan\phi \tan\delta$$



Energy Balanced Flux

$\bar{F}\downarrow SW\uparrow\uparrow = [F\downarrow SW\uparrow\uparrow / F\downarrow SW\uparrow\downarrow]\downarrow inst\ \bar{F}\downarrow SW\uparrow\downarrow$

retrieved albedo

H: day length
Phi: latitude
Delta: solar declination angle
So: solar constant: 1361 W/m2
(r0/r)^2: earth-sun distance
Theta0: solar zenith angle

BUGSrad MODIS-TERRA fv2_0 ToA SWdn vs CERES - 2008