Solar Spectral Variability and Climate Response

P. Pilewskie
Laboratory for Atmospheric and Space Physics (LASP)
University of Colorado, Boulder Colorado
peter.pilewskie@lasp.colorado.edu

Mechanisms of Sun-Climate Interactions

- Variability in solar irradiance
  - Total Solar Irradiance (TSI)
    - "Direct" forcing at the surface and lower troposphere.
  - Solar Spectral Irradiance (SSI)
    - Spectral variability is almost exclusively focused on the ultraviolet.
    - UV variability drives changes in stratospheric chemistry and dynamics.
    - Radiative and dynamic coupling between stratosphere and troposphere.
    - Can other spectral regions contribute?
- Variability in solar wind and energetic particles
  - Cosmic ray flux anti-correlated with solar activity

Where Does the Atmosphere Get Its Energy?

Heat Source	Heat Flux* [W/m^2]	Relative Input
Solar Irradiance	**340.20**	**1.000**
Heat Flux from Earth's Interior	0.0612	1.8E-04
Radioactive Decay	0.0480	1.4E-04
Geothermal	0.0132	3.9E-05
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Total Radiation from Stars	1.4E-05	4.0E-08
Energy Generated by Lunar Tidal Forces in the Atmosphere	1.0E-05	3.0E-08
Radiation from Zodiacal Light	3.4E-06	1.0E-08
Total of All Non-Solar Energy Sources	*0.0810*	*2.4E-04*

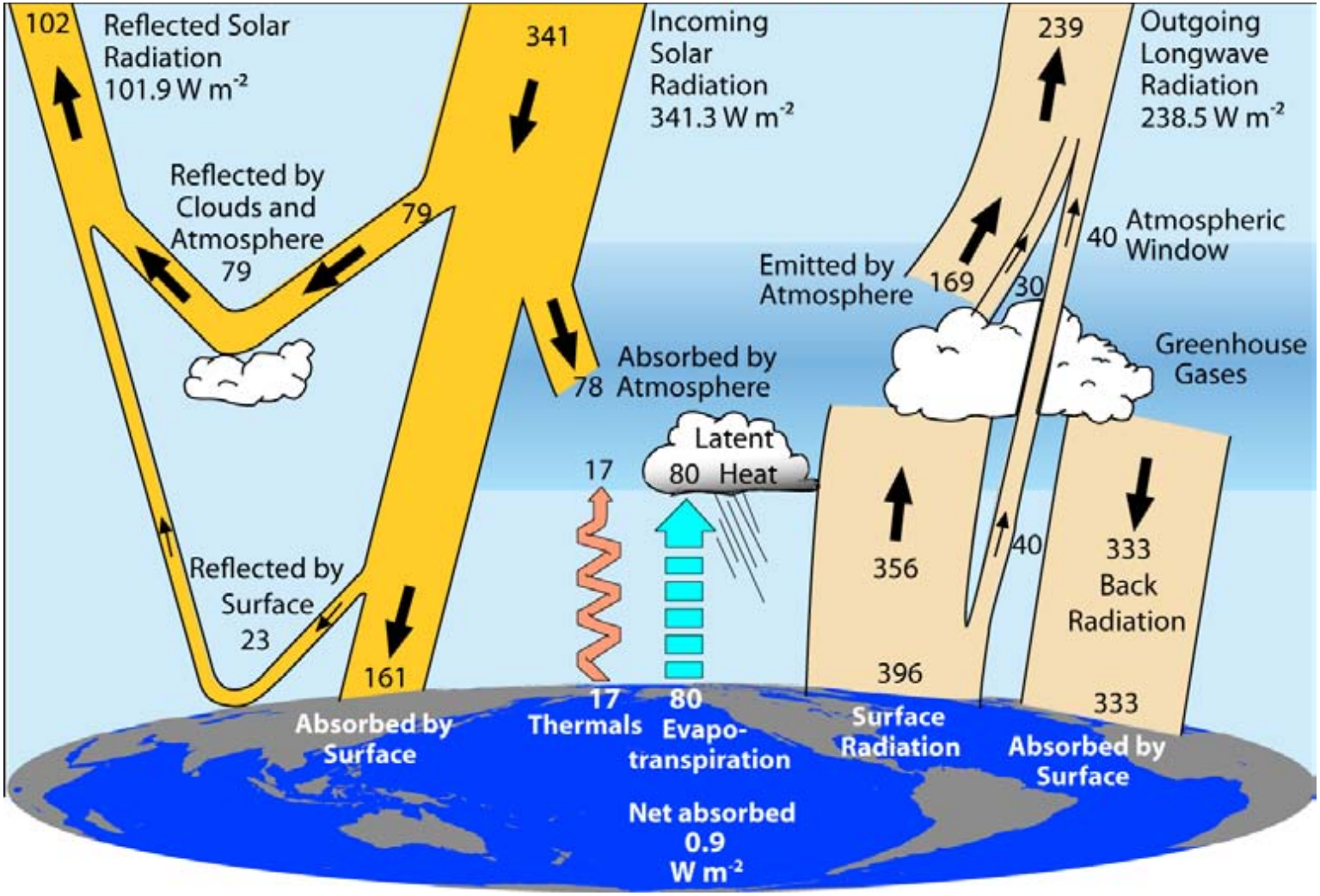
* global average

Solar Cycle **Variability** alone, ~ 0.1% of TSI, is ~ 10X larger than the second largest energy source

T ≈ 30 K without Sun

Physical Climatology, W.D. Sellers, Univ. of Chicago Press, 1965
Table 2 on p. 12 is from unpublished notes from
H.H. Lettau, Dept. of Meteorology, Univ. of Wisconsin.

Global Energy Budget



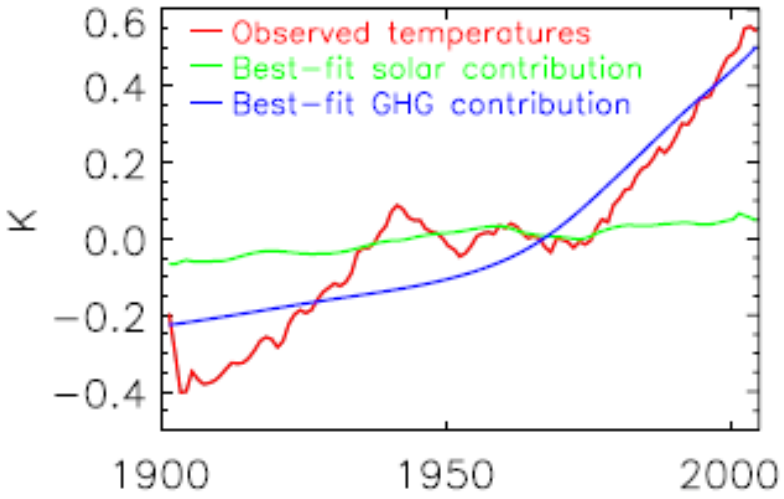
Trenberth, K.E., et al., *Bull Amer. Meteor. Soc.*, 2009

Why are Sun-climate links still uncertain?

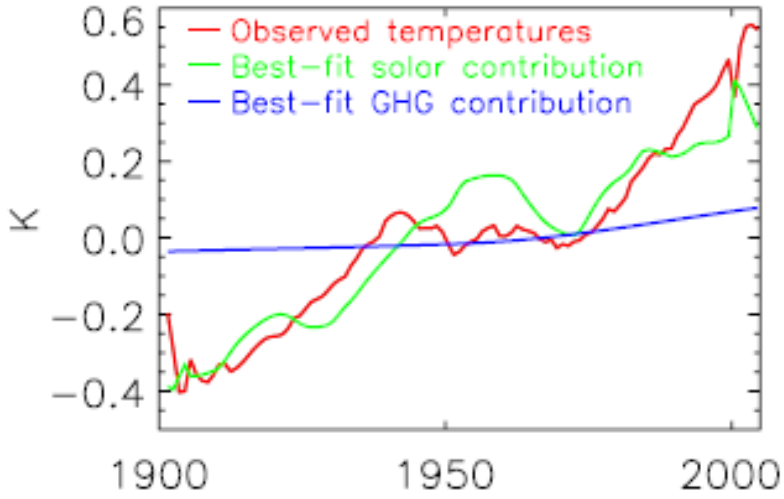
- Signals from different forcing agents are not different enough in shape to be distinguished.
- Climate response may be dominated by regional feedbacks.
  - response patterns uncorrelated with forcing.
  - different forcings can result is similar climate responses.
- Internal (unforced) modes of variability not well understood.
  - How are they influenced by external forcing?
- Tropospheric response is slow; solar forcing is quasi-periodic (at decadal scales).

Sun or Greenhouse Gases?

- Stepwise regression
  - Fit using variable with highest correlation; remove that variable; repeat with next highest correlation.



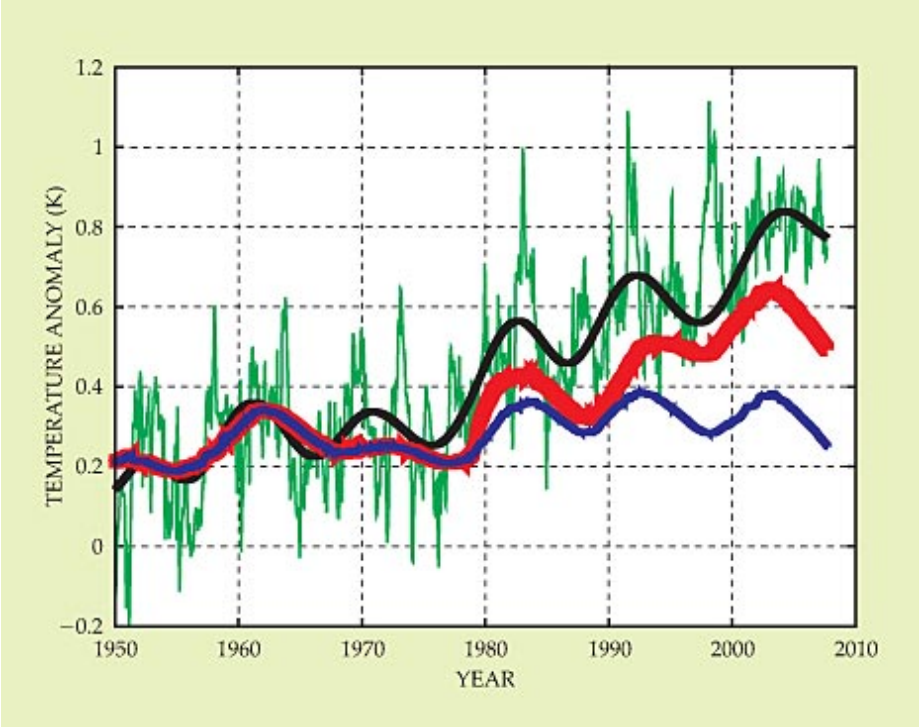
9-year running mean smoothing



11-year running mean smoothing

From Ingram, W.J., *Space Science Reviews* 125: 199–211, 2006.

Solar Contribution to 50 year Temperature trend?



Global Surface T anomalies

Filtered GST

Solar Reconstruction[1]

Solar Reconstruction[2]

1 Willson & Mordvinov, GRL, 2003

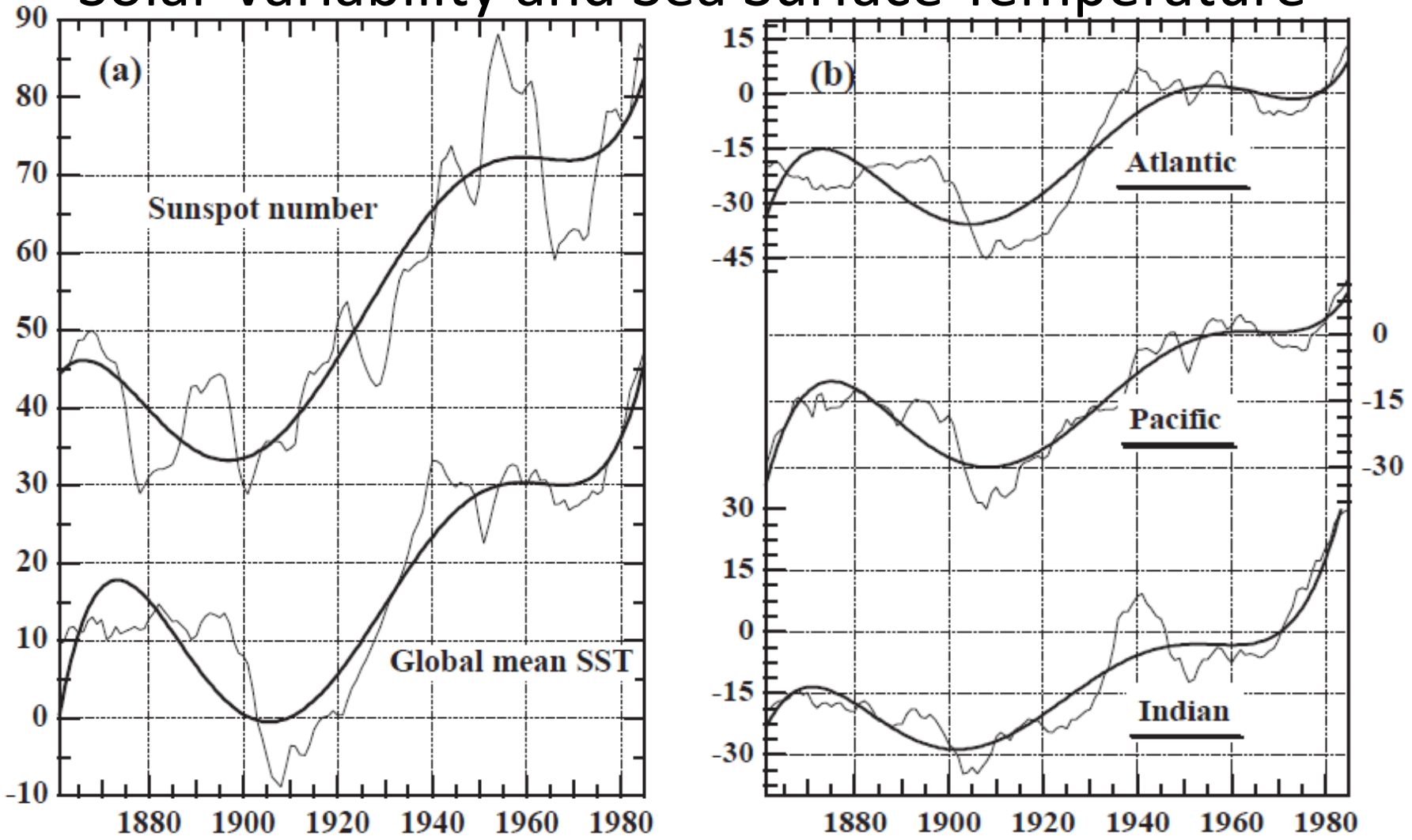
2 Fröhlich and Lean PMOD composite

Scafetta and West, Physics Today, 2008.

*"We estimate that the **Sun could account for as much as 69% of the increase in Earth's average temperature**, depending on the TSI reconstruction used."*

- **No feedbacks: requires 0.75% increase in TSI.**
- **With feedbacks: doubling in sensitivity, still requires a 0.4% increase in TSI over this period, or 700 ppm per decade.**
- **A trend of this magnitude has not been observed in TIM TSI.**

Solar Variability and Sea Surface Temperature



From Reid, G.C., *Space Science Reviews* 94: 1–11, 2000

White, O.R., 1977: *The solar output and its variation*.

"Since we do not yet have a firm, quantitative measure of the sensitivity of the Earth's climate and weather to changes in the solar constant, however, one very important problem in solar physics continues to be the absolute measurement of the solar constant and its variation with time."

Sun-Climate Questions

- What is the solar forcing at decadal and longer time scales?
  - Solar Irradiance Climate Data Record (CDR): time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change.
- How does the climate system respond?
  - What are the mechanisms of climate response? Requires measurement of wavelength-dependent irradiance variability.
  - Can a solar climate signal be attributed to unique mechanisms?
  - Is the climate more sensitive to solar forcing than to other forcings, for example, greenhouse gas forcing?

Attribution

- How much of the 20th-century warming trend was due to anthropogenic forcing?
  - Requires rigorous probabilistic analysis and highly accurate forcings.
- What are the expected climate changes for the 21st century?

Radiative Forcing

- Radiative Forcing: the change in ***Net*** irradiance
- Why is it useful?
  - Climate response (change in surface temperature) is linear with RF.

$$4\pi R^2 F_{net} = \pi R^2 F_{net,solar} + 4\pi R^2 F_{net,ir}$$

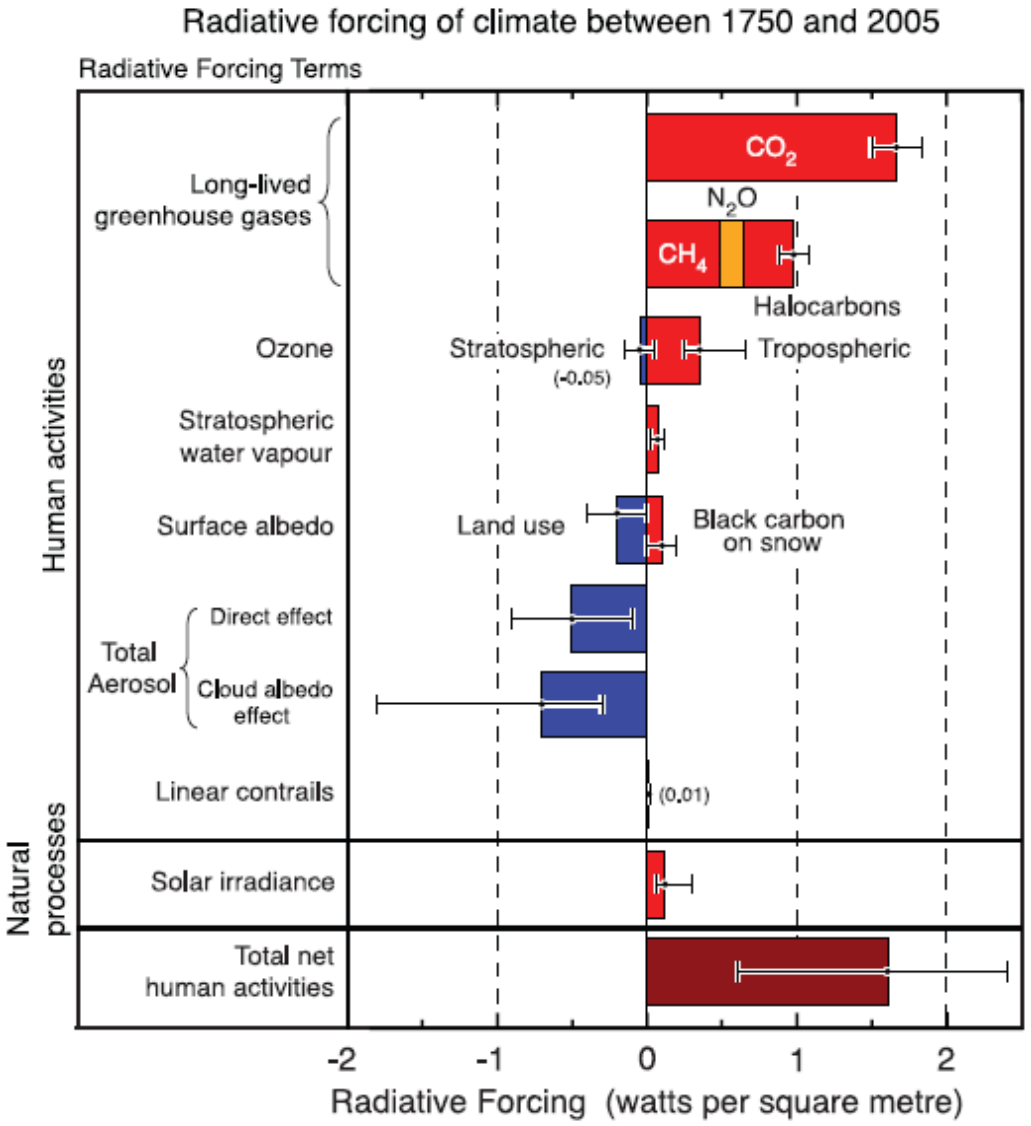
$$F_{net} = (1-a)S_0/4 - \sigma T_e^4 = (1-a)S_0/4 - (1-\varepsilon_e)\sigma T_s^4$$

$$\Delta F_{net} + \frac{\partial F_{net}}{\partial T_s}\Delta T_s = 0$$

$$\Delta T_s = \alpha \Delta F_{net}, \quad \alpha = -\left(\frac{\partial F_{net}}{\partial T_s}\right)^{-1} = \left(\frac{\partial F_{ir}^{\uparrow}(TOA)}{\partial T_s} - \frac{\partial (1-a)S_0/4}{\partial T_s}\right)^{-1}$$

$$\alpha = \left(\frac{4}{T_s} F_{ir}^{\uparrow}(TOA)\right)^{-1}$$

Fourth Assessment Report of the IPCC, 2007



There is uncertainty in solar forcing since the start of the industrial era but climate response is even more uncertain:

$$\Delta T_s = \left(\frac{\partial F_{net}}{\partial T_s} - \sum_{i=1}^{N} \frac{\partial \boldsymbol{F}_{net}}{\partial \boldsymbol{Q}_i} \frac{\partial \boldsymbol{Q}_i}{\partial \boldsymbol{T}_s} \right)^{-1} \Delta F_{net}$$

- Solar Irradiance: how is it dispersed spectrally and where is it deposited into the atmosphere and ocean?

How well do we know the incident spectral irradiance?

Circa late 1990s

Langley Extrapolation and the Extraterrestrial Spectrum

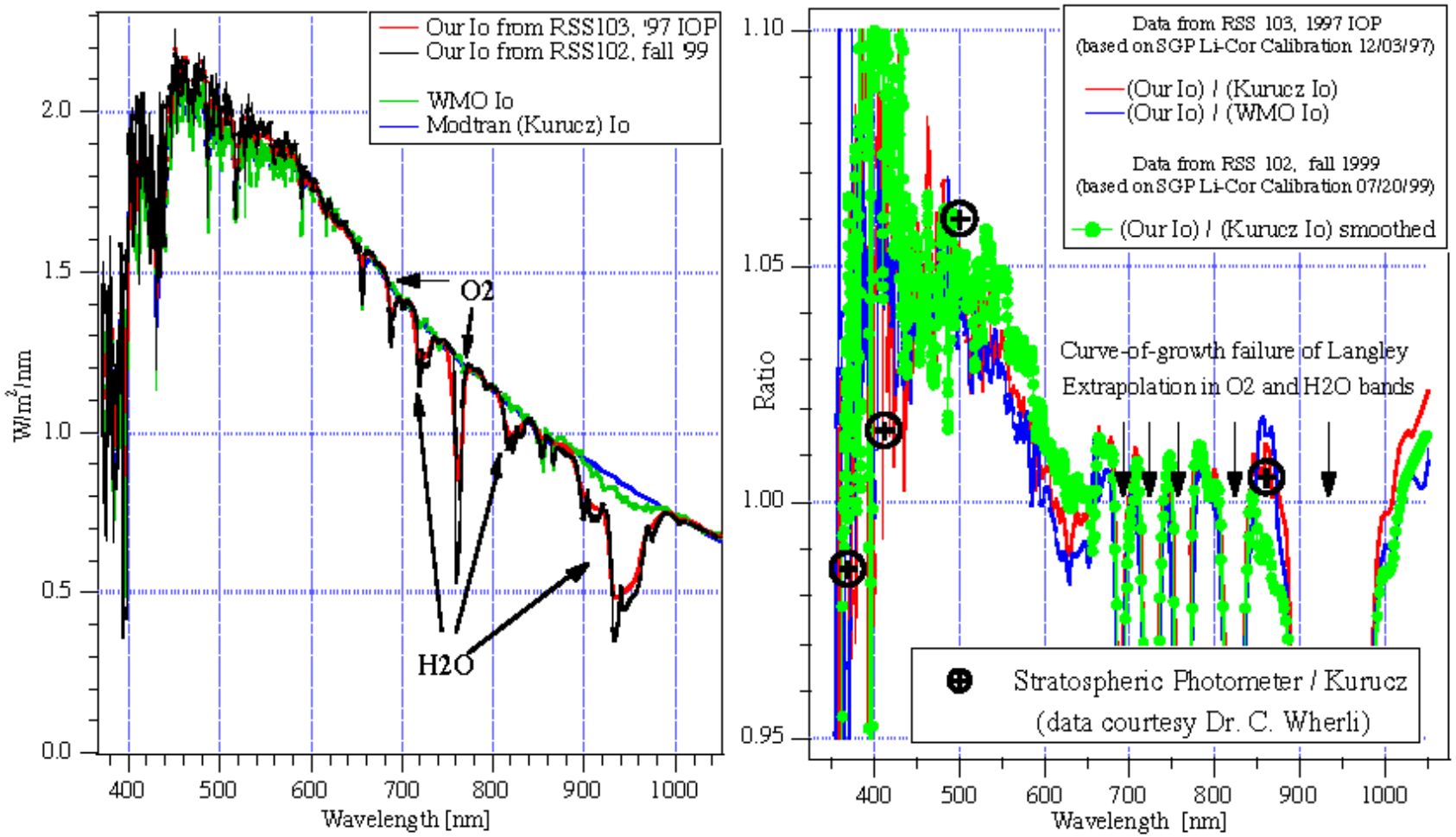
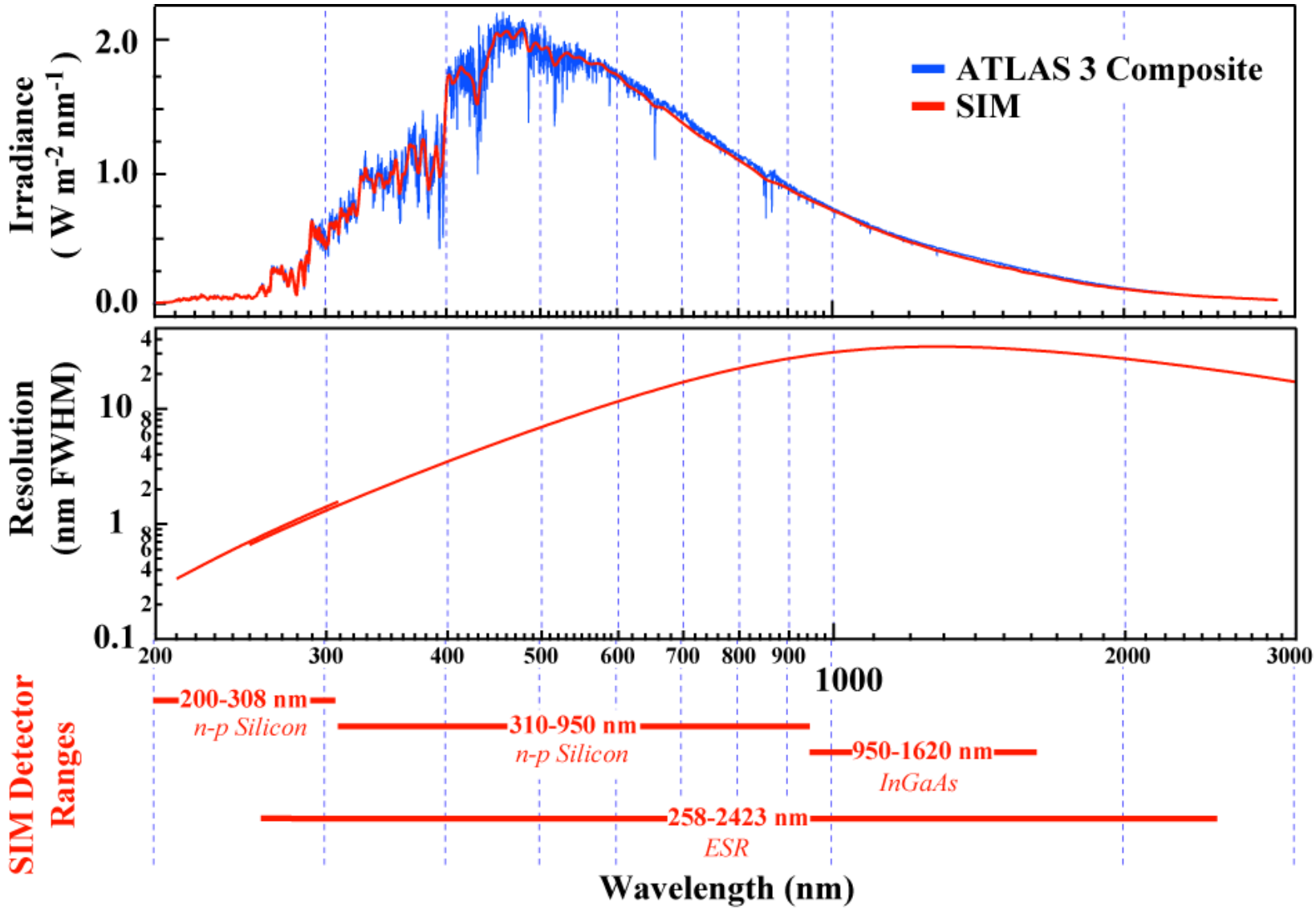


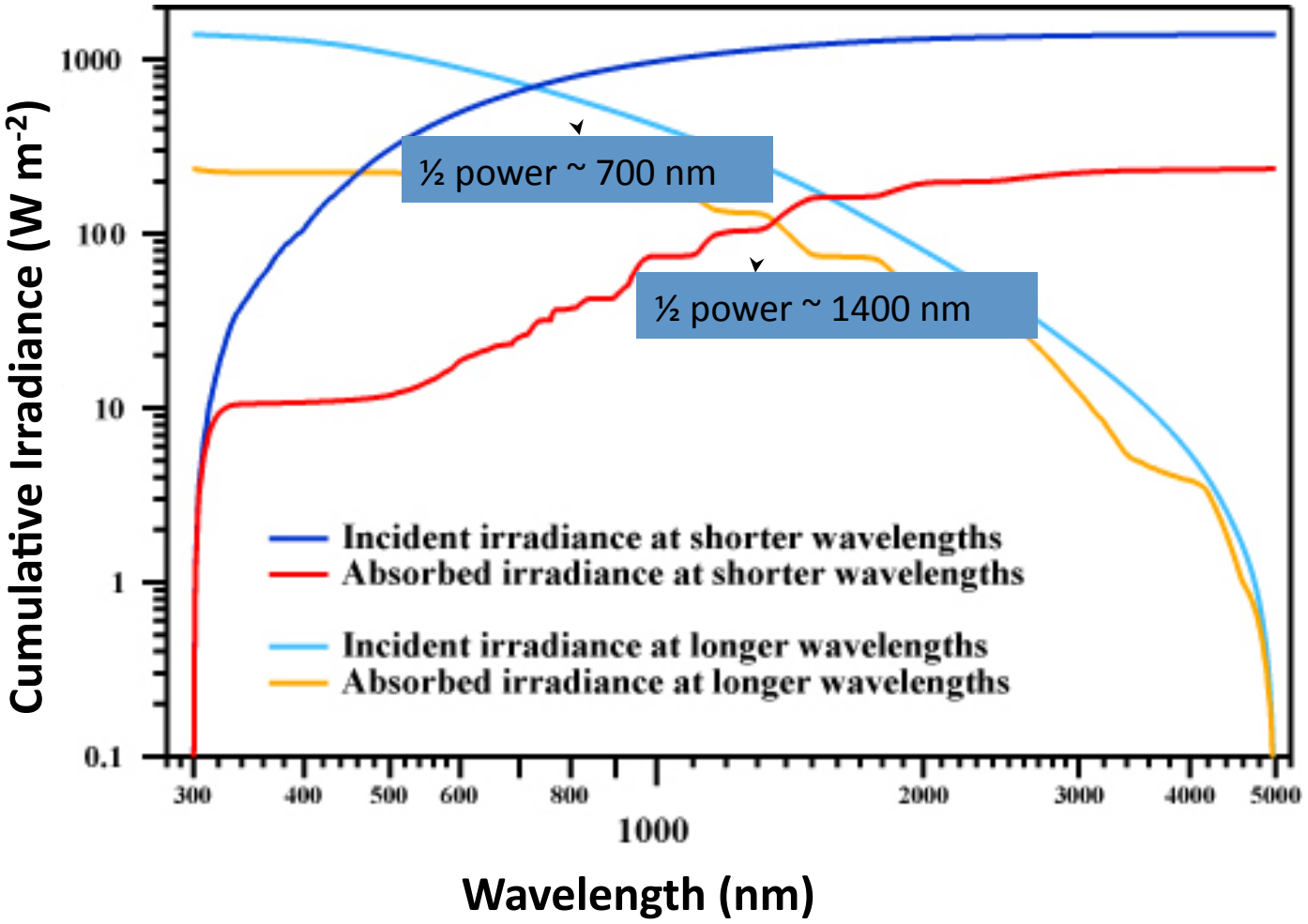
Figure 3: Comparison of Extraterrestrial Spectra, RSS data by Langley extrapolation at SGP.

SIM and SOLSPEC Irradiance Spectral

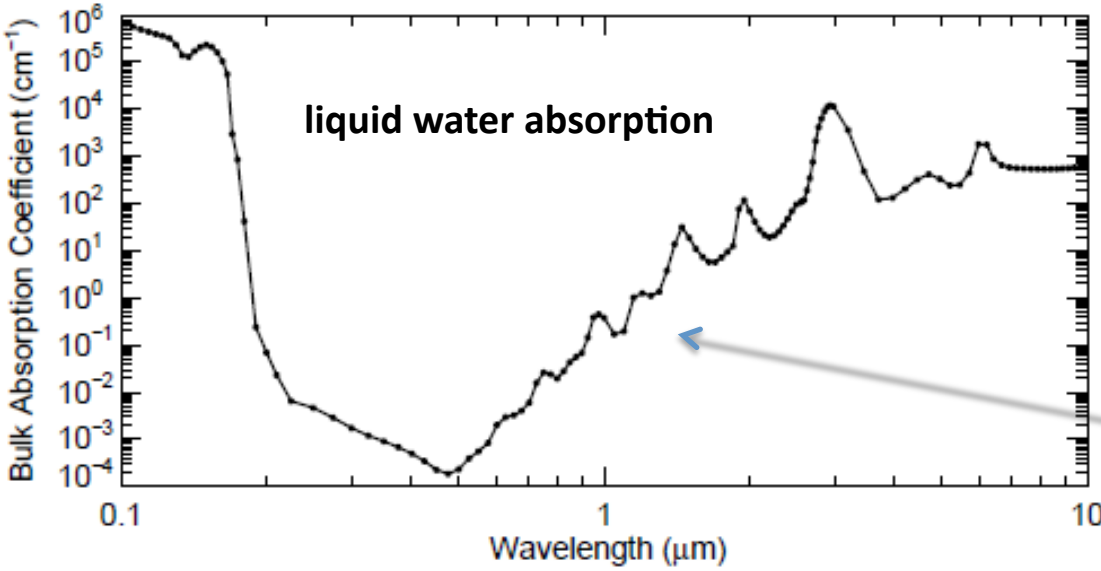


J.W. Harder, G. Thuillier, E.C. Richard, S.W. Brown, K.R. Lykke, M. Snow, W.E. McClintock, J.M. Fontenla, T.N. Woods, P. Pilewskie, 'The SORCE SIM Solar Spectrum: Comparison with Recent Observations' ,*Solar Physics*, **263**, Issue 1 (2010), pp 3, doi:10.1007/s11207-010-9555-y

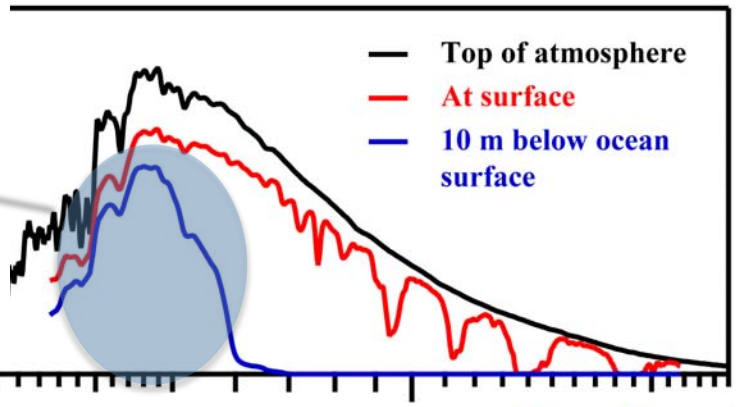
Cumulative Incident and Absorbed Shortwave Irradiance

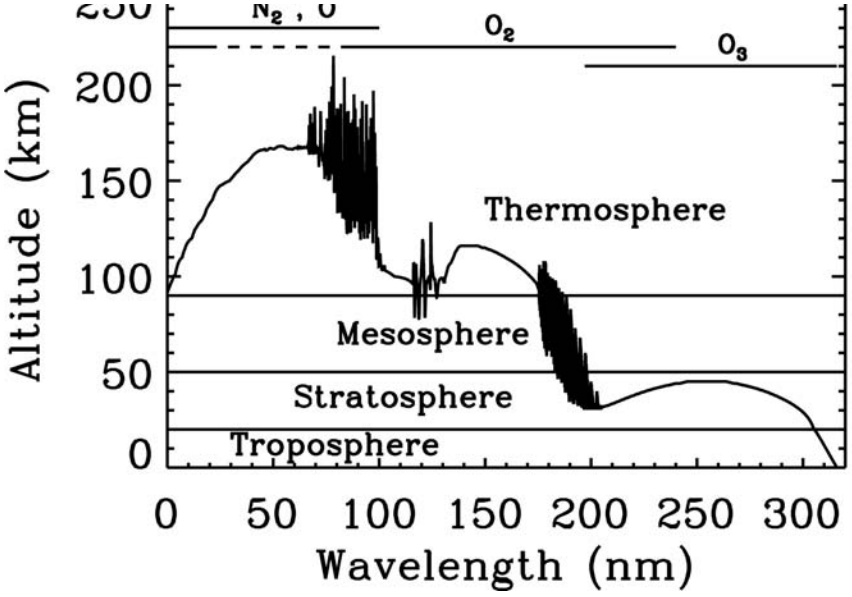


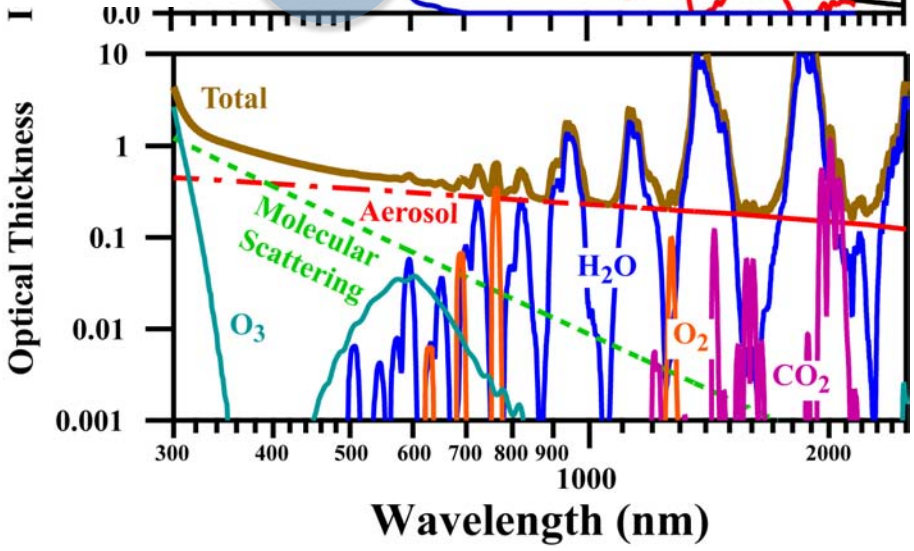
Transformation of solar spectral irradiance through the



visible, near infrared radiation affects
p., surface and ocean processes

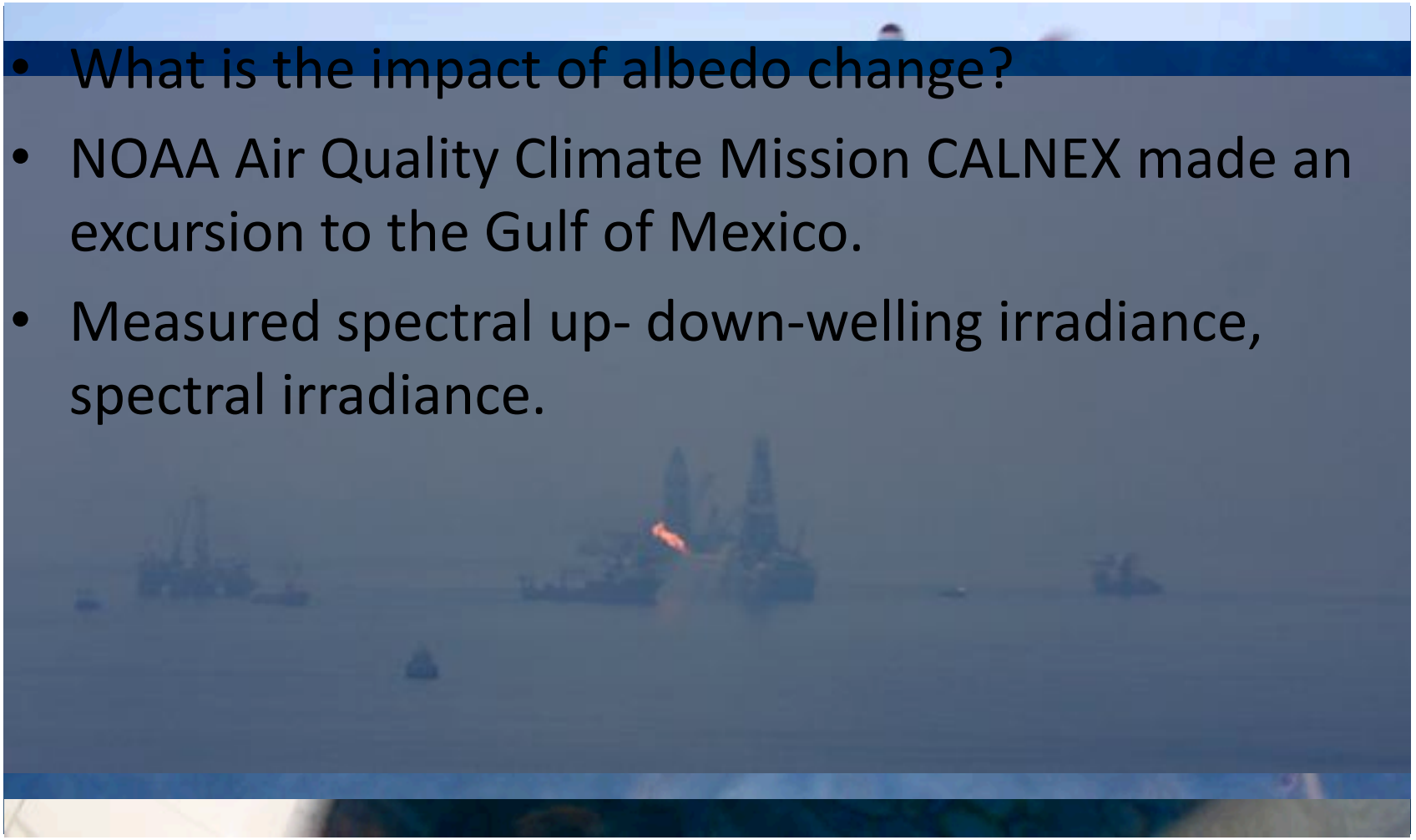






[Adapted from P. Pilewskie, *Solar Physics,* 2005]

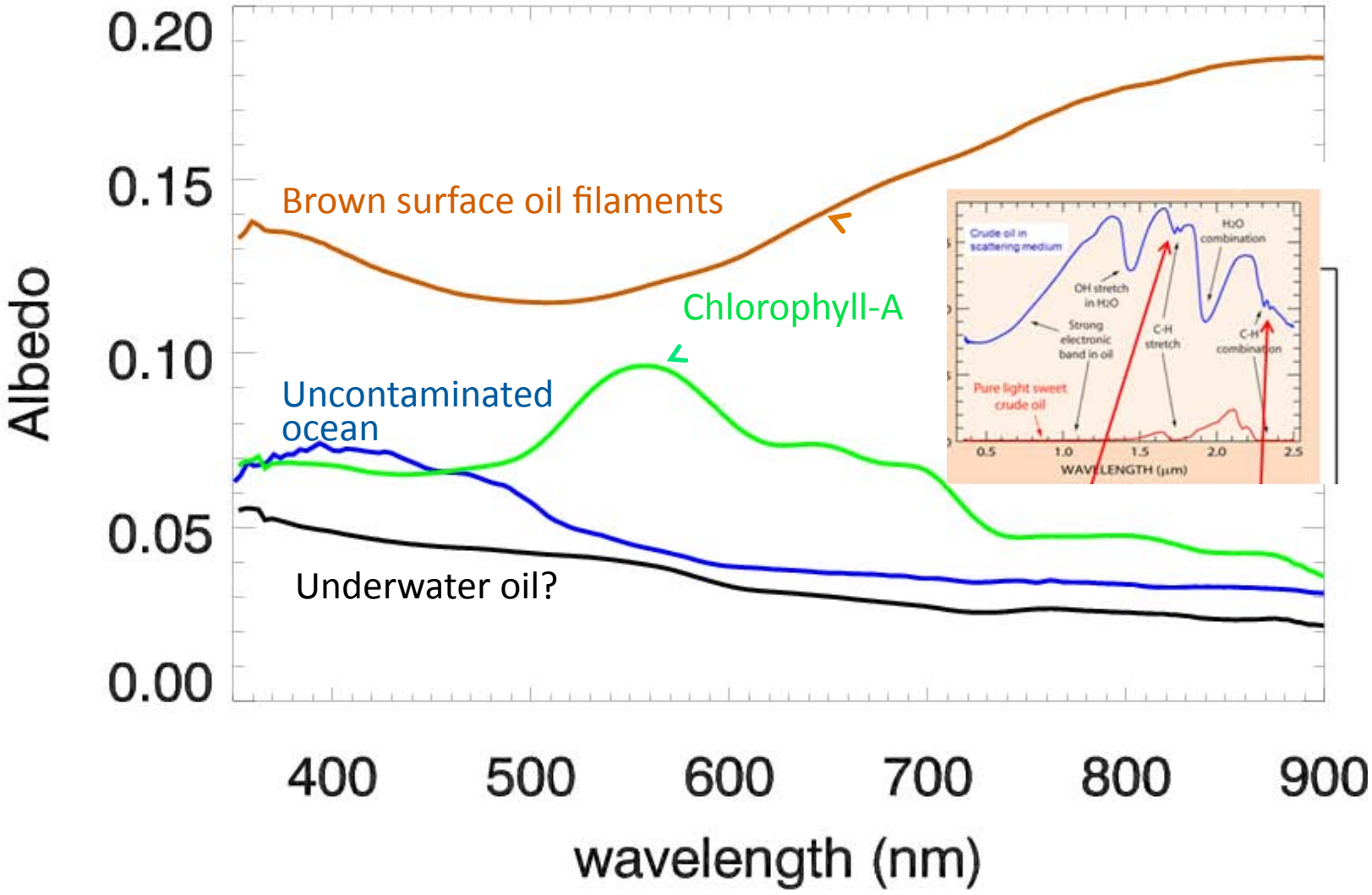
Now, an aside …



- What is the impact of albedo change?
- NOAA Air Quality Climate Mission CALNEX made an excursion to the Gulf of Mexico.
- Measured spectral up- down-welling irradiance, spectral irradiance.

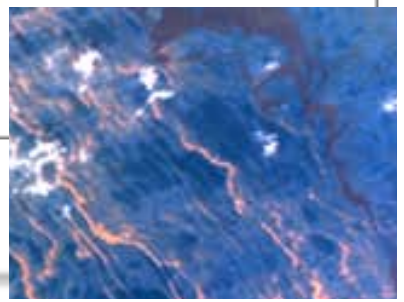
Sea Surface Spectral Albedo

Gulf of Mexico 8 June 2010



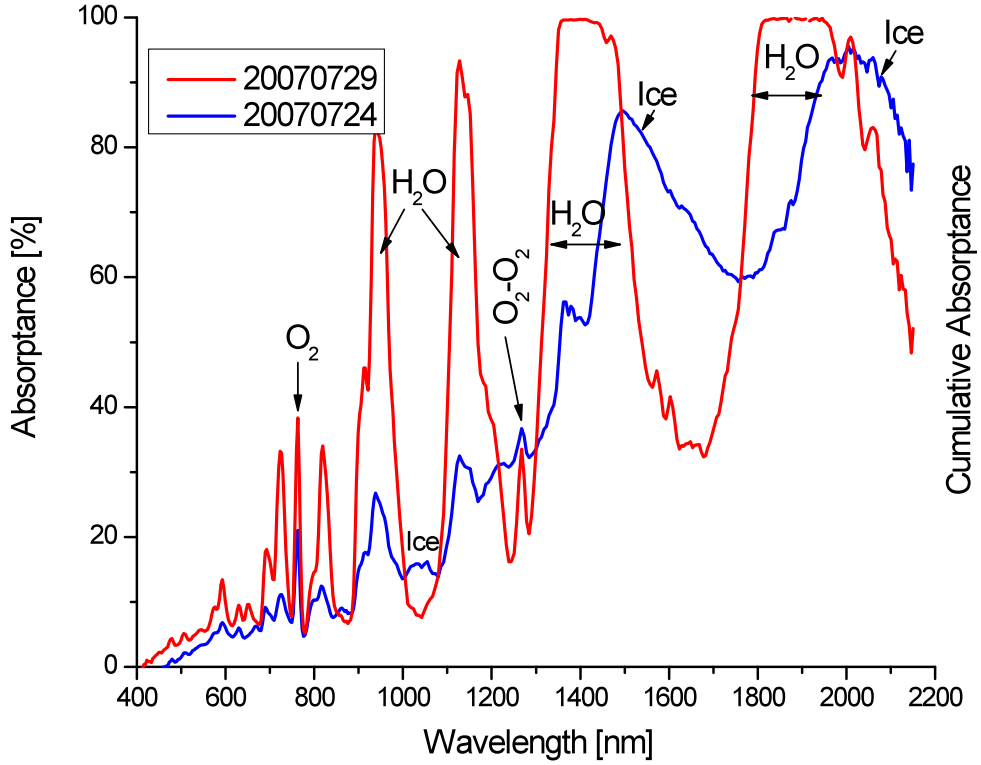
Sea Surface Albedo: variance along fight track

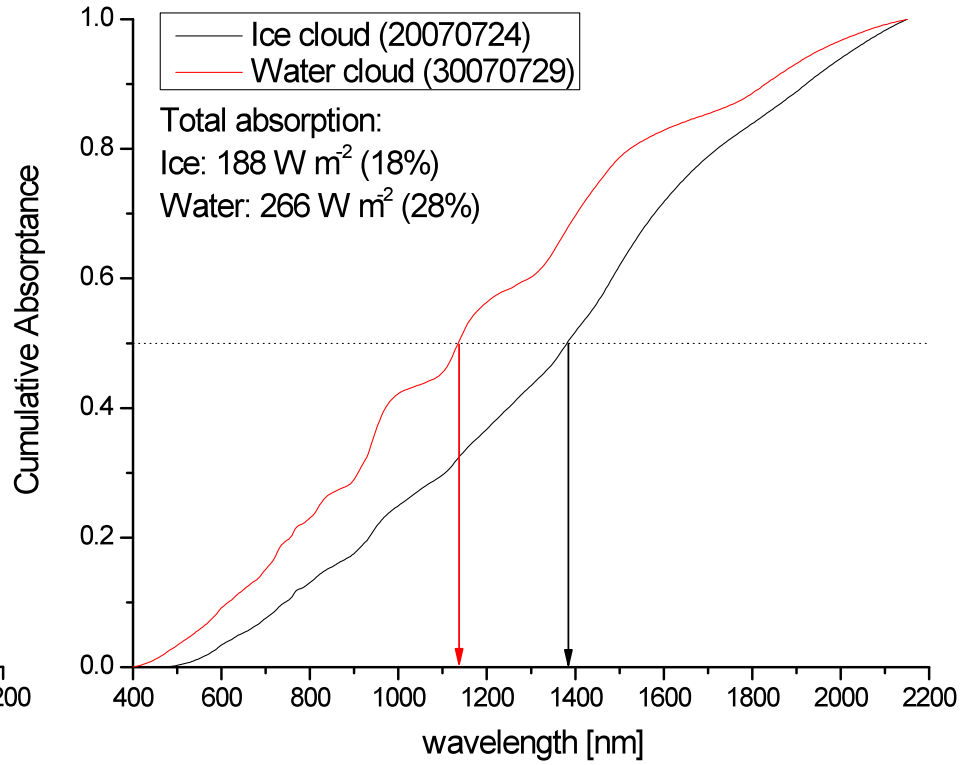
8 June 8 2010 True Color Composite (R=650 nm, G=550 nm, B=450 nm)



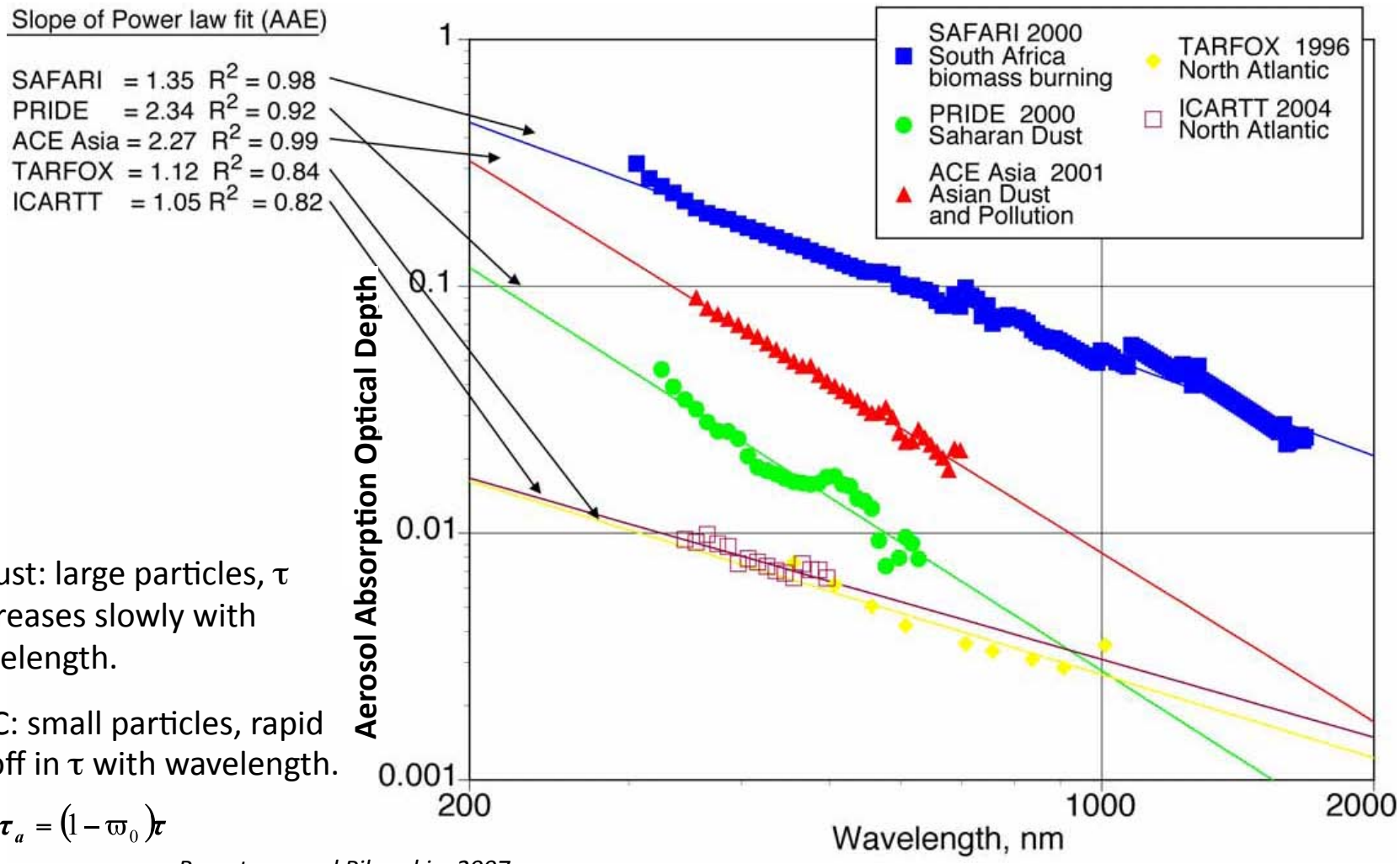
Clouds Modify Shortwave Absorption

Measured Water Cloud vs. Ice Cloud Absorption





Aerosol Spectral Absorption



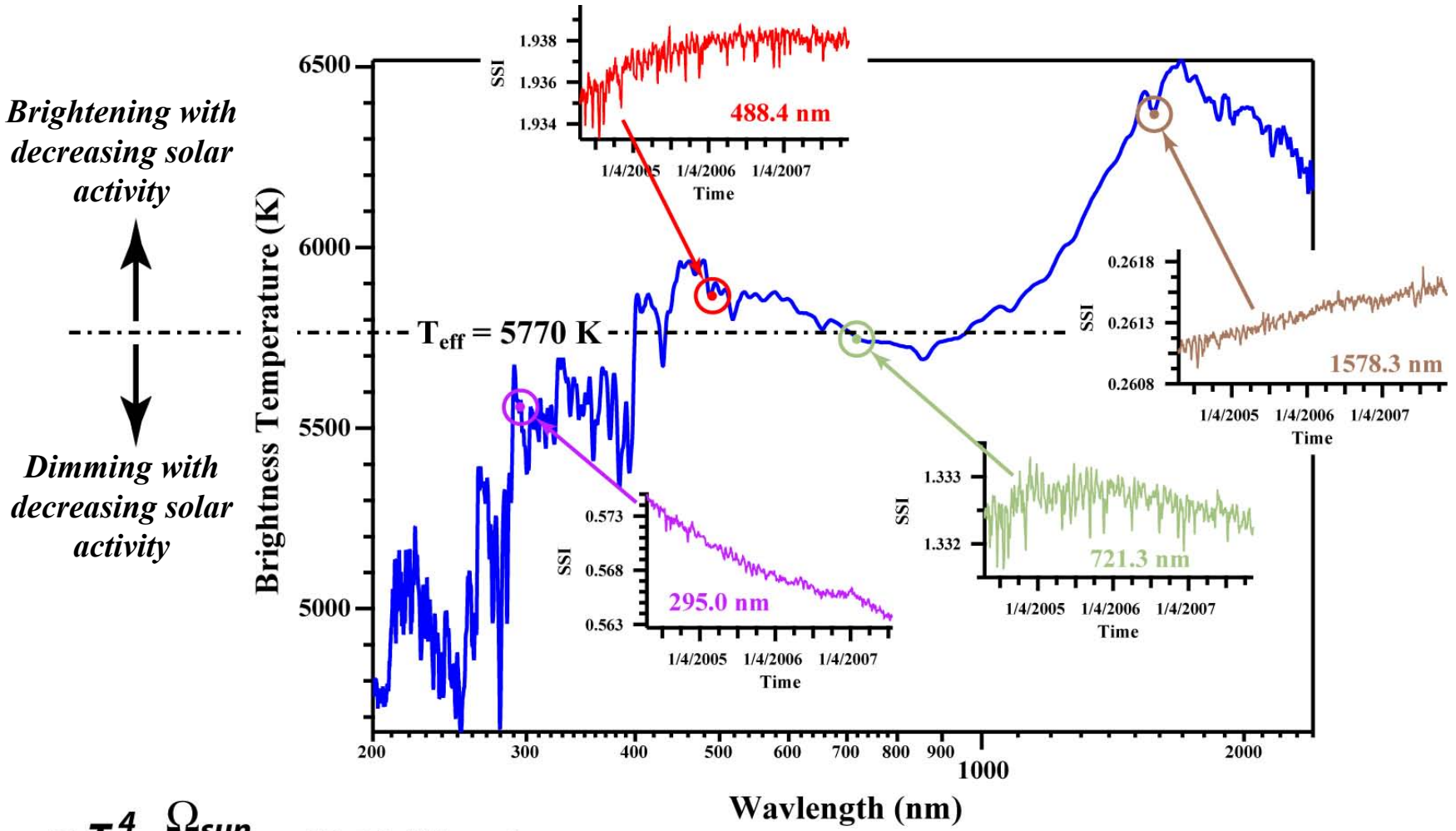
- Dust: large particles, τ decreases slowly with wavelength.
- BC: small particles, rapid falloff in τ with wavelength.

$$\tau_a = (1 - \varpi_0)\tau$$

Bergstrom and Pilewskie, 2007.

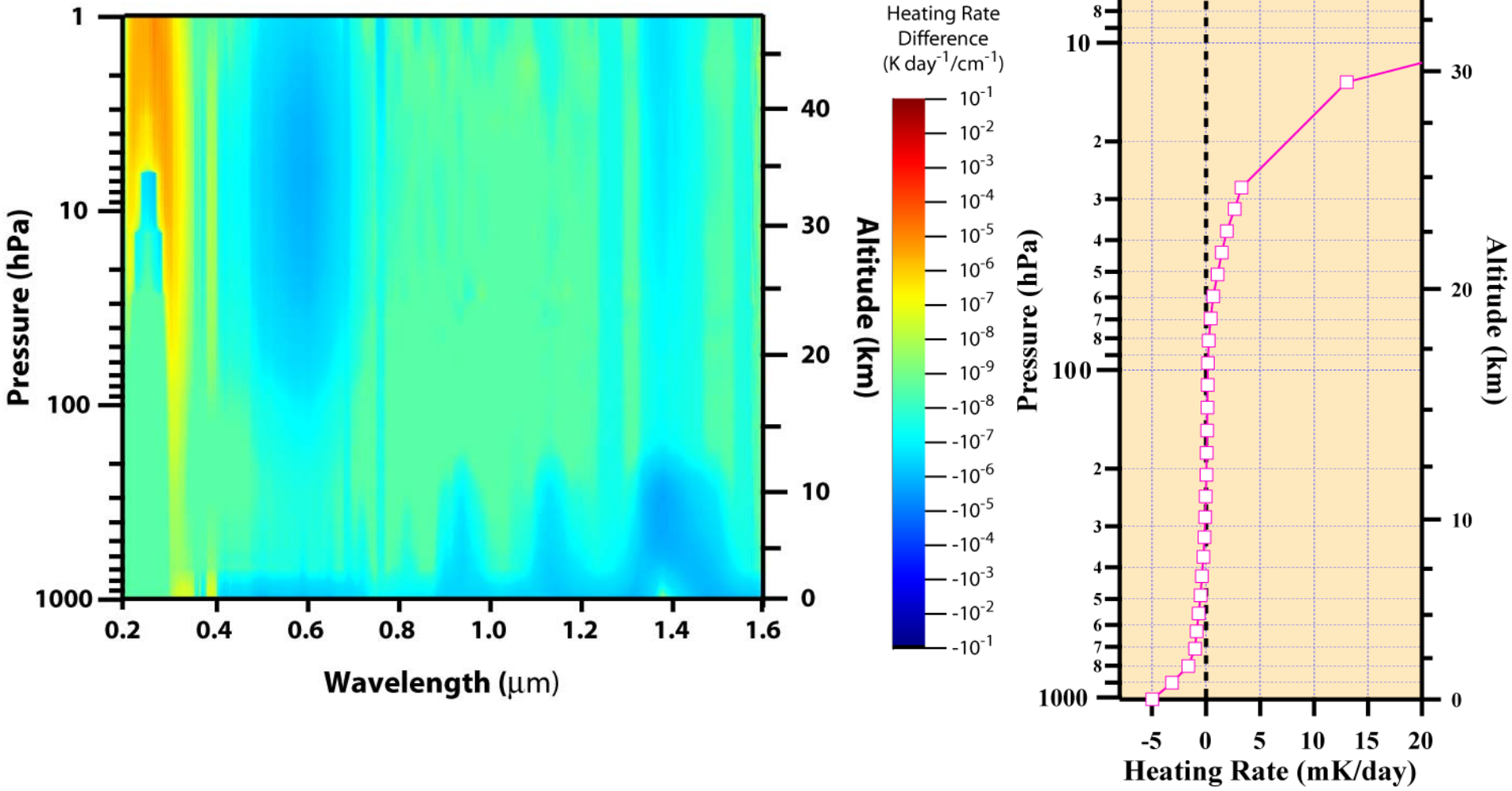
- Solar Irradiance: how is it dispersed spectrally and where is it deposited into the atmosphere and ocean?
- How does the solar spectral irradiance vary in time?

A Contrast in Spectral Variability

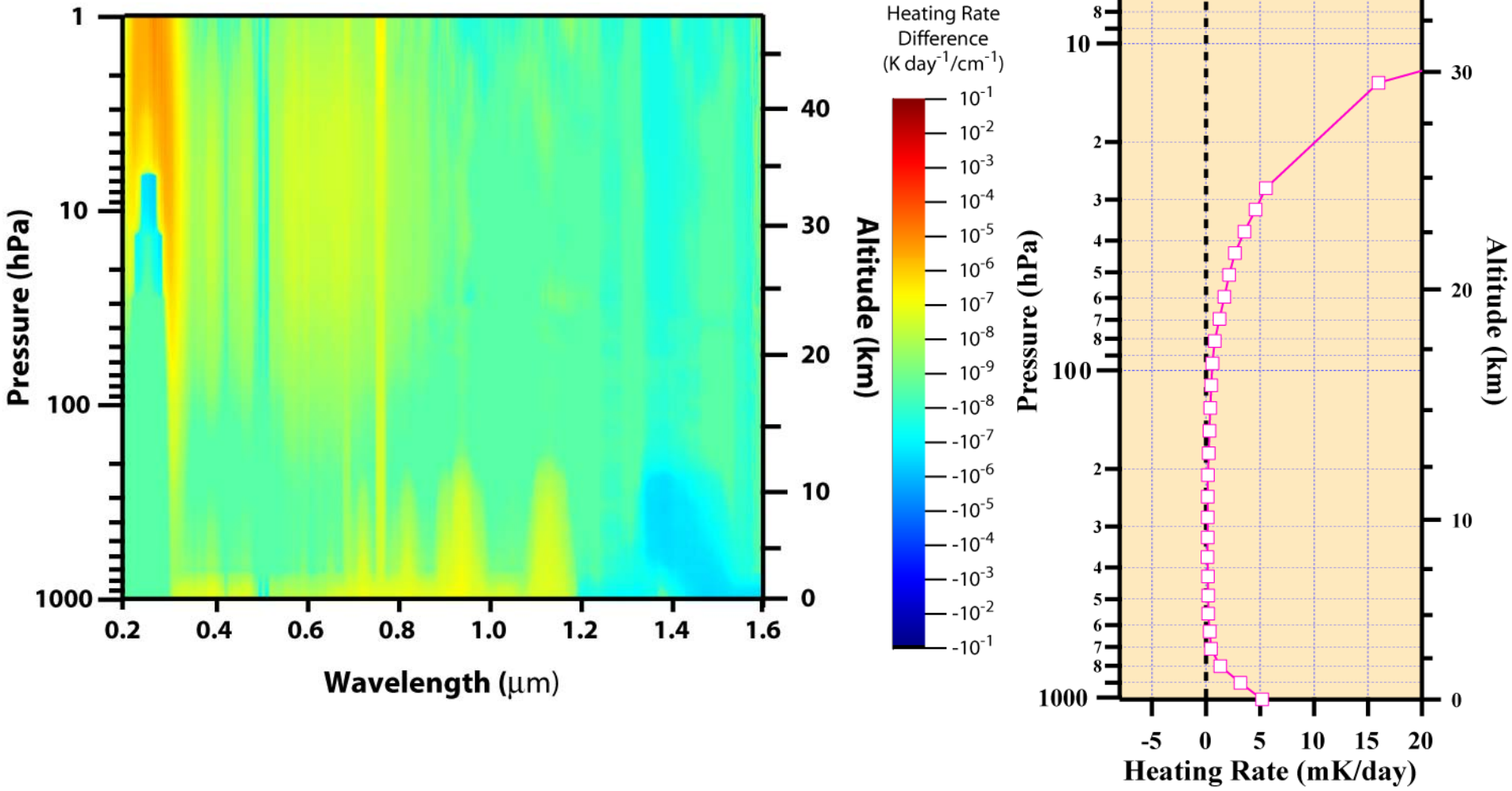


$$\sigma T_{eff}^4 \frac{\Omega_{sun}}{\pi} \approx 1361 \text{ W m}^{-2}$$

Spectral Heating Rate Differences:
Sunspot Case (2005/04/30)



Spectral Heating Rate Differences:
Facula/Plage (2005/08/29)



Summary and Further Questions

- Response of climate to solar variability is highly wavelength dependent:
  - Direct surface heating at near-ultraviolet wavelengths and longer.
  - Indirect processes through absorption of UV in the stratosphere and radiative and dynamical coupling with the troposphere.
- Greatest relative solar variability occurs in the ultraviolet (indirect); greatest absolute variability occurs in mid visible (direct).
- TOA spectral distribution of solar radiation and its variability is crucial in interpreting the highly spectrally dependent radiative processes in the troposphere (scattering and absorption by clouds, aerosol particles, and gases) and at the surface.

Summary and Further Questions

- Are there mechanisms for significant hydrological cycle responses?
- What improvements are necessary in current climate models to determine the impacts of variability in the visible and near-infrared?
- What improvements are required in the measurements of solar spectral irradiance?