AccuRT: a versatile tool for radiative transfer simulations in a coupled atmosphere-water system

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Information Provided by e-mail

- **Technical Notes**
  (AccuRT-ASIO-TN_v36.pdf)

- **Applied Sciences paper***
  (AccuRT-paper-AppliedSciences-2018.pdf)

- **User Manual for VM (Virtual Machine) AccuRT**
  (AccuRT-User-Manual-VM_v2.pdf)

- **Simulation package**
  (OCsim_AccuRT_package.zip)

*Stamnes, K., B. Hamre, S. Stamnes, N. Chen, Y. Fan, W. Li, Z. Lin, and J. J. Stamnes, Progress in forward-inverse modeling based on radiative transfer tools for coupled atmosphere-snow/ice-ocean systems: A review and description of the AccuRT model, Applied Sciences, in press, 2018.

Outline

- Background/Motivation
- Brief Review of Current Status – Future Needs?
- Unified Treatment of Atmosphere and Water:
  - DIScrete Ordinate Radiative Transfer (DISORT) for a Coupled Atmosphere-Water System
- Overview of AccuRT/Key Features:
  - A Robust, User-friendly, and Reliable Tool for Radiative Transfer Simulations throughout an Atmosphere Overlying a Water Body
- Results
  - Comparison with Benchmarks
  - Radiance Simulations
- Summary
- Practical Matters: Installation, Configurations
- Examples of Use

Background/Motivation

Good radiative transfer (RT) simulation tools are important because, for user-specified inherent optical properties (IOPs), they:

- can be used to generate
  1. **irradiances** at any user-specified levels in an atmosphere-water system as well as
  2. **radiances** [$I(\tau, \mu, \phi)$, **see Eq. (1) below**] at any user-specified levels and directions;
- will avoid unnecessary loss of time spent on developing tools that in general will be:
  – less reliable, less general, and
  – more likely to produce erroneous results
- will lead to significant progress in research areas such as:
  – **remote sensing algorithm development**
  – **climate research**
  – **other atmospheric and hydrologic applications.**

Brief Review of Current Status – Future Needs?

Typical tools currently available:

- SBDART, Streamer, LibRadtran – atmosphere **only**
  - good tools for atmospheric applications
  - no coupling to underlying water body – oceanic input is a boundary condition
- Hydrolight – ocean (natural waters) **only**
  - good tool for marine optics applications – provides water-leaving radiance, but no TOA radiance
  - no coupling to atmosphere – atmospheric input is a boundary condition

Very few reliable, well-tested, and user-friendly RT tools for a **coupled** atmosphere-water system are available. Therefore, the **AccuRT** tool described here:

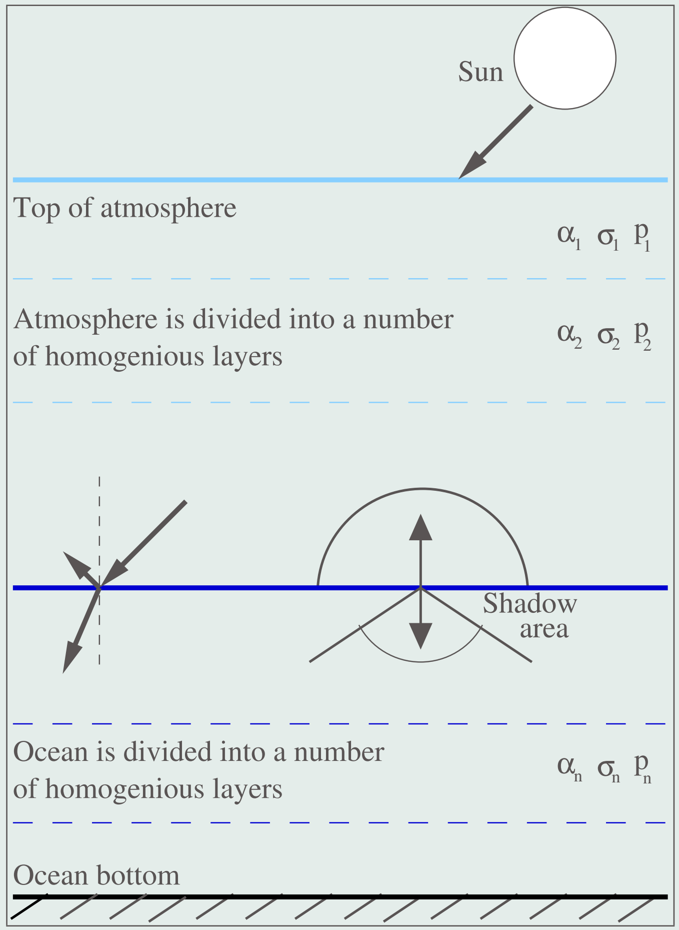
- **will fill an existing need.**

AccuRT is well-tested and was designed to be:

- **reliable, robust, versatile, and easy-to-use.**

Schematic Illustration of Atmosphere – Water System

The coupled atmosphere ocean system



Note: $\sigma \rightarrow \beta$ in the following!

Unified Treatment of Atmosphere and Water

In either of the two slabs (atmosphere or water), the diffuse radiance distribution $I(\tau, \mu, \phi)$ can be described by the radiative transfer equation (RTE):

$$\begin{aligned} \mu \frac{dI(\tau,\mu,\phi)}{d\tau} &= I(\tau,\mu,\phi) - S^*(\tau,\mu',\phi') - [1-\varpi(\tau)]B(T(\tau)) \\ &- \frac{\varpi(\tau)}{4\pi}\int_0^{2\pi} d\phi' \int_{-1}^{1} p(\tau,\mu',\phi';\mu,\phi)I(\tau,\mu',\phi')d\mu'. \end{aligned} \tag{1}$$

Here μ is the cosine of the polar angle θ, and ϕ is the azimuth angle. **The inherent optical properties (IOPs) are: the absorption coefficient, $\alpha(\tau)$, the scattering coefficient, $\beta(\tau)$, and the scattering phase function, $p(\tau, \mu', \phi'; \mu, \phi)$.** The ratio $\varpi(\tau) = \beta(\tau)/[\alpha(\tau)+\beta(\tau)]$ is called the single-scattering albedo, $S^*(\tau, \mu', \phi') \propto \varpi F_0$, where F_0 is the incident solar irradiance, and $B(T(\tau))$ is the Planck function. The differential vertical optical depth is

$$d\tau(z) = -[\alpha(\tau) + \beta(\tau)]dz \tag{2}$$

where the minus sign indicates that τ increases in the downward direction, whereas z increases in the upward direction. The scattering angle Θ and the polar and azimuth angles are related by

$$\cos\Theta = \cos\theta\ \cos\theta' + \sin\theta'\ \sin\theta\ \cos(\phi' - \phi).$$

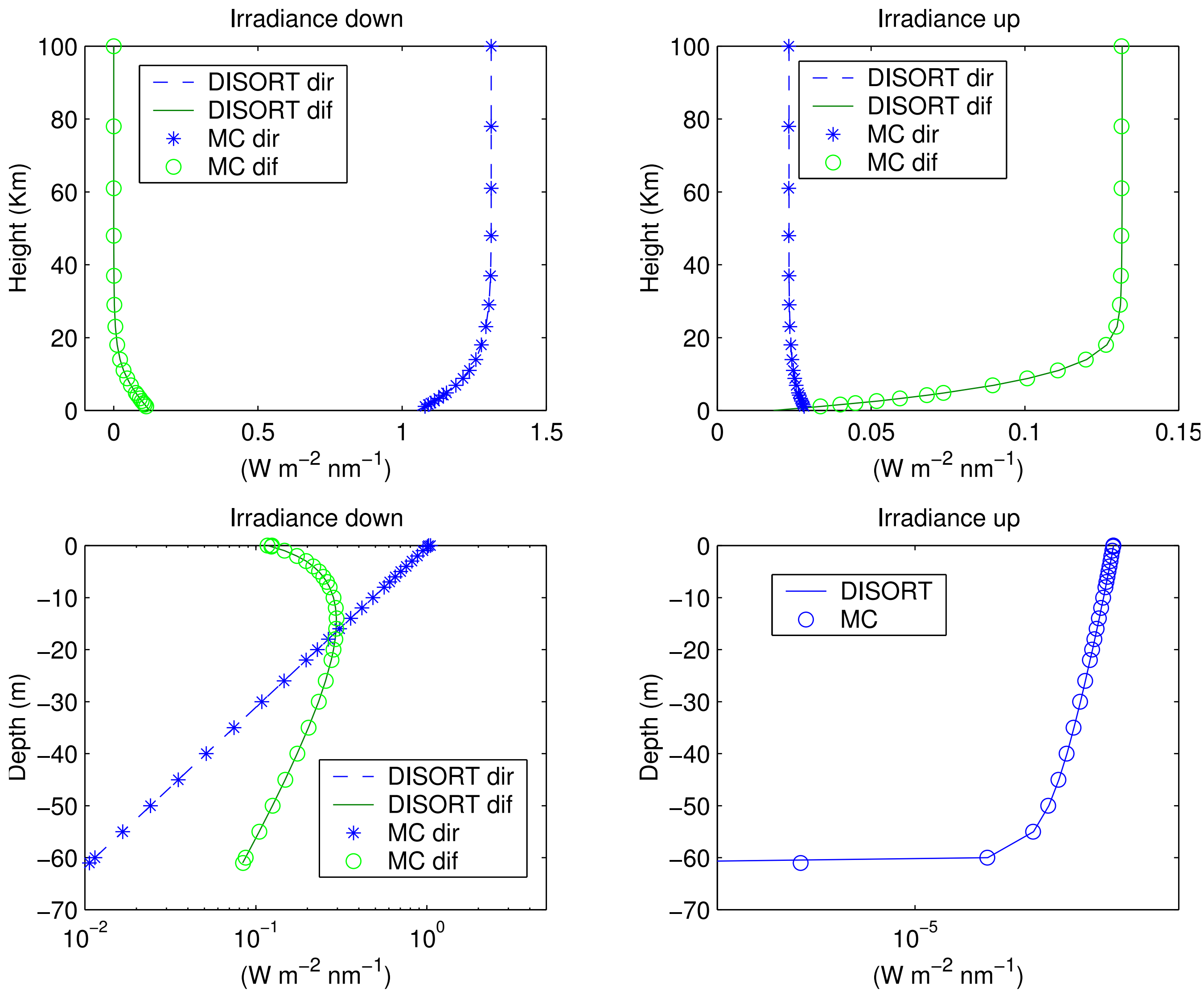
Overview of AccuRT/Key Features

AccuRT works as follows:

1. Slab$_1$ (atmosphere) and slab$_2$ (water) are separated by a plane interface at which the **refractive index changes from m_1 in slab$_1$ to m_2 in slab$_2$**.
2. Each of the two slabs is divided into a sufficiently large number of homogenous horizontal layers to adequately **resolve the vertical variation** in its IOPs.
3. **Fresnel's equations** for the reflectance and transmittance are **applied at the slab$_1$-slab$_2$ (air-water) interface**, in addition to the **law of reflection and Snell's Law** to determine the directions of the reflected and refracted rays.
4. Discrete-ordinate (DISORT[†]) solutions to the RTE are computed separately for each layer in the two slabs.
5. Finally, **boundary conditions** at the top of the atmosphere and the bottom of the water are applied, in addition to **continuity conditions** at layer interfaces within each of the two slabs.

[†] K. Stamnes, S. C. Tsay, W. J. Wiscombe, and K. Jayaweera, Numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media, Applied Optics, 27, 2502-2509, 1988.

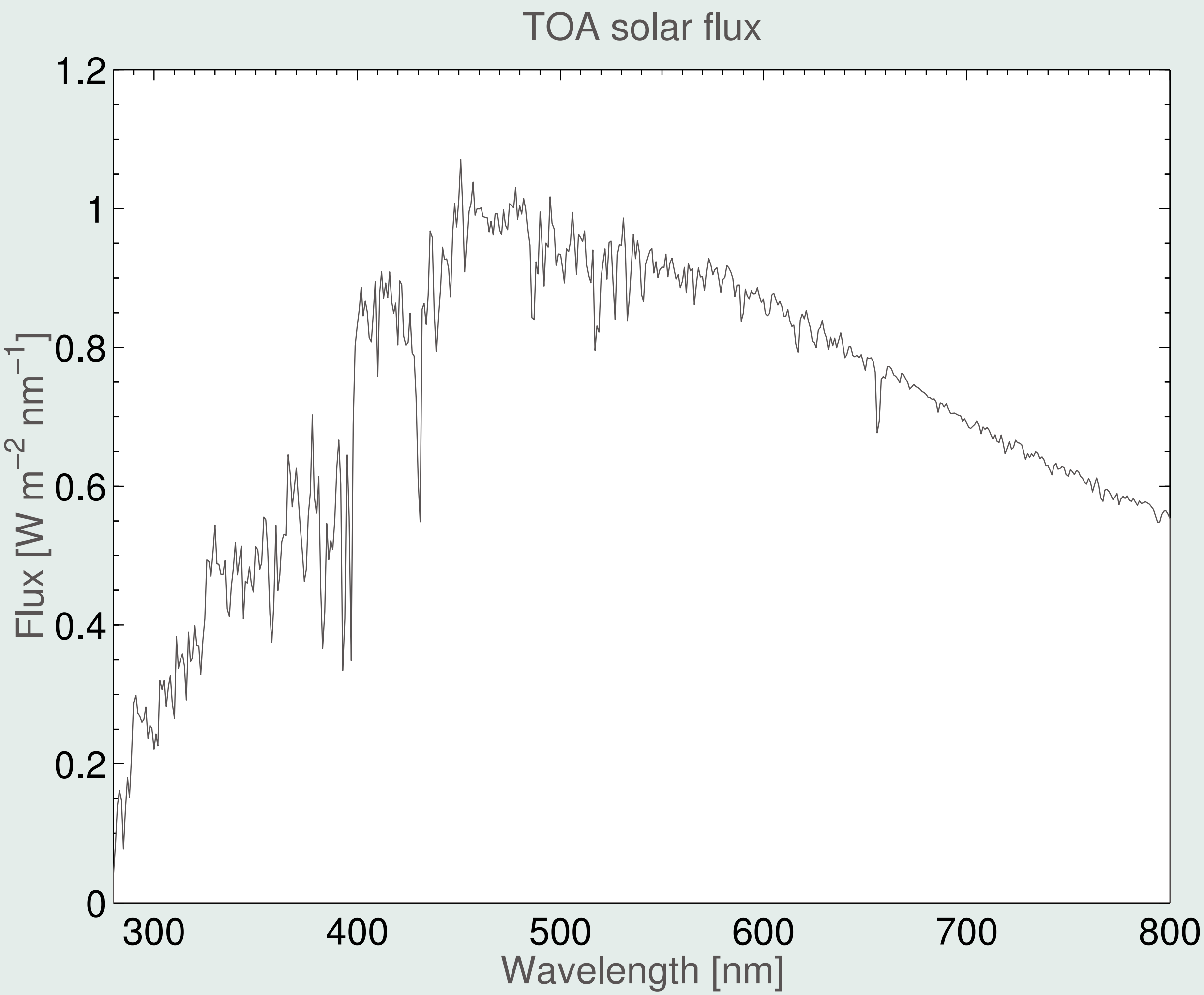
Results – Validation against Monte Carlo



For details, see: K.I. Gjerstad, J.J. Stamnes, B. Hamre, J.K. Lotsberg, B. Yan, and K. Stamnes, Monte Carlo and discrete-ordinate simulations of irradiances in the coupled atmosphere-ocean system, Appl. Opt. 42, 2609-2622 (2003).

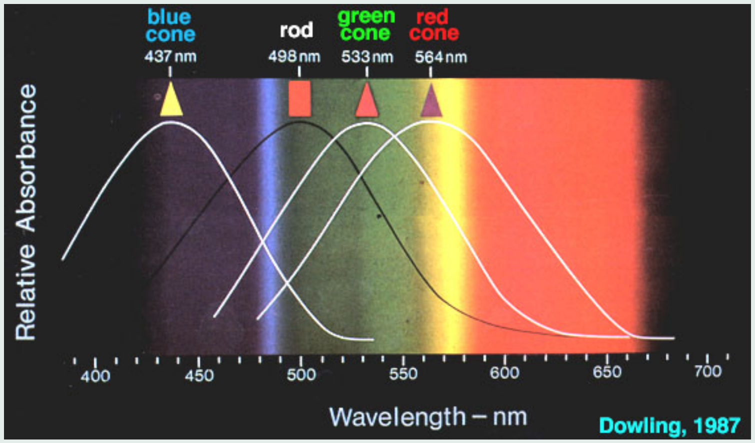
Results – Simulated Radiation Field (1)

Solar spectrum

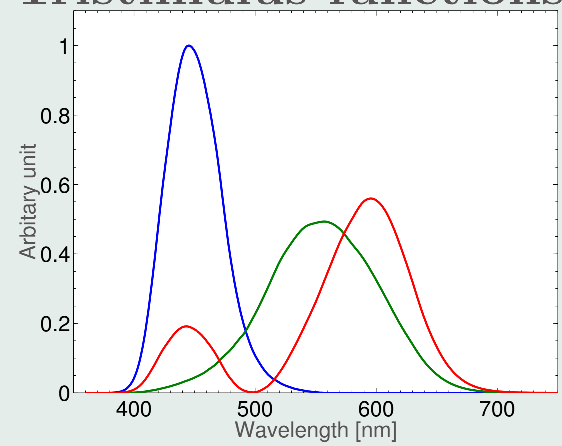


Results – Simulated Radiation Field (2)

Color response functions of the eye



Tristimulus functions



Tristimulus values

$$X = \int_0^\infty F(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y = \int_0^\infty F(\lambda)\bar{y}(\lambda)d\lambda$$

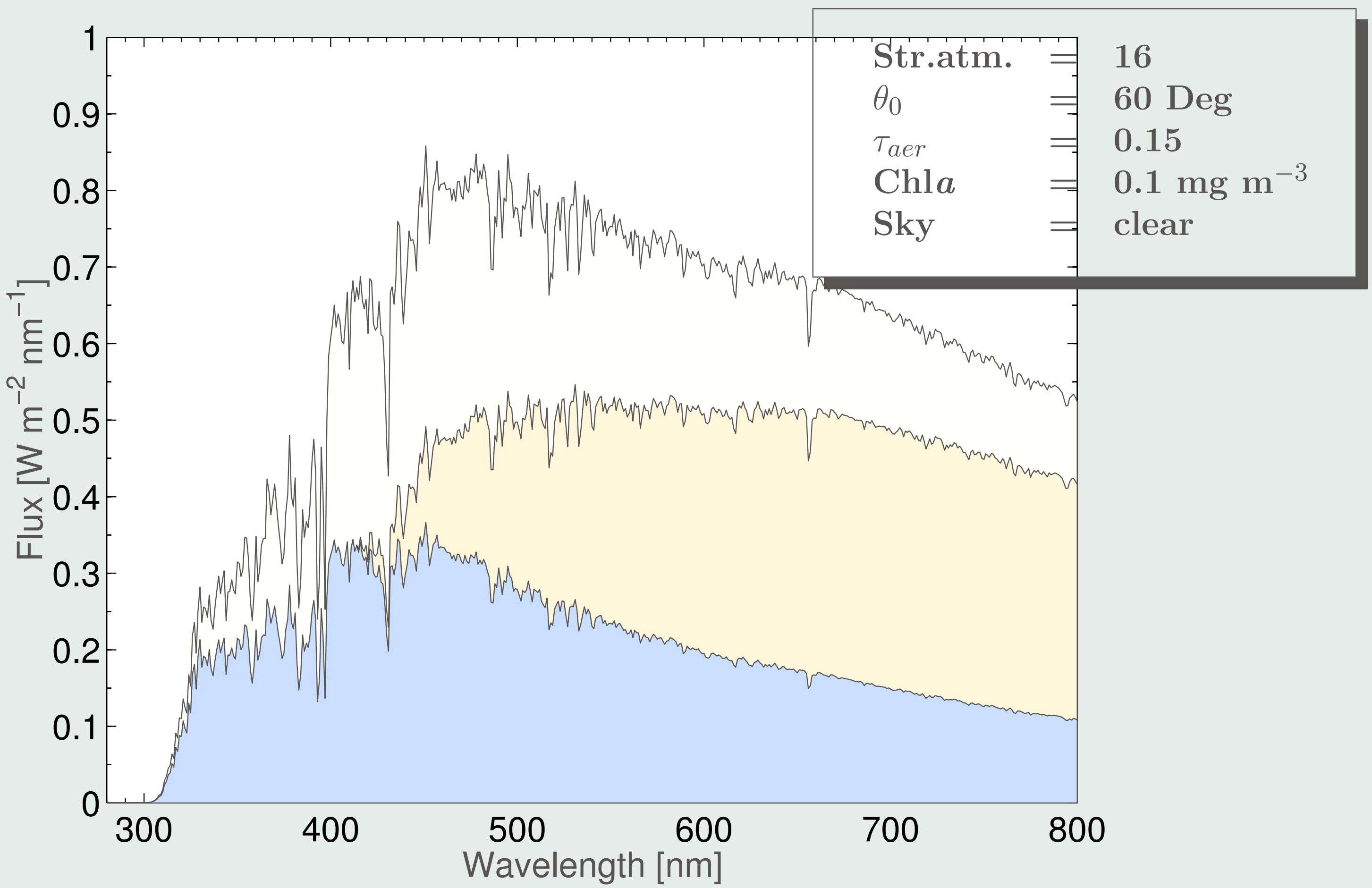
$$Z = \int_0^\infty F(\lambda)\bar{z}(\lambda)d\lambda$$

rgb color space

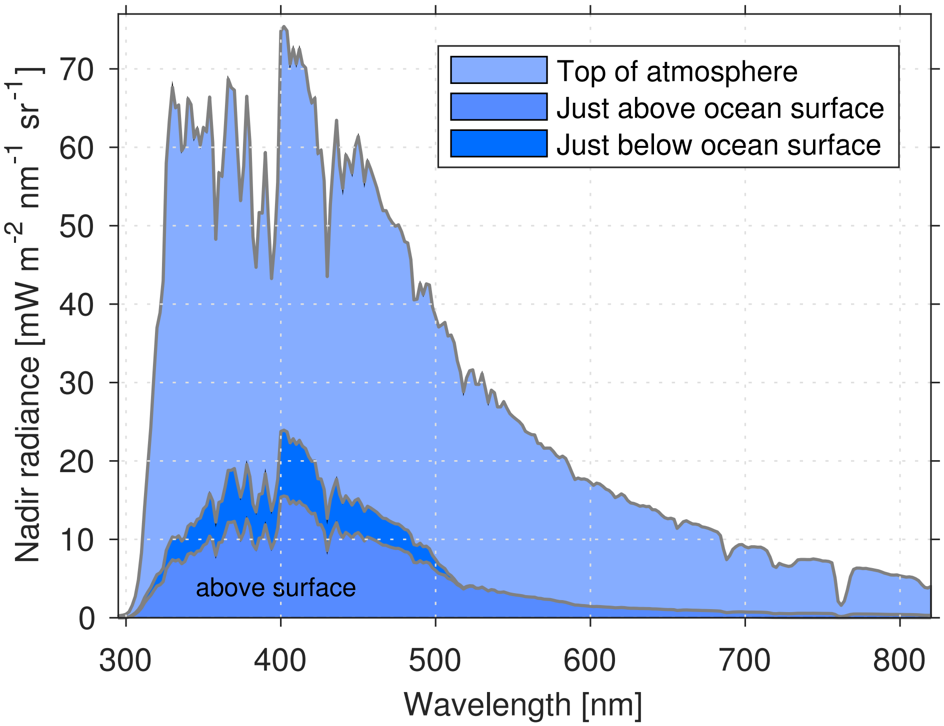
$$\begin{bmatrix} r \\ g \\ b \end{bmatrix} = \left(\begin{bmatrix} \textbf{A 3 x 3} \\ \textbf{conversion} \\ \textbf{matrix} \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ X \end{bmatrix} \right)^{\frac{1}{2.2}}$$

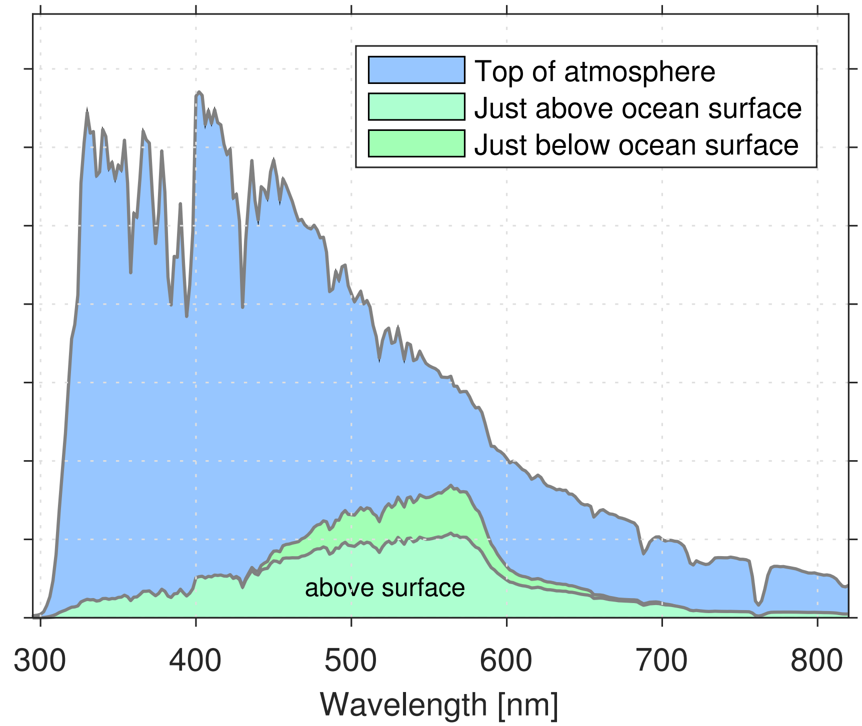
Results – Simulated Radiation Field (3)

Modeled downward surface solar radiation



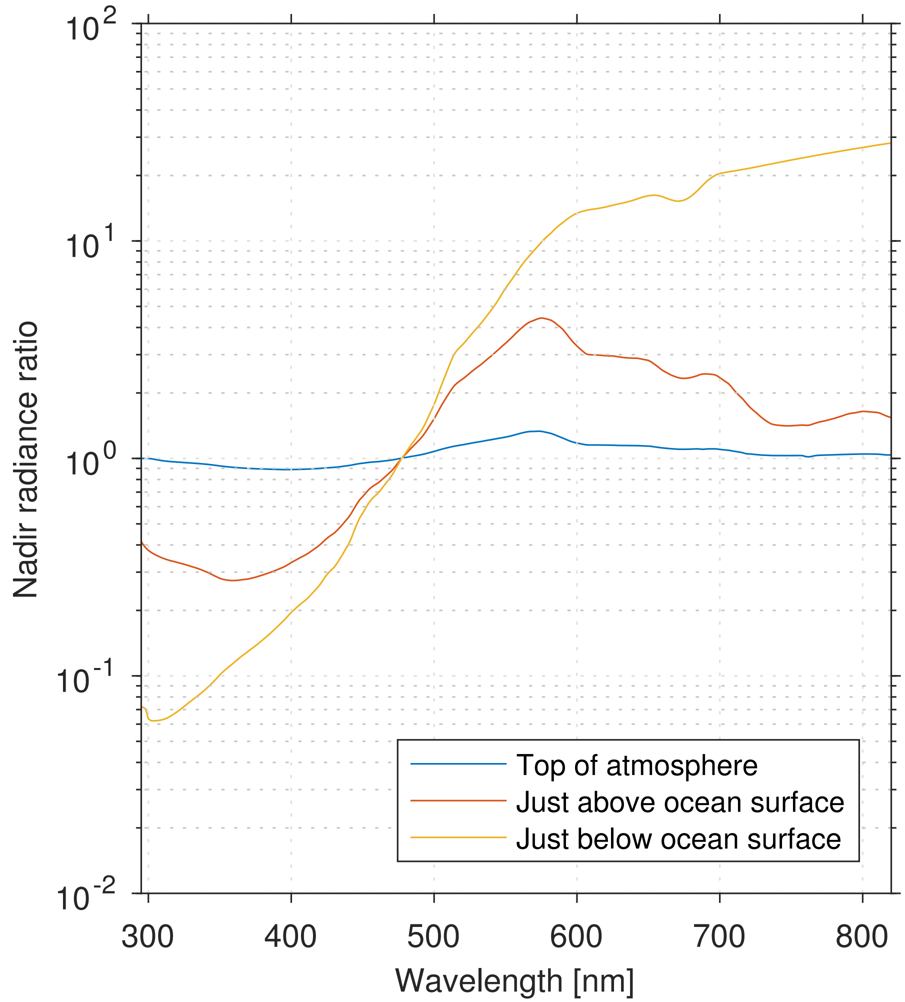
Results – Simulated Radiation Field (4)





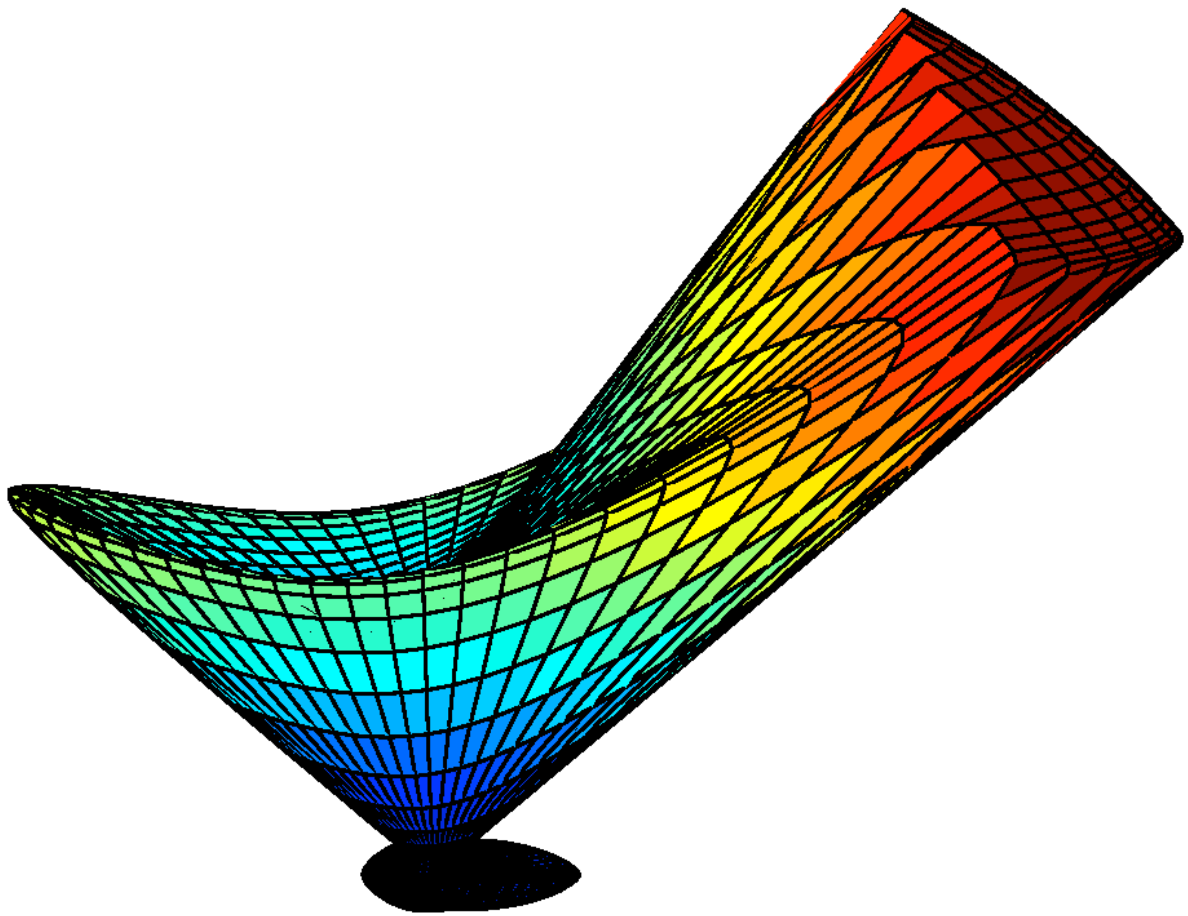
Simulated **upward radiance in the nadir direction** at the top of the atmosphere and close to the ocean surface.
Solar zenith angle = 45°, US Standard atmosphere with aerosol optical depth = 0.23 at 500 nm.
(**Left**) Clear water with chlorophyll concentration = **0.1 mg·m^{-3}**, MIN = 0.003 g·m^{-3}, CDOM443 = 0.003 m^{-1} (CCRR bio-optical model).
(**Right**) Turbid water with chlorophyll concentration = **10 mg·m^{-3}**, MIN = 0.1 g·m^{-3}, CDOM443 = 0.1 m^{-1}.

Results – Simulated Radiation Field (5)

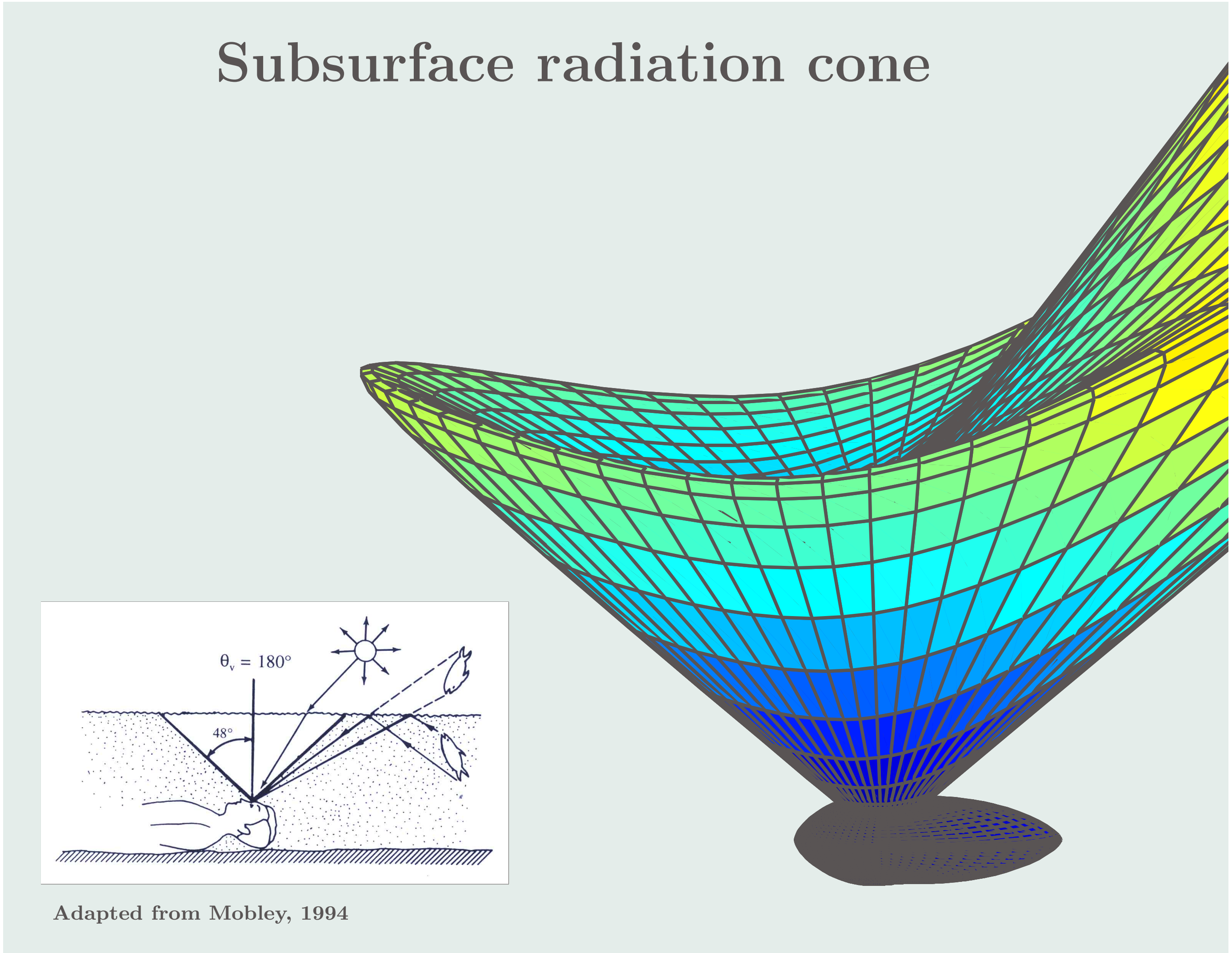


The ratio of the values for turbid water to those for clear water in the figure above.

Results – Simulated Subsurface Radiation Cone (1)



Results – Simulated Subsurface Radiation Cone (2)



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Summary (1)

We have provided a brief description of **AccuRT**:

- **a reliable, robust, user-friendly, and versatile tool for radiative transfer simulations in a coupled atmosphere-water system.**

The required input parameters are:

- layer-by-layer optical depths and IOPs consisting of absorption and scattering coefficients as well as the scattering phase function.

AccuRT has the following unique features:

1. it allows for a user-specified number of layers in the atmosphere and water to adequately resolve the vertical variation in IOPs;
2. it computes upward and downward irradiances, scalar irradiances, and diffuse attenuation coefficients at user-specified optical depths in the atmosphere and water;
3. it computes radiances in user-specified directions at user-specified optical depths in the atmosphere and water.

Summary (2)

The IOPs can be:

- either user-specified or selected from a suite of IOPs based on published models and data, including IOP models for open ocean and turbid coastal waters;
- clear-sky atmosphere IOPs include molecular scattering and gaseous absorption;
- standard models for aerosol/cloud scattering and absorption are included.

AccuRT is designed to address the needs of researchers interested in:

- analyzing irradiance and radiance measurements in the field or laboratory
- making simulations of irradiances or radiances in support of
  - remote sensing algorithm development
  - climate research (data assimilation)
  - other atmospheric and hydrologic applications.

In conclusion: **AccuRT** is expected to fill an existing need and be:

- ***a valuable and indispensable tool for teachers, students as well as researchers in the atmospheric optics, ocean optics, climate research, and remote sensing communities.***

Next: Practical matters (important details)....

Installation of VM version of AccuRT

The configuration of this Debian Linux w/ AccuRT Virtual Machine (VM) is as follows (see Section 3 of User manual for details):

1. debian 9 with xfce4 GUI
2. AccuRT v1.0.716
3. openssh enabled
4. Firefox ESR browser
5. GNU Octave (free alternative of MATLAB) 6. FileZilla (free FTP client)

You can **run AccuRT** on this VM and **plot results** using Octave. FileZilla allows you to **transfer your results to other machines** as needed and the command line sftp/scp tools are also available. (Or you can use your VM software to transfer to/from the VM to your host machine.)

To start using this VM version of AccuRT, you need to download Oracle VirtualBox from the following website:

https://www.virtualbox.org/wiki/Downloads

Table 1: Core materials included in AccuRT.

Core Material	options	allowed position	descriptions
earth_atmospheric_gases			
	1. gasIOP 2. air	upper slab	profiles of atmospheric molecular absorption and Rayleigh scattering optical depths.
aerosols			particulate matter in the atmosphere.
clouds	1. water cloud 2. ice cloud	upper slab	clouds consisting of liquid water droplets and ice particles in the atmosphere.
pure_water		lower slab	pure water.
water_impurities_ccrr		lower slab	dissolved and particulate matter in the water based on the CCRR bio-optical model.
water_impurities_gsm		lower slab	dissolved and particulate matter in the water based on the GSM bio-optical model.
vacuum		both slabs	synthetic material which allows for either of the two slabs comprising the coupled medium to be transparent.
Cryosphere Material	options	allowed position	descriptions
snow	1. ISIOP 2. Mie	upper slab	snow material
ice	1. ISIOP 2. Mie	lower slab	ice floating over ocean

AccuRT Configuration (1)

Basic structure

"Earth solar" or "Constant one"

TOA

Upper slab

Layer 1

Layer 2 ···

··· Layer N

- Atmospheric gases (Rayleigh & gas IOPs)
- Aerosols
- Cloud
- Snow
- Vacuum
- User specified

Interface n_1 n_2

Lower slab

Layer 1

Layer 2 ···

··· Layer N

- Pure water
- Water impurities (CCRR or GSM model)
- Sea ice
- Vacuum
- User specified

Bottom

"Loamy sand" or "White"

AccuRT Configuration (2)

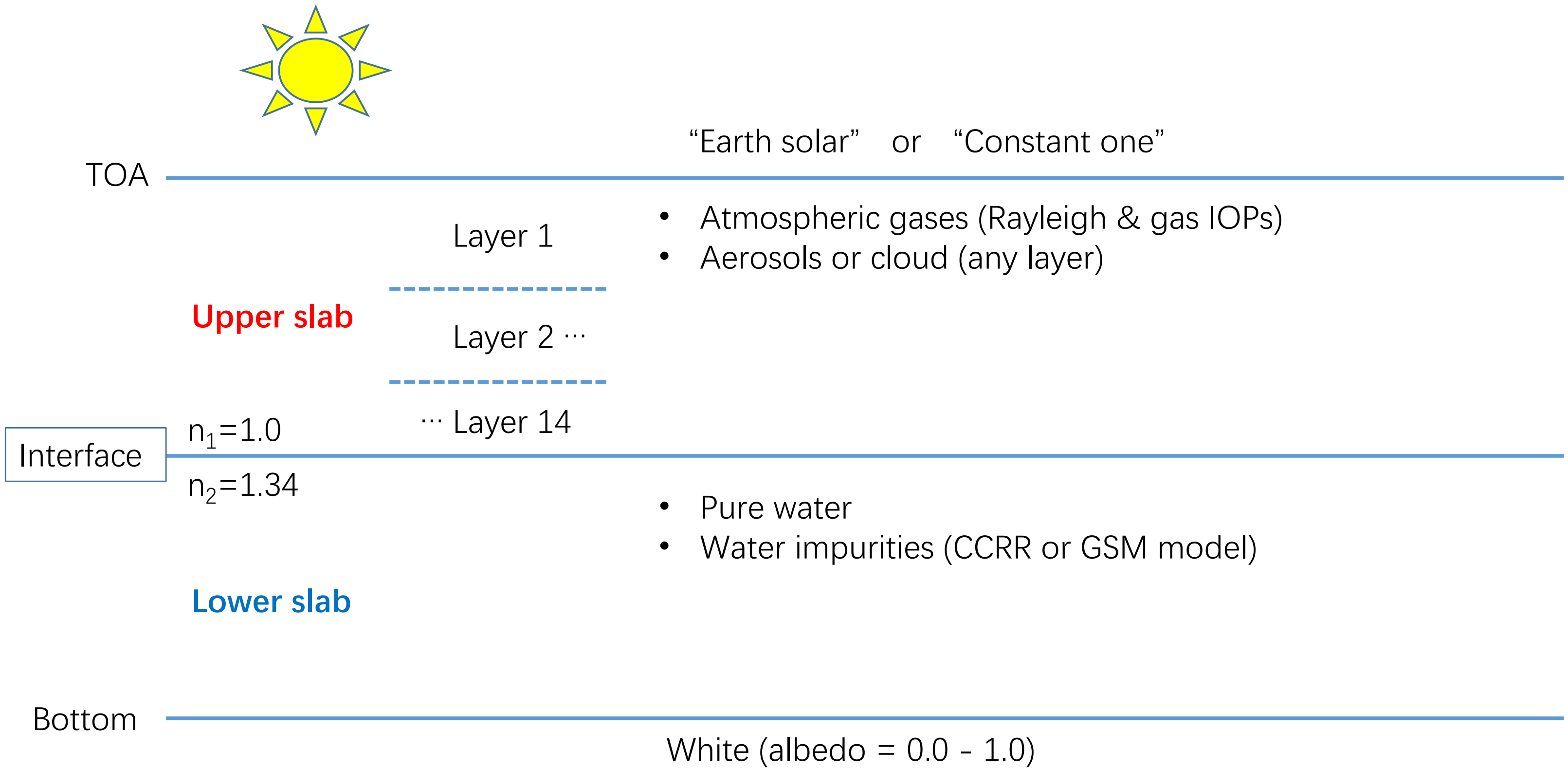
STR1 = number of streams in upper slab.

Setup AccuRT

- **Source:** solar spectrum or "constant one"; scaling factor is 1.0 by default, solar zenith angle is 45 by default.
- **Bottom:** "loamy sand" or if "white" (no wavelength dependence); specify albedo, default is 0.0.
- **Streams:** stream number can be set in the upper slab, stream number in the lower slab is computed as: $STR2=STR1*n_2^2$.
- **Layers:** layers can be set by specifying various depths in the upper or lower slab. Total depth of the upper slab is 100 km.
- **Materials:** materials can be added in desired layers by setting the material profile. General format of the material profile is: layer number, amount of materials.
- **Output:** specify output depths, angles, wavelengths, irradiances, radiances, IOPs, etc.

AccuRT Examples (1)

AccuRT examples: Coupled atmosphere-ocean system



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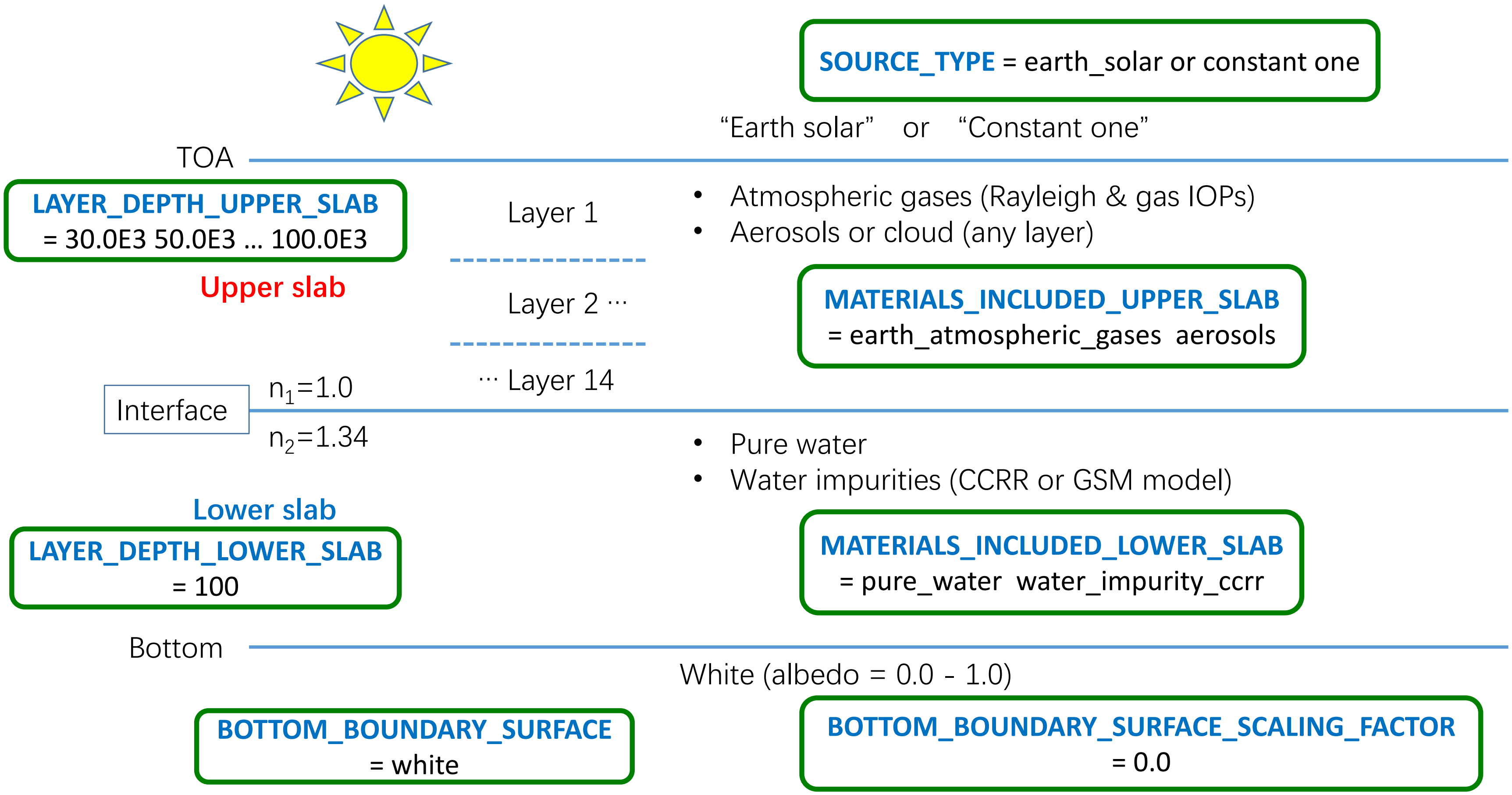
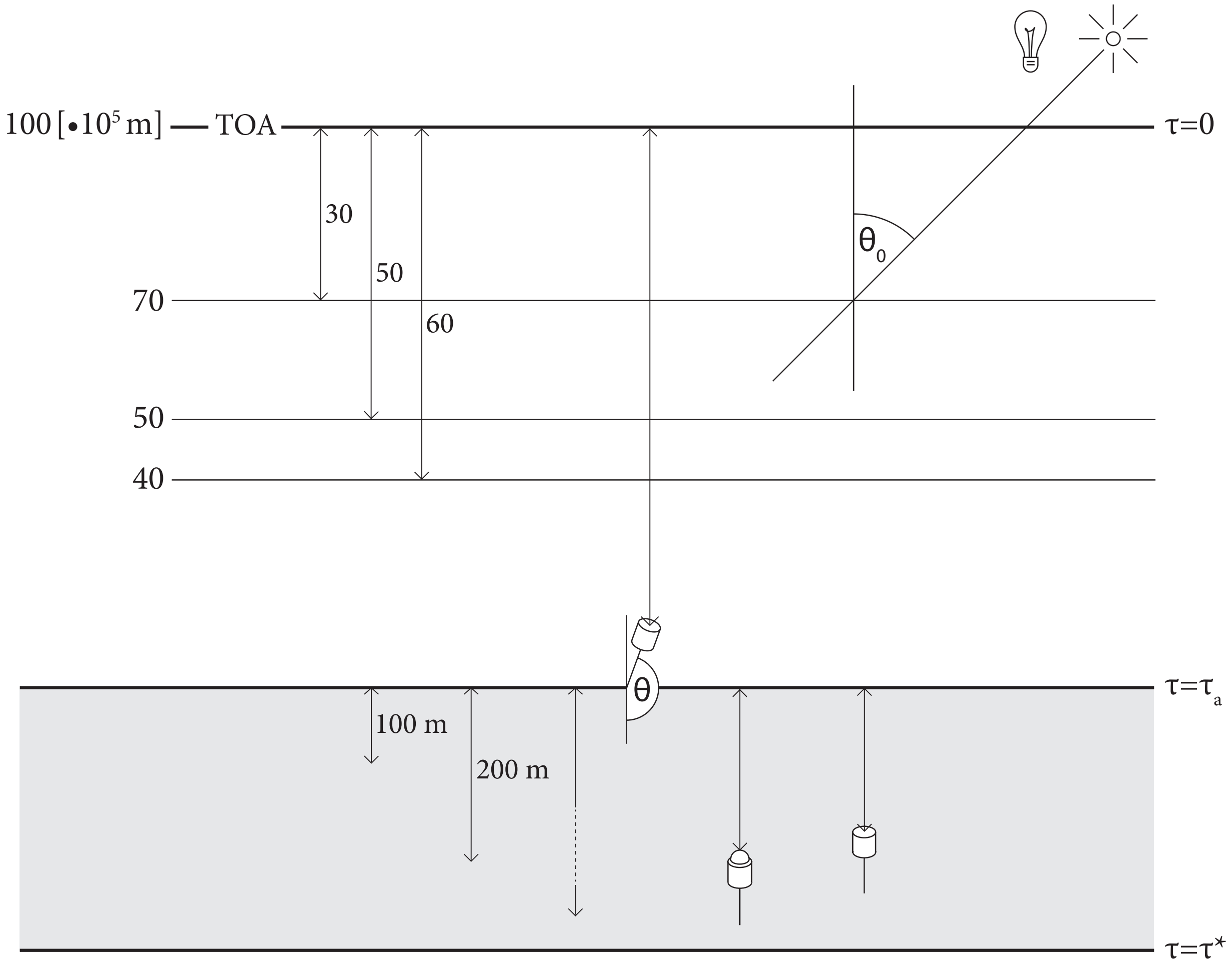
AccuRT Examples (2)

AccuRT examples of configuration file: Coupled atmosphere-ocean system



See Appendices of User Manual for description of configuration files.

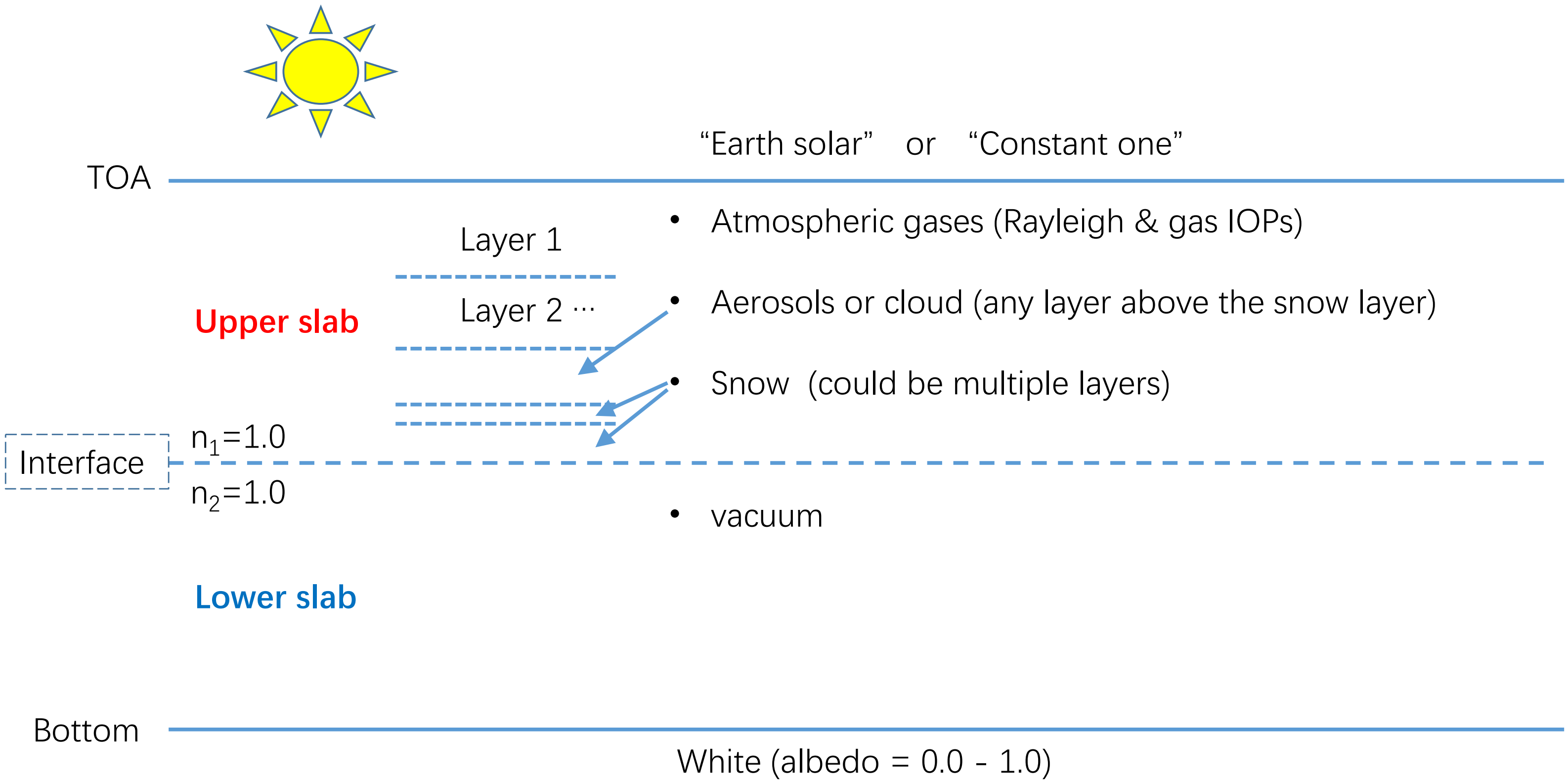
AccuRT Examples (2b)



See Appendix 1 (page 19) of User Manual for details.

AccuRT Examples (3)

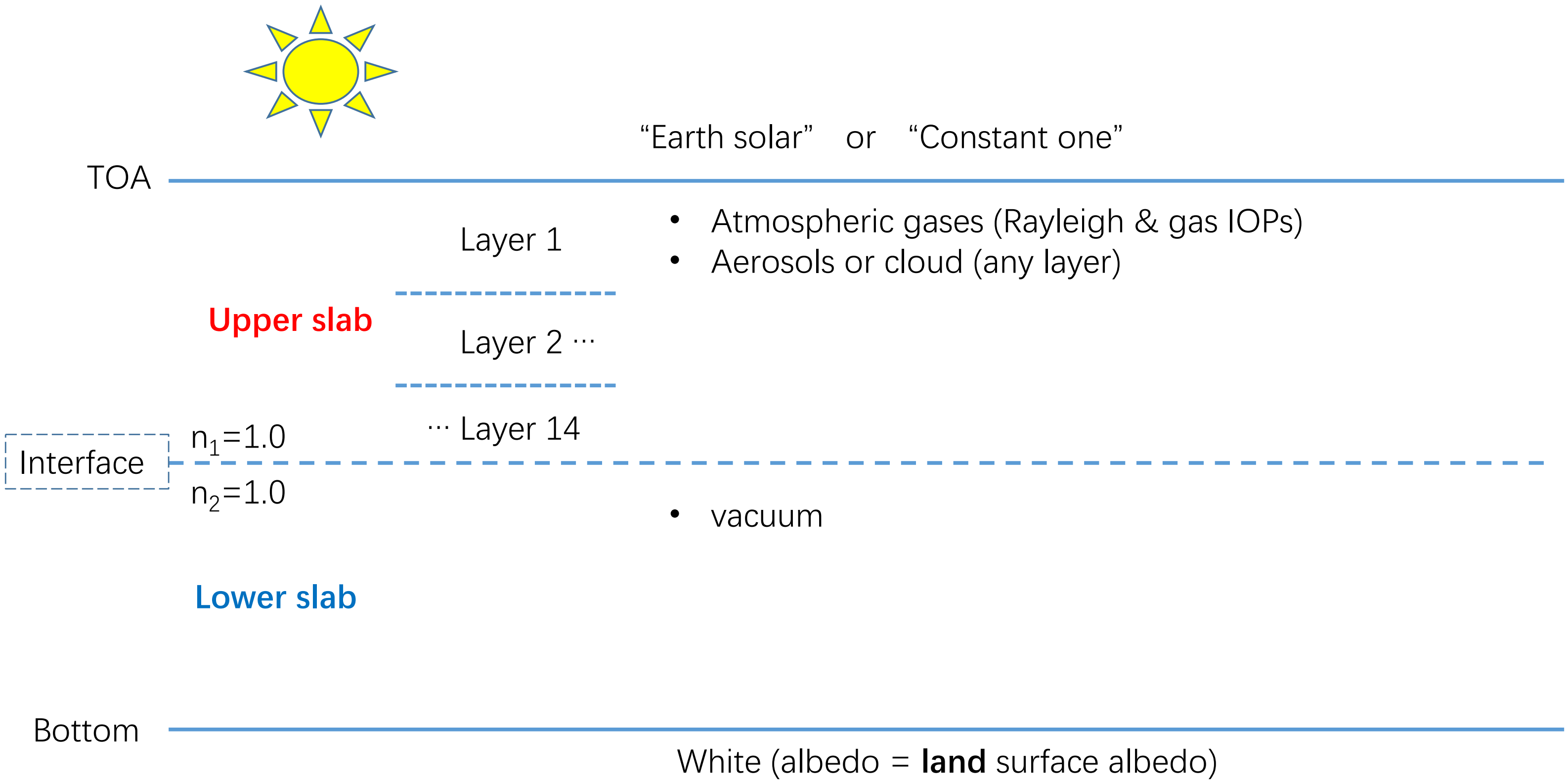
AccuRT examples: Coupled atmosphere-snow system



Note: We treat snow as a “cloud” on the ground consisting of particles (snow flakes) that scatter and absorb radiation.

AccuRT Examples (4)

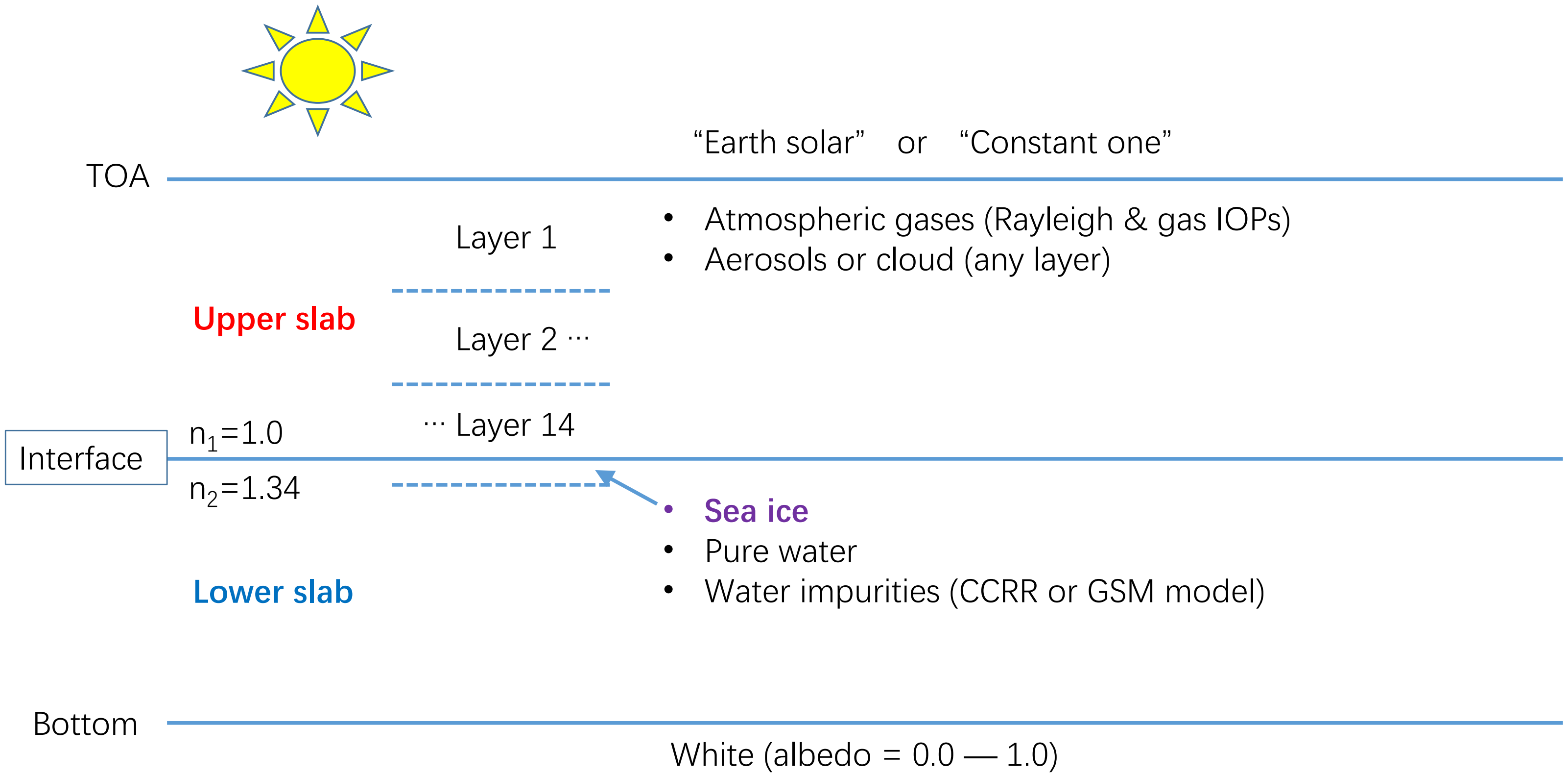
AccuRT examples: Coupled atmosphere-land system



Note: We set $n_2 = n_1$, put "vacuum" in the lower slab, and specify albedo as a boundary condition at the bottom of the lower slab.

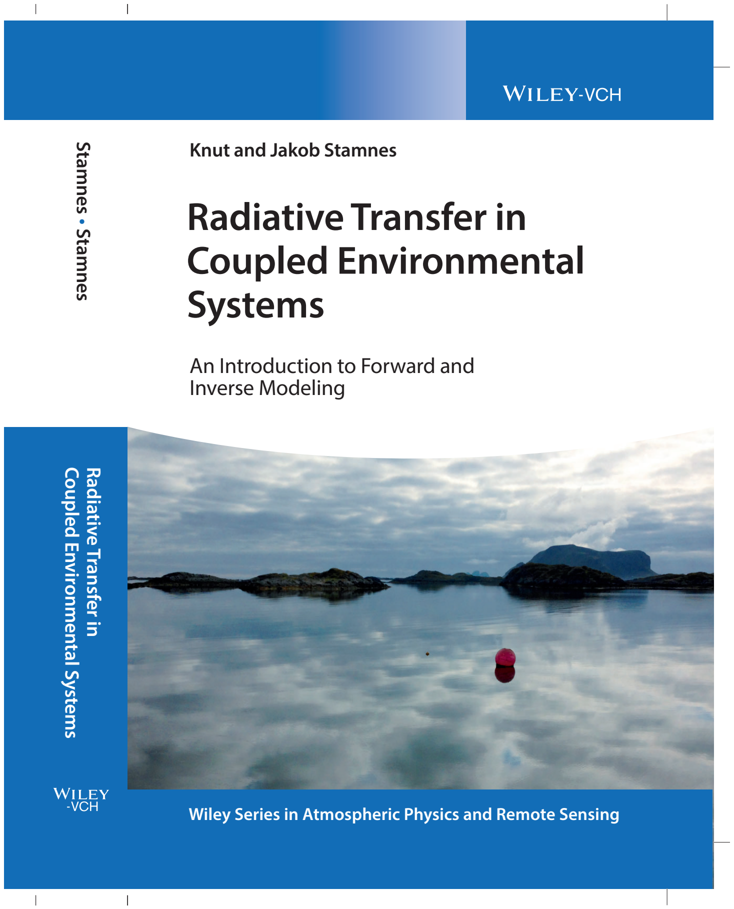
AccuRT Examples (5)

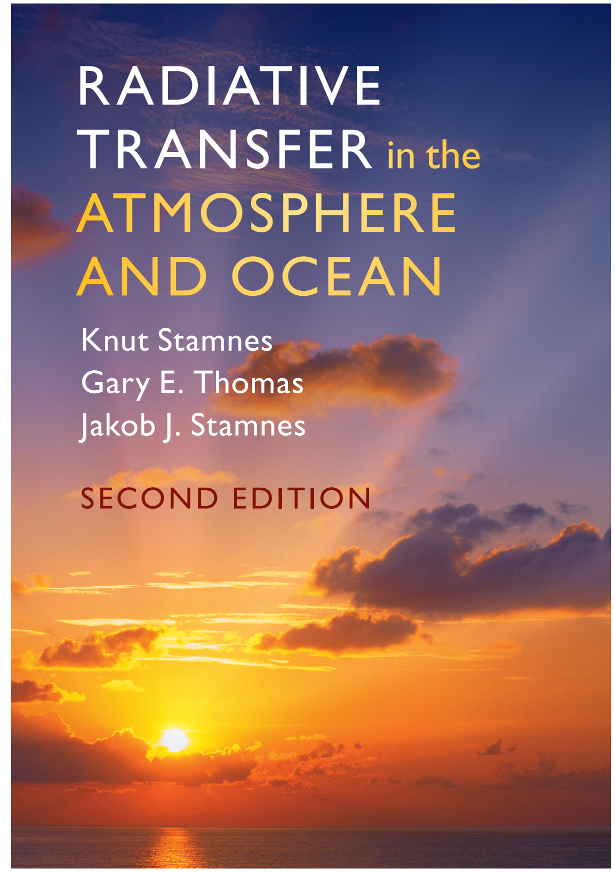
AccuRT examples: Coupled atmosphere-ice-ocean system



Note: We set $n_2 = 1.34$, put **ice** in the top layer of the lower slab, and **water** with embedded impurities underneath (**water** on top of **ice** is also possible).

Questions – Comments – Suggestions – Further reading?





THANK YOU FOR YOUR ATTENTION!