Environmental challenges for polar remote sensing: surface (water) to top-of-atmosphere

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$$\mu \frac{dL(\tau,\mu,\phi)}{d\tau} = L(\tau,\mu,\phi) - \frac{\varpi(\tau)}{4\pi}\int_0^{2\pi} d\phi' \int_{-1}^{1} d\mu' p(\tau,\mu',\phi';\mu,\phi) L(\tau,\mu',\phi')$$
$$- \frac{\varpi(\tau)}{4\pi} p(\tau,-\mu_0,\phi_0;\mu,\phi) F^s e^{-\tau\, Ch(\mu_0)}.$$

The vertical optical depth is defined as $\tau(z) = \int_z^\infty c(z)dz$, implying that $\tau(z)$ increases downwards from the value $\tau(z=\infty) = 0$ at the top-of-the-atmosphere (TOA). **Pseudo-spherical:** $Ch(\mu_0)$. **Plane-parallel:** $Ch(\mu_0) \rightarrow 1/\mu_0$.

The Generic Problem: The small ocean signal!

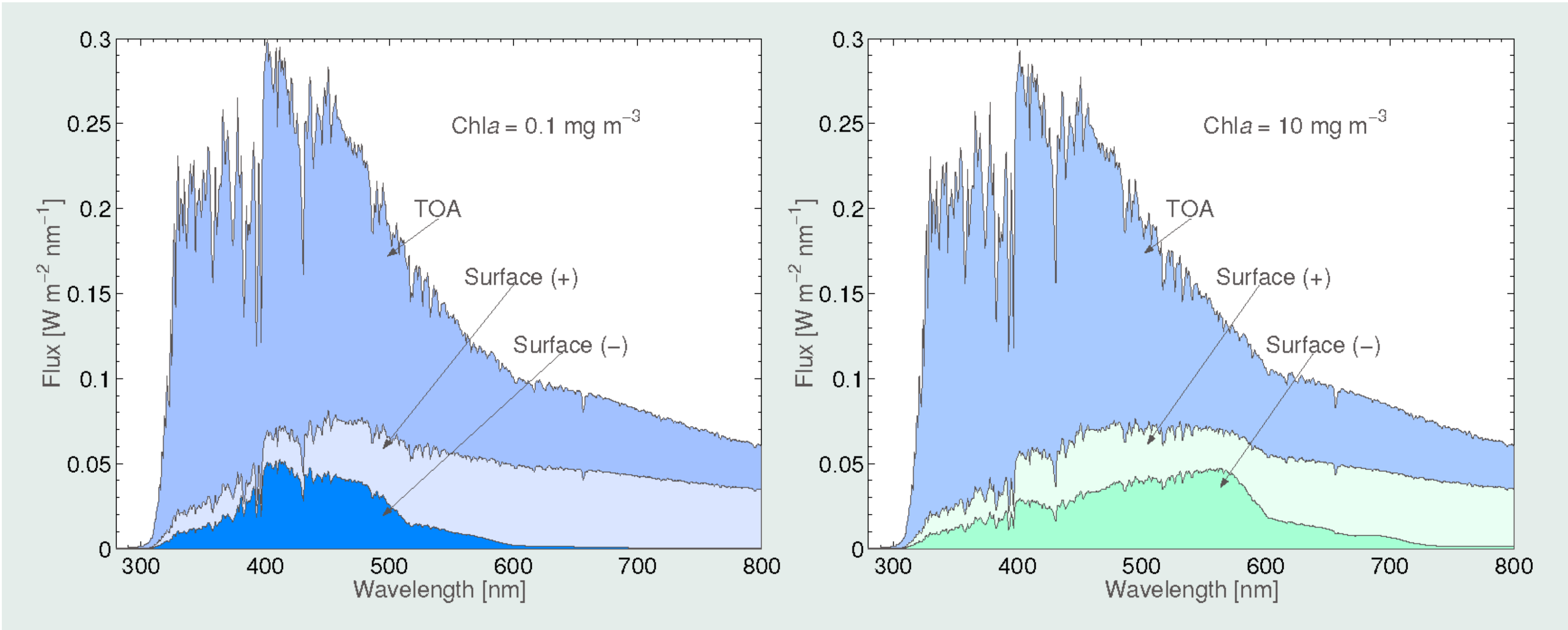

Figure 1: **Left:** Simulated upward irradiance at TOA (upper curve filled with blue color), just above the ocean surface (middle curve filled with light blue color), and just below the ocean surface (lower curve filled with dark blue color). **Right:** Same as left panel, except that the chlorophyll concentration is $\times 100$ larger.

The simulation in the figure above shows that

- there is **a significant change** in sub-surface color with increasing chlorophyll concentration, while at the same time
- there is **only a slight change** in color at the TOA: **the TOA spectra are dominated by light from atmospheric scattering**.

Environmental challenges: What are the problems?

- **The persistence of clouds and fog:**
  - High latitude areas are characterized by **heavy cloud cover**, and
  - as soon as sea ice melts and open waters come into direct contact with the atmosphere, **fog develops** near the sea surface.
- **The prevailing low solar elevations:**
  - the solar zenith angle is often larger than the maximum for which atmospheric correction algorithms have been developed (generally $70°$).
  - the quality of standard atmospheric corrections for solar zenith angles larger than $70°$ must be assessed.
- **Standard ocean color algorithms do not work well in the Arctic:**

  Arctic continental shelves, occupying 50% of the area, are characterized by
  - high concentrations of CDOM due to freshwater inputs
  - low chlorophyll-specific absorption coefficients due to pigment packaging,

  Atmospheric correction does not work well at high latitudes.

Problem 1: The persistence of clouds and fog

Accurate and reliable **cloud screening** becomes a very important task:

- How is cloud screening done currently?
- Will the current approach work also at high latitudes?
- How will the presence of sea ice impact our ability to find cloud-free pixels that are not contaminated by its presence?
- If the current approach does not work, is it possible to modify it to make it work, or is a new approach required?

What about fog?

- Located close to the surface, fog is very difficult to detect and correct for.
- How do we distinguish between cloud/fog in a pixel and partial sea ice cover?
- How do we reliably "screen out" such pixels?

Another problem: For presumably clear (cloud/fog-free) pixels:

- How do we reliably convert the measured radiance to the corresponding nadir radiance used in standard (SeaDAS) retrieval schemes? How do we deal with
- this problem at high latitudes with low solar elevations and complex waters?

Problem 2: The prevailing low solar elevations

The **plane parallel approximation (PPA)** breaks down for solar zenith angles larger than about 70°. How do we proceed?

- One option: use the **pseudo-spherical approximation (PSA)** [Eq. (1)]:
  - the direct beam single scattering (solar pseudo-source) term is treated in spherical geometry: $e^{-\tau/\mu_0} \longrightarrow e^{-\tau\, Ch(r,\mu_0)}$ $\longleftarrow$ **PSA**
  - while the multiple scattering term is treated using the PPA:

$$\mu \frac{dL(\tau,\mu,\phi)}{d\tau} = L(\tau,\mu,\phi) - \overbrace{\frac{\varpi(\tau)}{4\pi}\int_0^{2\pi} d\phi' \int_{-1}^{1} d\mu' p(\tau,\mu',\phi';\mu,\phi) L(\tau,\mu',\phi')}^{\text{multiple scattering}}$$
$$- \overbrace{\frac{\varpi(\tau)}{4\pi} p(\tau,-\mu_0,\phi_0;\mu,\phi) F^s e^{-\tau\, Ch(\mu_0)}}^{\text{single scattering}} . \qquad (1)$$

- What about the lower boundary: 1-D or 2-D Gaussian?
- Explore advantage of using a 2-D Gaussian distribution of surface slopes?

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Advantage of using a 2-D Gaussian distribution of surface slopes

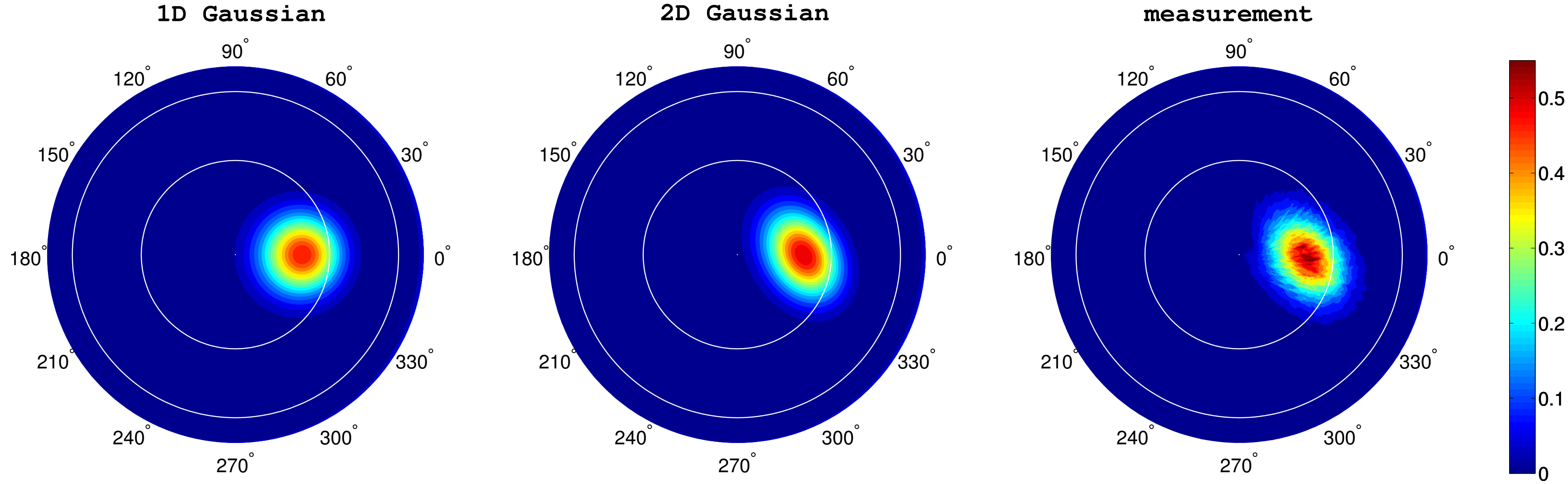


Figure 2: Comparison of reflectances for model simulations assuming a 1-D Gaussian BRDF (left), a 2-D Gaussian BRDF (middle), and measurements (right).

Use of
(1) a 2-D Gaussian surface slope distribution for singly scattered light, and
(2) a 1-D Gaussian surface slope distribution for multiply scattered light
is quite successful because the 2-D BRDF simulates the sunglint very well, while the 1-D BRDF is sufficient to simulate the smoother sky reflectance.

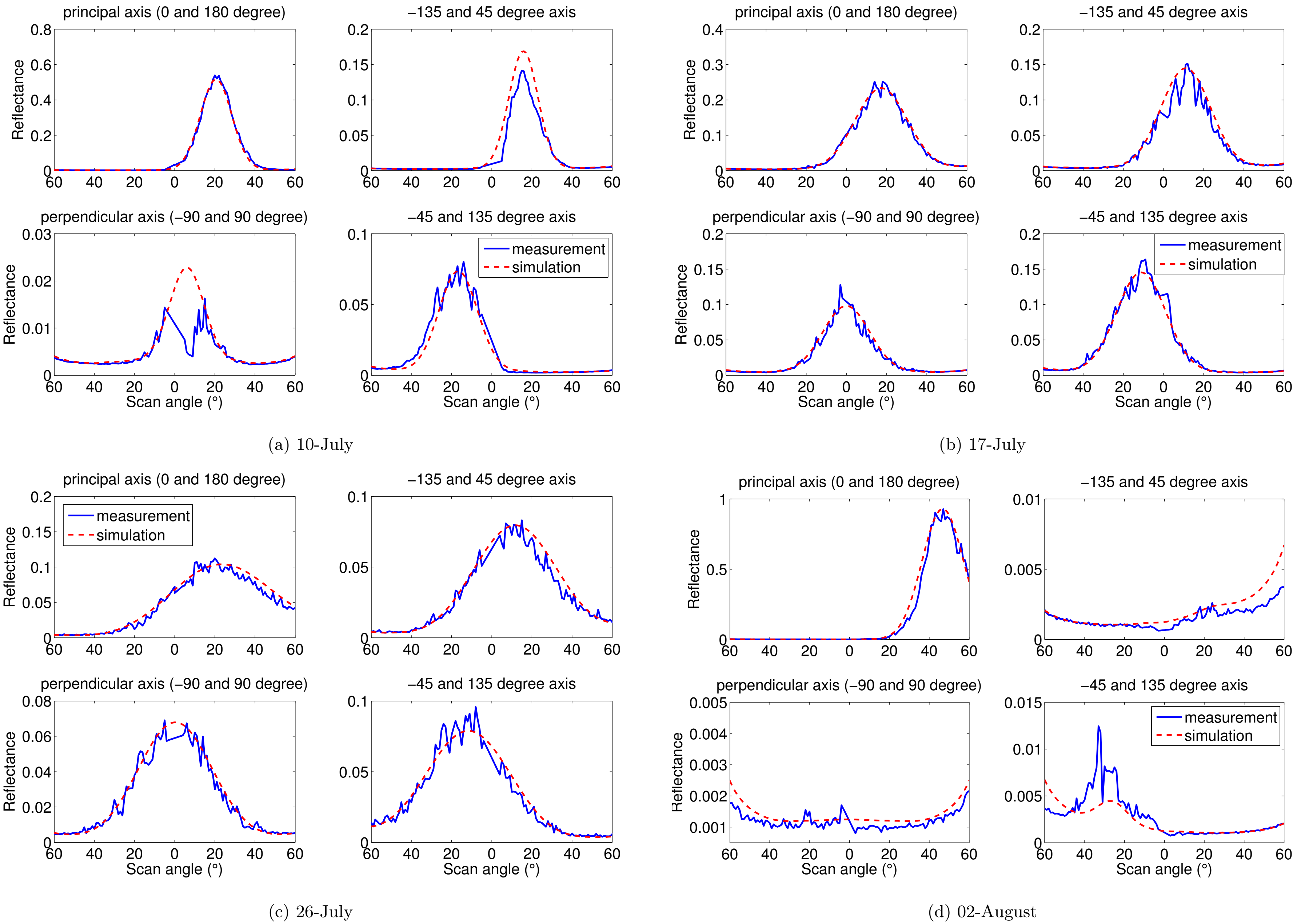


Figure 3: Comparison between model simulated reflectances and measured reflectances for different geometries.

Advantage of using the pseudo-spherical approximation

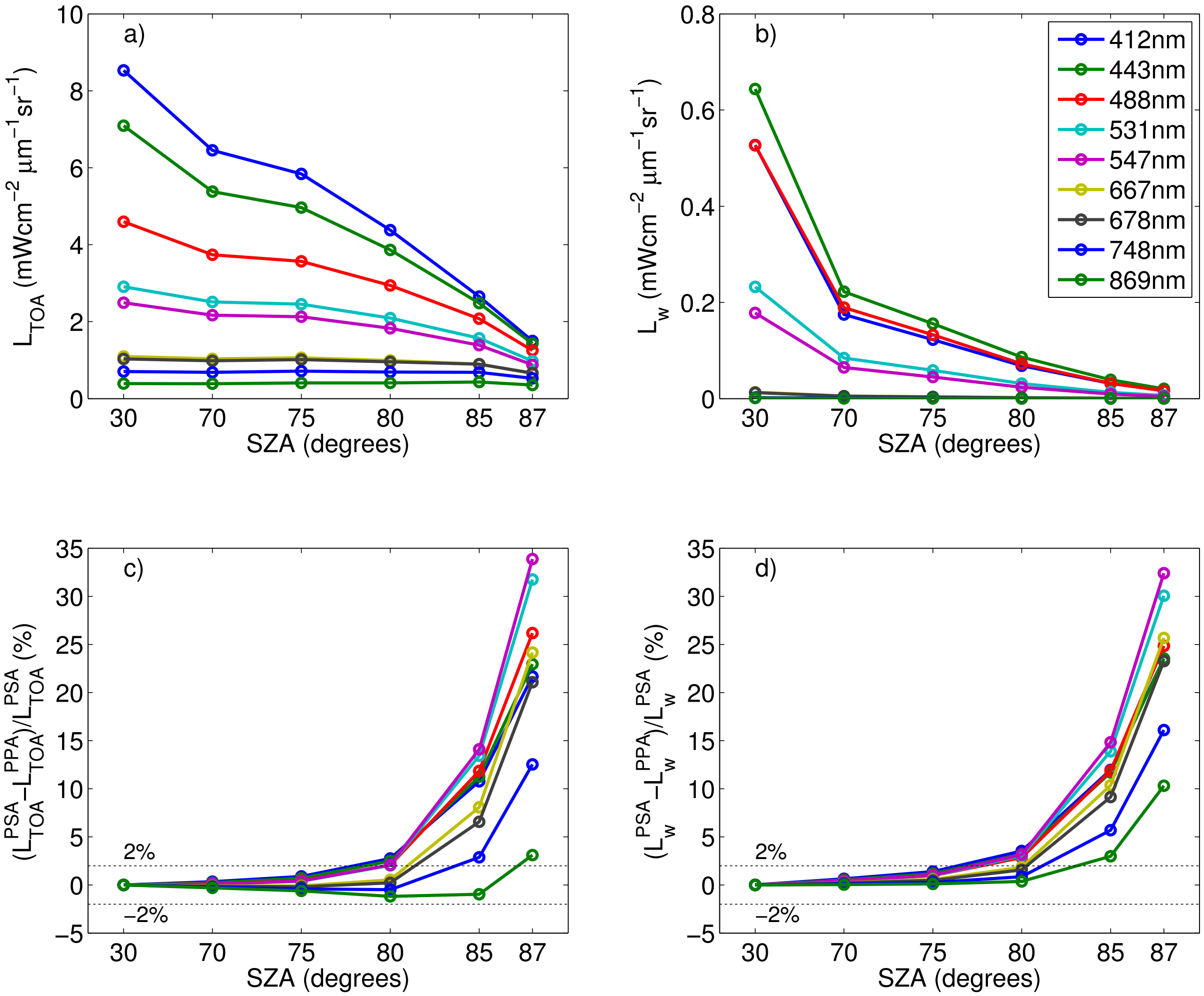
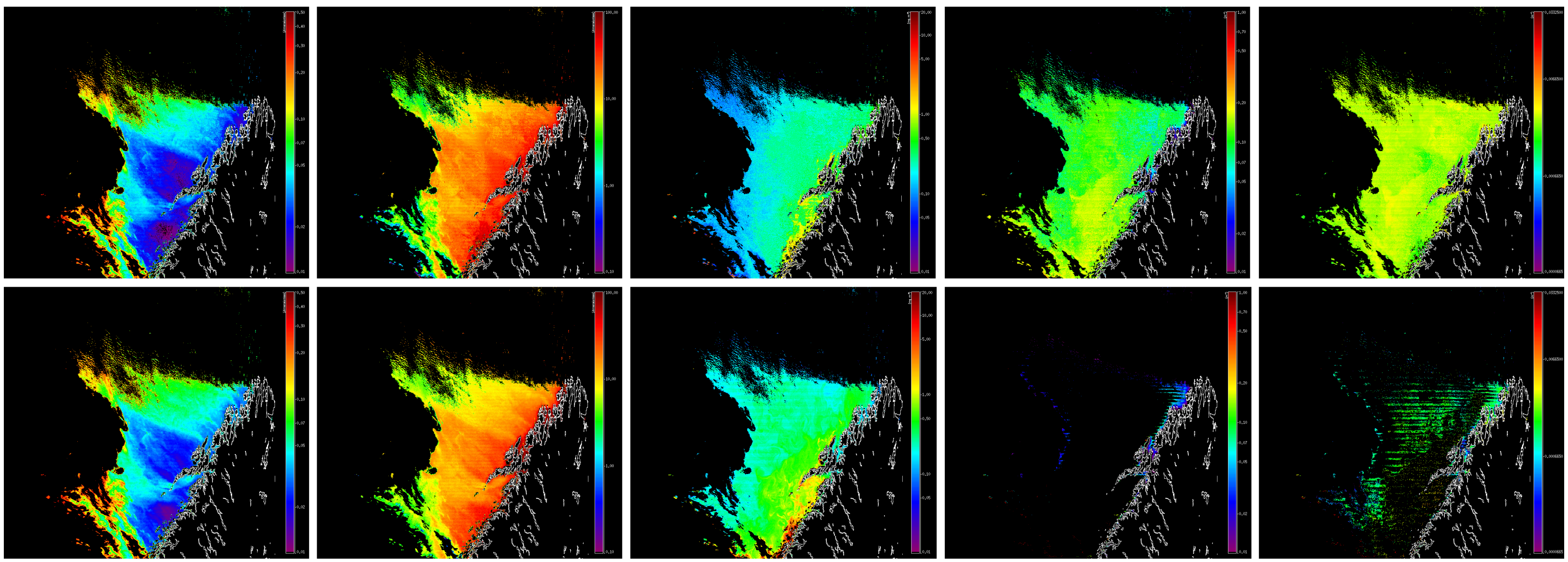


Figure 4: a) TOA radiance (L_{TOA}) and c) relative difference incurred by using plane-parallel geometry (PPA) for several values of solar zenith angle (SZA) between 30° and 87°. b) Same as for a) but for the water-leaving radiance and d) relative difference incurred by using PPA. Viewing geometry: $\phi = 120°$; $\tau_a(865) = 0.05$. Fraction of small vs. large aerosol particles was set to 0.5. Water bio-optical properties: Chla =0.1 mg m^{-3}, colored detrital absorption coefficient at 443 nm = 0.05 m^{-1}, particulate backscattering coefficient at 443 nm = 0.001 m^{-1}.

Problem 3: Standard ocean color algorithms do not work well at high latitudes

Below (lower panels) is an example of the problem caused by the infamous **negative** water-leaving radiance problem due to failure of the atmospheric correction.

- Can the failing atmospheric correction be fixed? Or should it be
- entirely avoided by using **simultaneous atmosphere/ocean retrieval** based on RT models for the coupled atmosphere/ocean system (upper panels)?



Comparison between **simultaneous** (OC-SMART, top) and **standard** (SeaDAS, bottom) retrievals for a MODIS image on 04/18/2014 over a coastal area in northern part of Norway. From left to right: τ_{869}, f, CHL, CDOM and b_{bp}, respectively.

Final thought: What about using vector (polarized) RT simulations?

- Preliminary results indicate that even for **radiance-only** measurements:
- **the accuracy of the retrievals could be improved by using a vector (polarized) forward RT model to compute the radiances used in the inversion step.**

  Hence, for high latitude ocean color retrievals:

- **It might be worthwhile exploring the advantage of using the pseudo-spherical approximation combined with polarized (vector) radiative transfer simulations and a 2-D Gaussian distribution of surface slopes.**

THANK YOU FOR YOUR ATTENTION!