Radiative transfer modelling for satellite ocean color remote sensing

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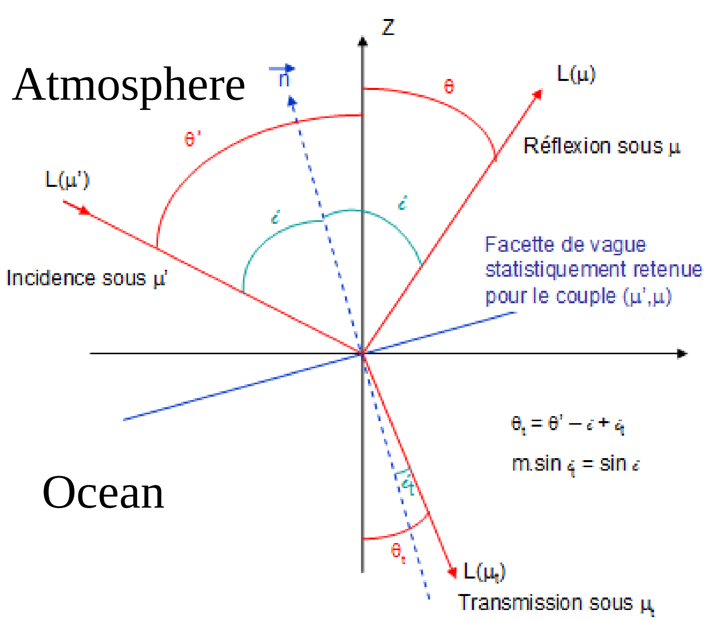
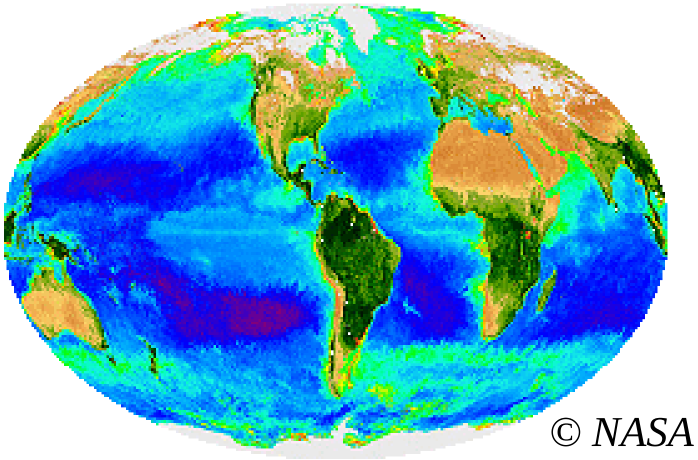




Outline

1. Introduction

2. Scientific interests of the ocean observation by satellite remote sensing

3. Radiative transfer modelling for satellite data analysis

4. Conclusions

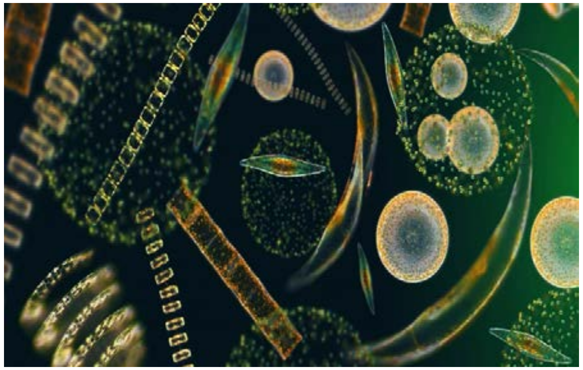
1. Introduction

- ✓ Carbon exchanges between various components of the Earth system are important : this is the so-called Carbon Cycle
- ✓ Photosynthesis = process that enables the synthesis of organic matter and oxygen (O_2) from light, carbon dioxyde (CO_2) and nutrients

- ✓ Through photosynthesis :

~50% of O_2 produced by the organisms comes from the ocean

~50% of atmospheric CO_2 is absorbed by the ocean

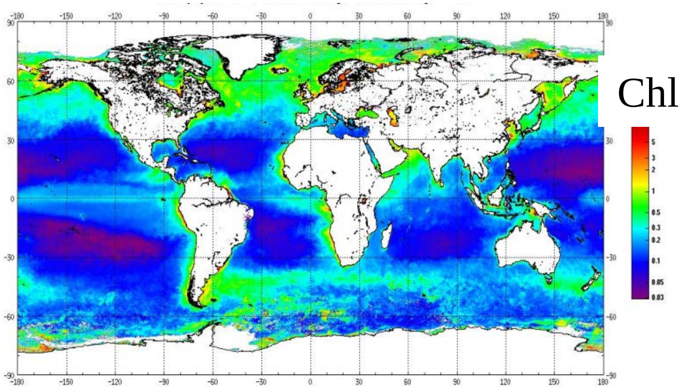


Phytoplankton : unicellular micro-organism showing an extreme diversity (0.5µm→ 200µm)

<u>Role of phytoplankton in the ocean</u>

- ✓ 1st element of marine foodweb
- ✓ Conversion of CO_2 into organic carbon
- ❑ absorption of light → primary production
- ❑ impact on the global carbon cycle and on climate

Importance of determining the biomass concentration at global scale



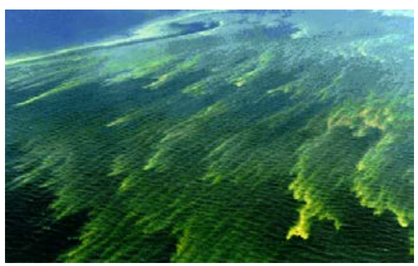
What do we call « ocean color» ?

✓ Methodology that enables the quantification of hydrosols (phytoplankton, mineral material, detritus, colored dissolved organic matter)

✓ Basis of the ocean color technique

→ influence of hydrosols on the optical properties of the ocean

→ variation of the color of the sea



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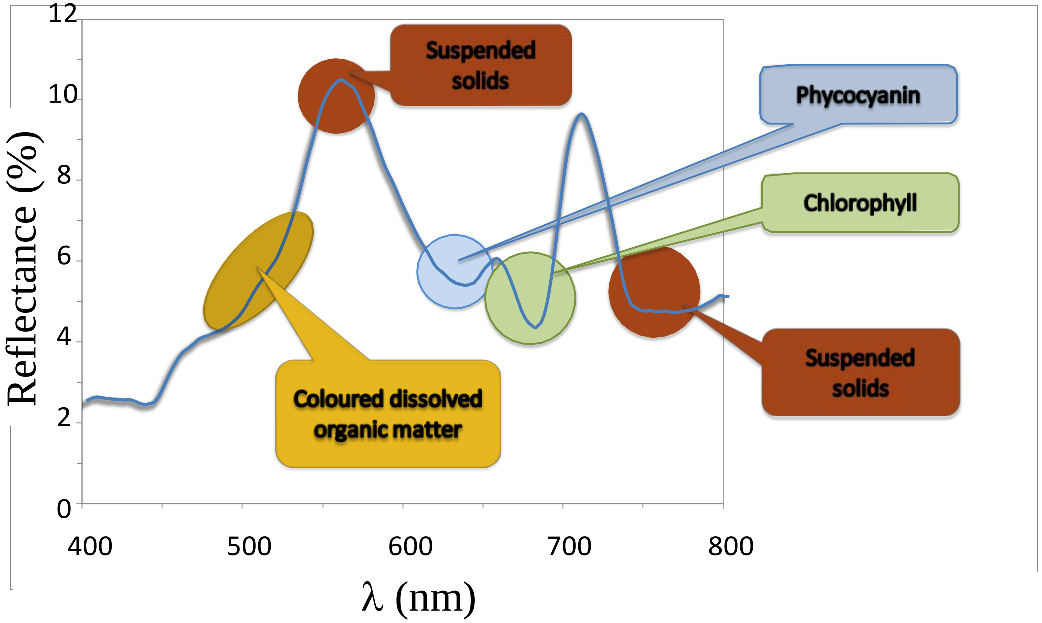
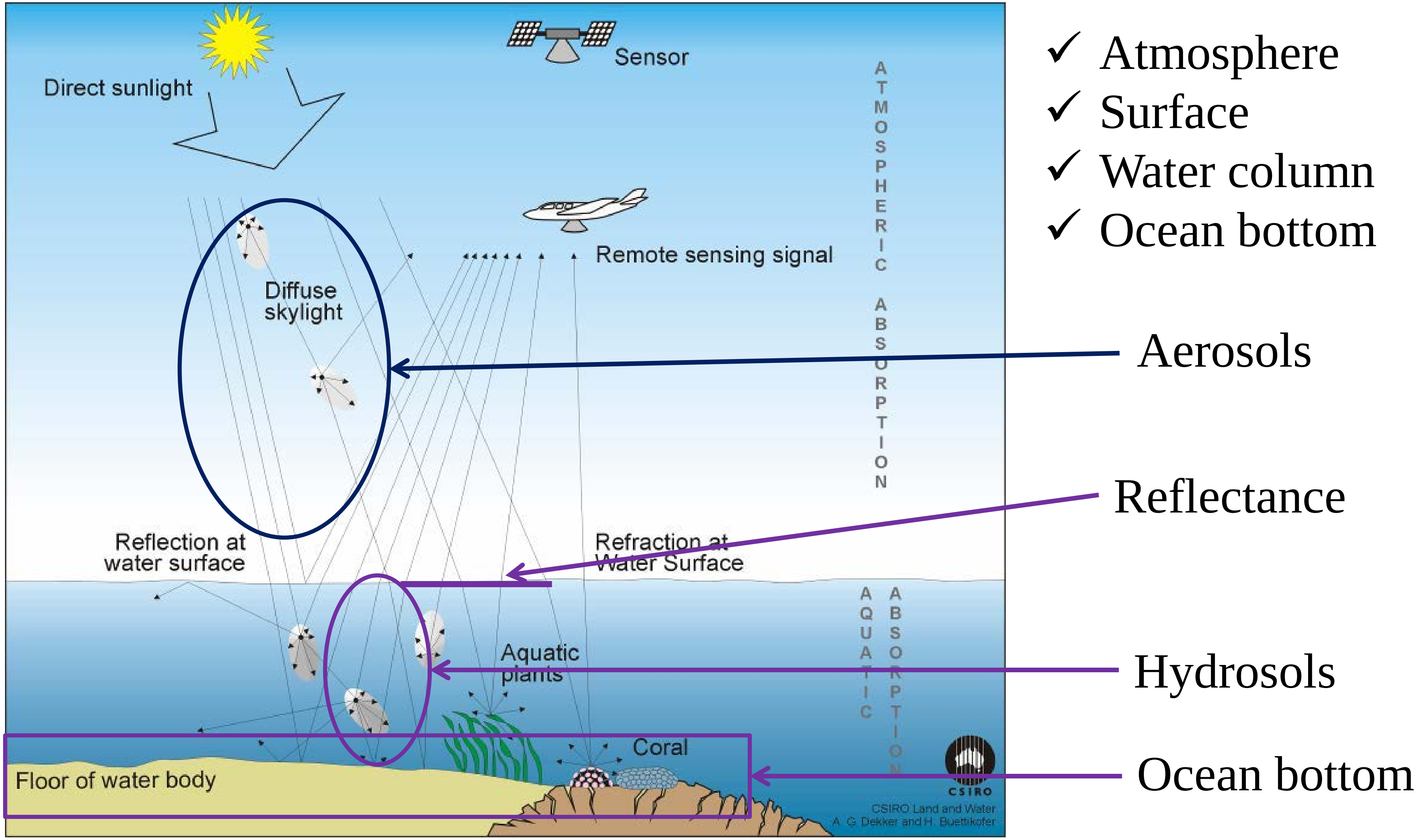
✓ Typical relation between the oceanic radiation (reflectance) and the hydrosols



✓ Reflectance ~ absorption^{-1}
→ detection of organic matter

✓ Reflectance ~ backscattering
→ detection of mineral-like particles

2. Scientific interests of the ocean observation by satellite remote sensing



- ✓ Atmosphere
- ✓ Surface
- ✓ Water column
- ✓ Ocean bottom

Interests for the remote sensing of phytoplankton

✓ Determination of phtyoplankton algal group

→ Importance for the coastal primary production (carbon cycle)

✓ Detection of harmful algal blooms

→ Impact on tourism activities

✓ Eutrophisation of coastal and inland waters

→ Impact on shellfish activities (oysters, mussels,…)

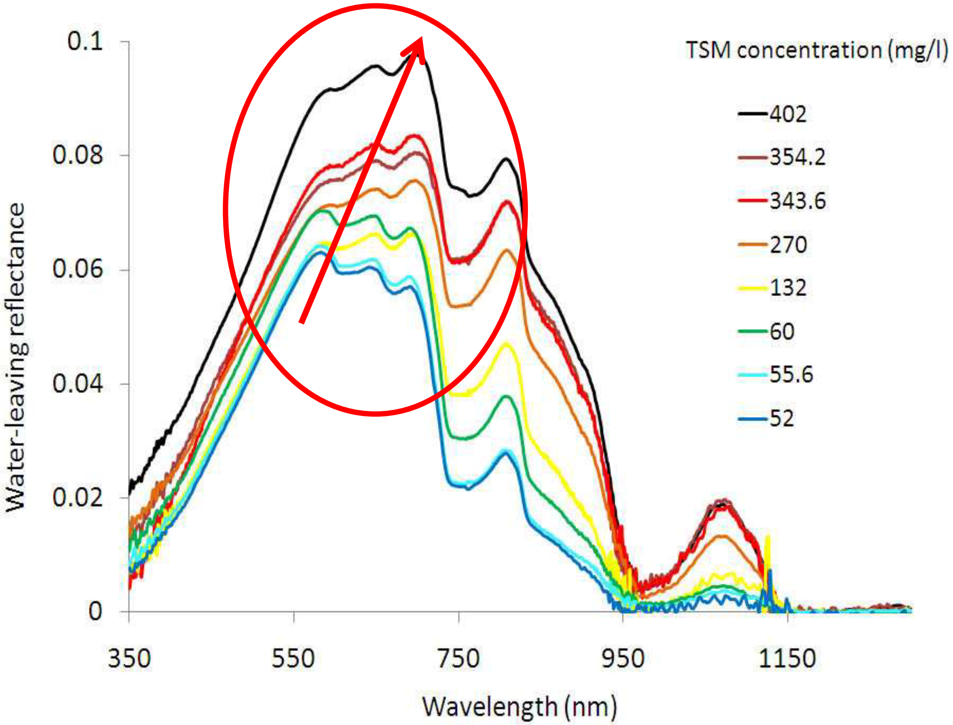
✓ Impact of the turbulence on the spatial distribution of phytoplankton

→ Importance for the analysis of coastal dynamics and fishing activities

Interests for the remote sensing of mineral-like particles

✓ Rivers discharge → marine pollution

Rio de La Plata (Argentina)



✓ Spectral shift of the reflectance with higher turbidity

Others important interests

- ✓ Bathymetry (depth of the ocean bottom)

→ Coastal erosion, defence applications

- ✓ Composition of the bottom (coral reefs, algal species, sand)

➢ Coral reefs

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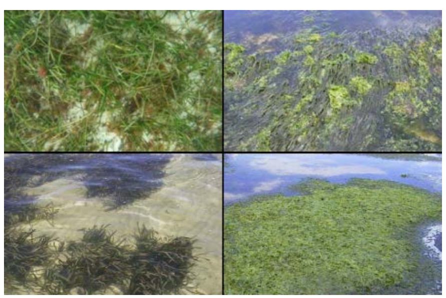
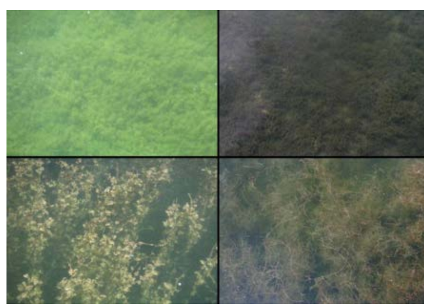
➢ Benthic species





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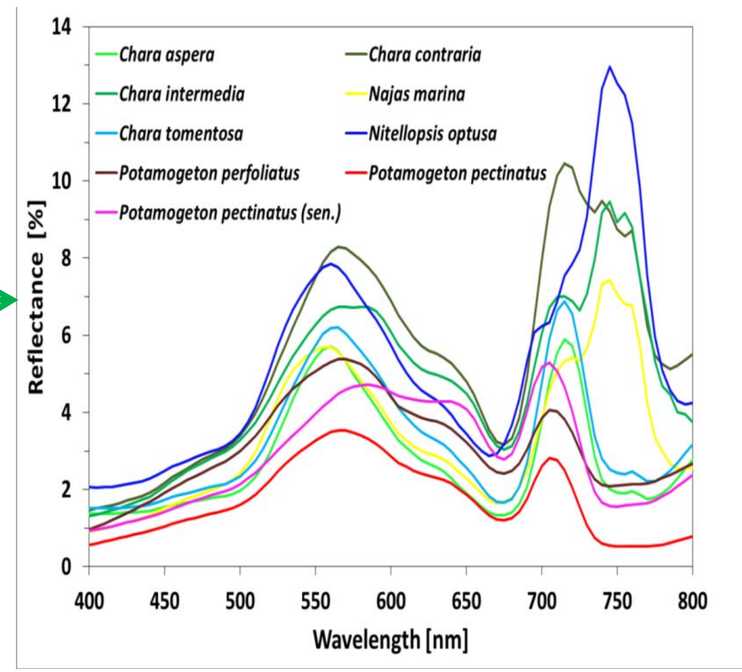
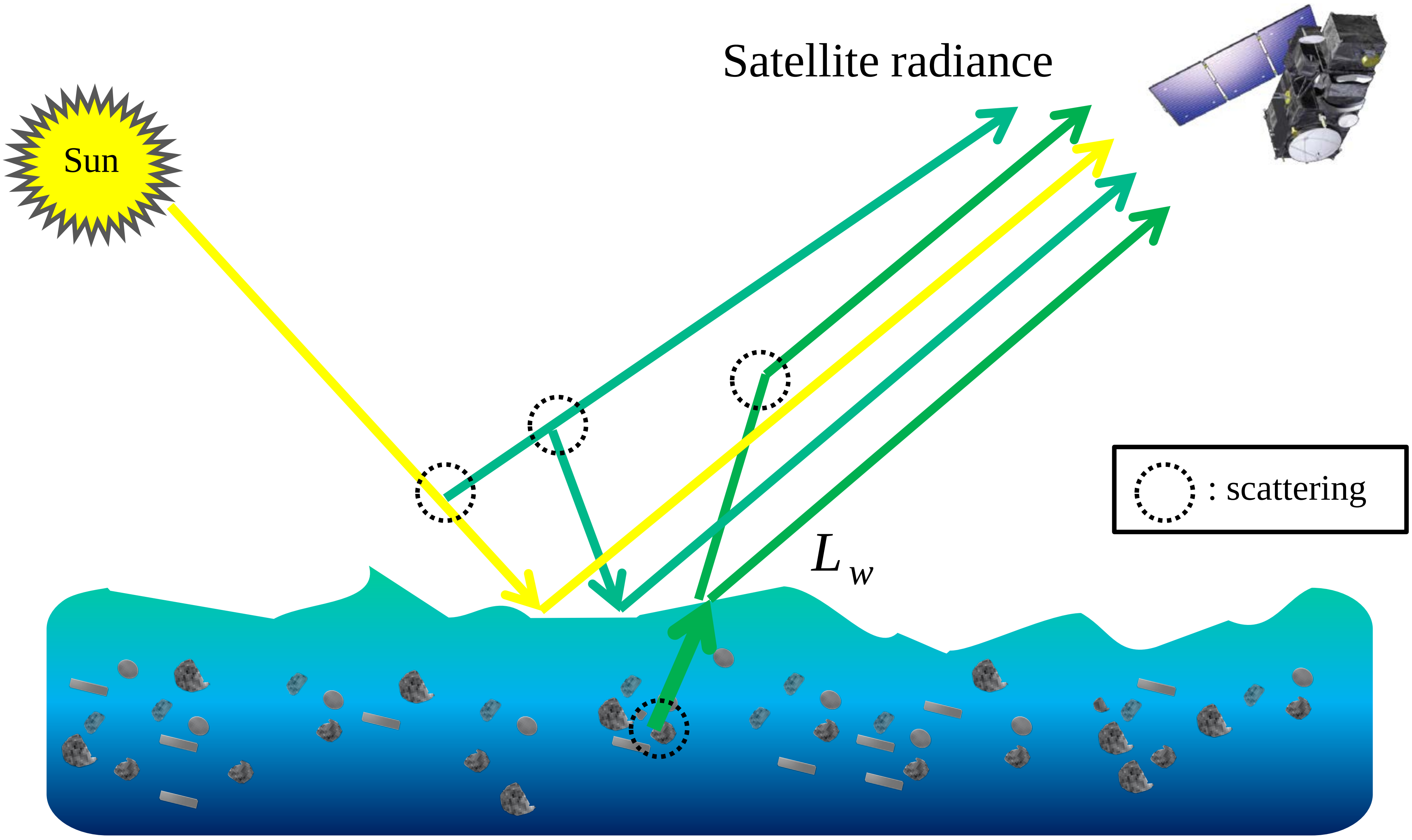


Pinnel (2007)

3. Radiative transfer modelling for satellite data analysis



→ Contribution of the skyligh, of the sunglint, of the skylight reflection on the sea surface, and of the water leaving radiance (L_w)

Radiative transfer model OSOAA (Chami et al., 2015)

→ OSOAA = Ocean Successive Orders with Atmosphere Advanced

→ ocean-atmosphere coupled system

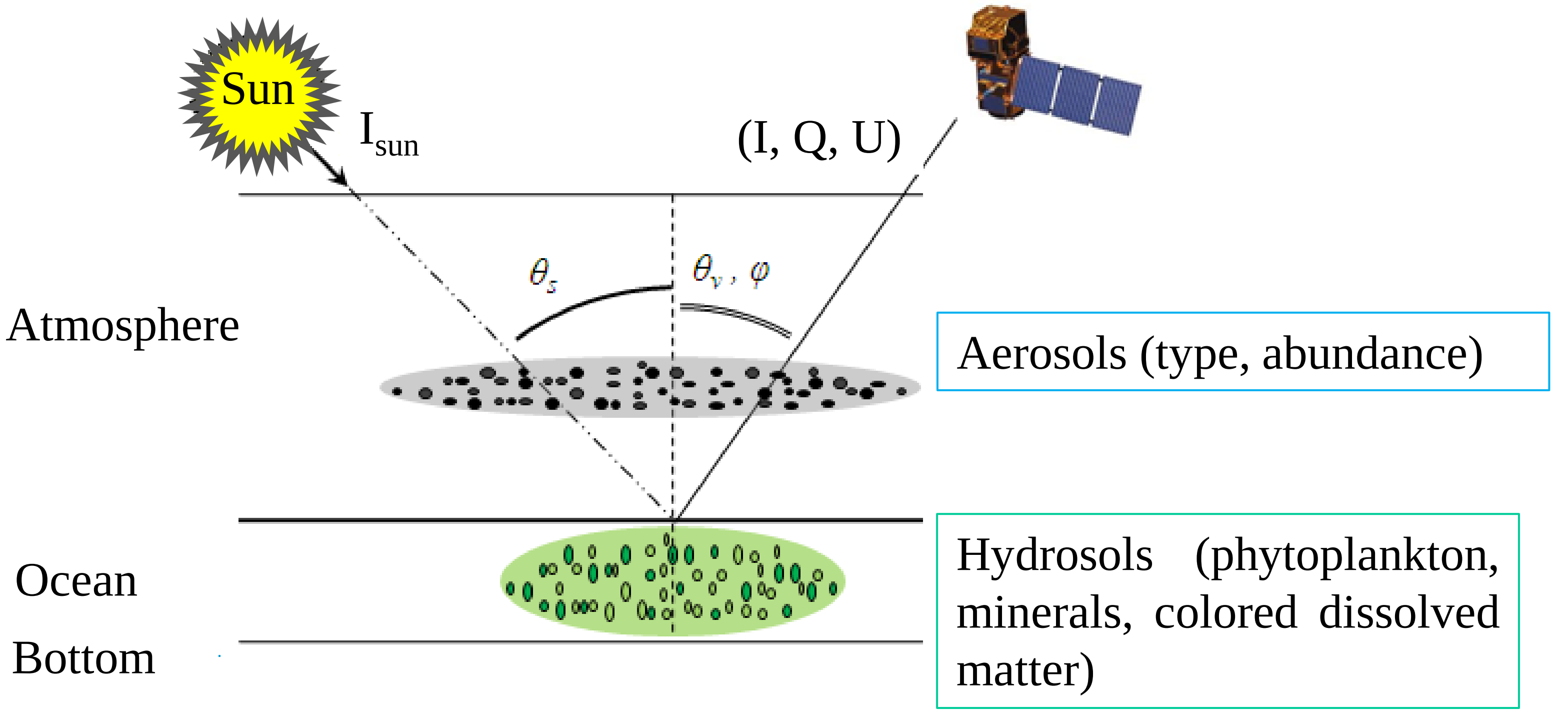
→ open source model freely available online (hosted by CNES)

https://github.com/CNES/RadiativeTransferCode-OSOAA

✓ Main features

- → code 1D
- → Size distribution + spectral properties + directional properties of aerosols and hydrosols
- → bio-optical relationships between concentrations and absorption/scattering properties of hydrosols
- → consideration of waves (i.e., rough surface)
- → weak computing time
- → user friendly interface (Graphical Unit Interface, detailed user guide)

✓ More complete description of the model



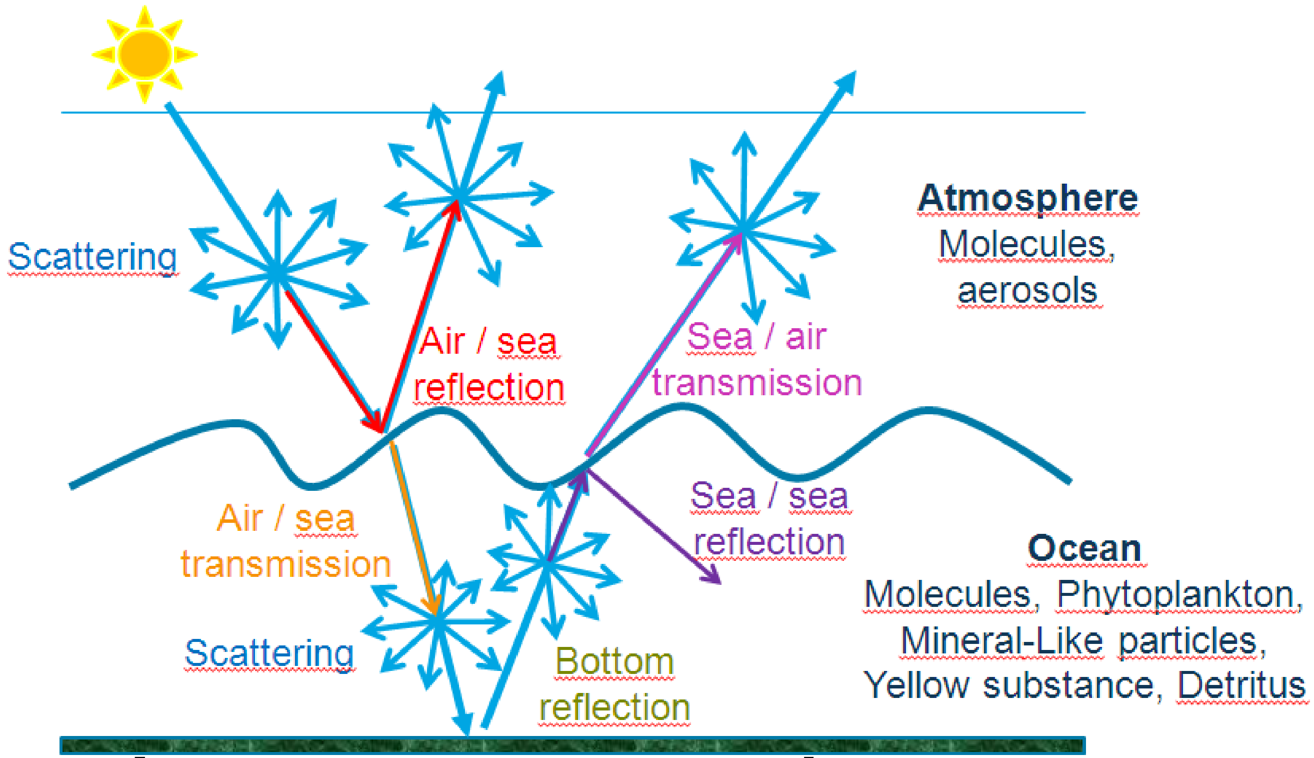
- Light field is defined by Stokes parameters (I, Q, U) (Stokes, 1852)

→ I ~ energy transported by the electromagnetic wave (i.e., radiance)

→ Q ~ information on the degree of polarization

→ U ~ information on the direction de polarization

✓ Simulation of the physical interactions encountered by the radiation



- atmospheric and ocean scattering, ocean absorption

- interactions with the sea surface (Cox and Munk): transmission & reflection

- ocean bottom reflection

- simulation of the light field: intensity + polarization

→ successive orders: radiance at a given scattering order « n » is derived from the radiance at the order « n-1 »

✓ Model inputs

- aerosols (type, abundance): various and consistent with observations
- hydrosols (type, abundance)
  - → phytoplankton
    - chlorophyll *a* concentration (pigment related to light)
    - vertical profile of absorption and scattering coefficients
    - phase function (refractive index, multi-modal size distribution)
  - → mineral-like particles
    - concentration
    - vertical profile of absorption and scattering coefficients
    - phase function
  - → detrital matter
    - purely absorbing material
    - absorption coefficients

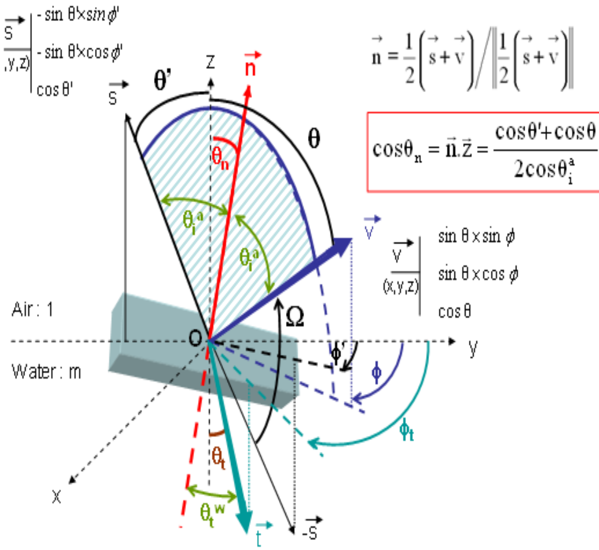
✓ Model outputs

- radiance, reflectance, flux (upward, downward) at each depth (e.g., bottom, sea surface) and altitude (atmosphere, satellite)
- degree of polarization
- spectral range: from 400 nm to 900 nm (visible-near infrared)

✓ Advantages of an analytical solution of the radiative transfer equation

- fast numerical computations
- quantification of the multiple scattering
- appropriate modeling of the rough sea surface

(reflection and transmission of the radiation)



✓ Running the OSOAA model

- Shell script as command lines (key words, values)
- user guide
- Graphical Unit Interface

✓ Limitations of the model

- plane-parallel atmosphere (i.e., no spherical curvature)
- no consideration of the gaseous atmospheric absorption
- no consideration of the inelastic scattering (Raman and fluorescence)

4. Conclusions

A. Interests of ocean color satellite remote sensing

- ✓ Determination of phytoplankton algal group
- ✓ Eutrophisation of coastal and inland waters (e.g., harmful algal blooms)
- ✓ Impact of the turbulence on the spatial distribution of phytoplankton
- ✓ Rivers discharge and marine pollution
- ✓ Bathymetry
- ✓ Composition of the ocean bottom (e.g., benthic habitats)

B. Radiative transfer modelling : OSOAA

- ✓ robust numerical model to simulate the radiation in the atmosphere-ocean system, including the polarization and a rough sea surface
- ✓ freely available online as an open source model

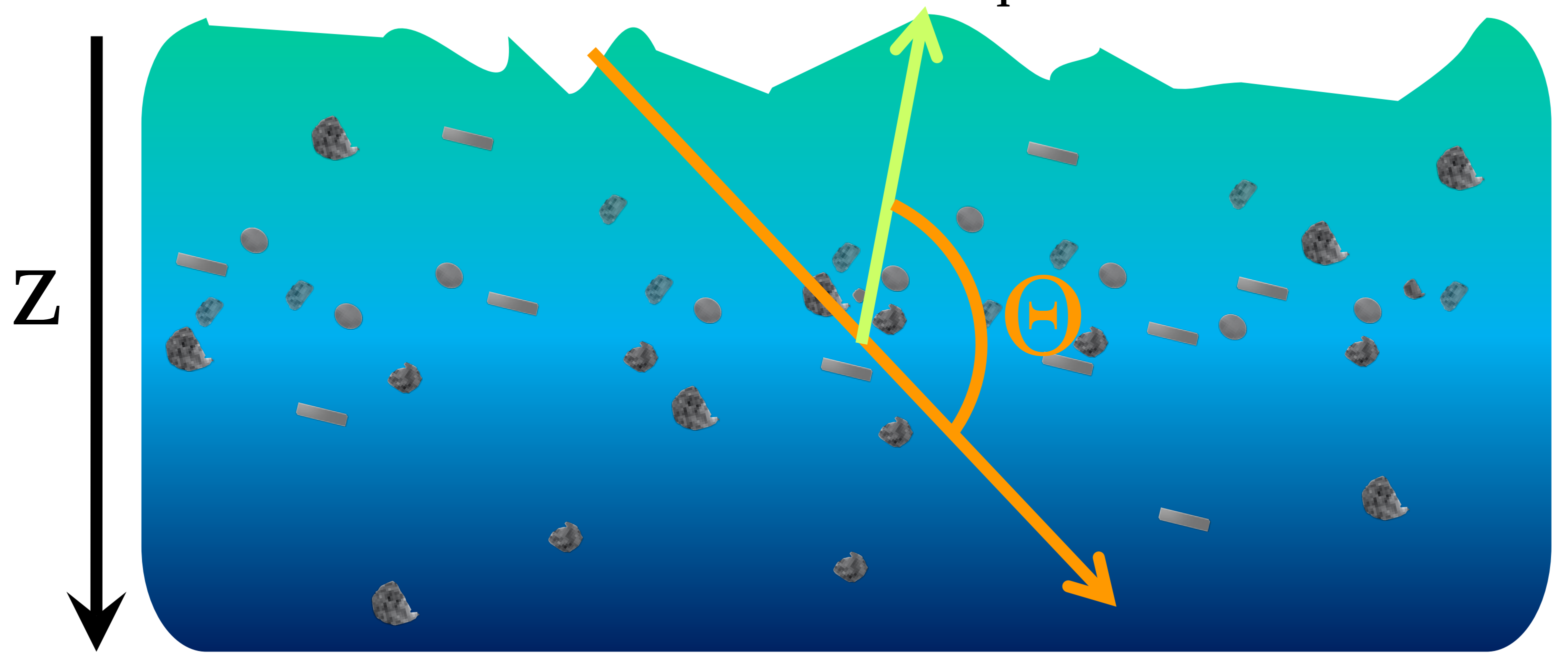
C. Acknowledgments

- ✓ CNES (A. Meygret, B. Fougnie)

Thank you for your attention

Back up slides

Radiative transfer equation



Vector formalism (with polarisation) : I = Stokes vector, M = phase matrix

$$\nabla \mathbf{I}(r,\Theta) = -c(r,\Theta)\mathbf{I}(r,\Theta) - 2\pi \int_{\Theta'=0}^{\pi} \mathbf{M}(r,\Theta' \rightarrow \Theta)\mathbf{I}(r,\Theta')\sin\Theta' d\Theta'$$

Scalar formalism (no polarization) : I = Radiance

$$\nabla I(z,\Theta) = -c(z,\Theta) I(z,\Theta) - 2\pi \int_{\Theta'=0}^{\pi} VSF(z,\Theta' \rightarrow \Theta) I(z,\Theta')\sin\Theta' d\Theta'$$

c = attenuation coefficient, VSF = phase function of hydrosols

Models accounting for atmosphere + ocean layers

- ✓ more accurate to model the ocean layer

A few examples of bi-layers models « atmosphere + ocean »

- ✓ Scalar model (i.e., no polarization)
- → Hydrolight (Mobley, 1989) : commercial model (~10 Keuros)

- ✓ Vectorial models (i.e., with polarization)
- → *discrete ordinates* method : Jin et al. (2006-COART), Sommersen et al. (2010)
- → *Monte Carlo* method : Kattawar et al. (1989), You et al. (2009)
- → *successive orders of scattering* method: Chami et al. (2015), Zhai et al. (2010)
- → « *T-matrix* » *(adding doubling)* method: Chowdhary et al. (2006), He et al. (2010-PCOART), Ota et al. (2010), Hollstein and Fischer (2012-MOMO)
- → *finite element* method: Bulgarelli et al. (1999)