Emissions of International Shipping as seen by Satellites

H. Bovensmann, V. Eyring, K. Franke, A. Lauer, M. Schreier, A. Richter, J.P. Burrows

Institute of Environmental Physics, University of Bremen FB1,
P.O. Box 33 04 40, D-28334 Bremen, Germany.
Tel:+49-421-218-4081, Fax: +49-421-218-4555
Heinrich.Bovensmann@iup.physik.uni-bremen.de

and

DLR Institute of Atmospheric Physics
Oberpfaffenhofen, Germany, Veronika.Eyring@dlr.de

SeaKLIM - Junior Research Group
Impact of Ship Emissions on Atmosphere and Climate

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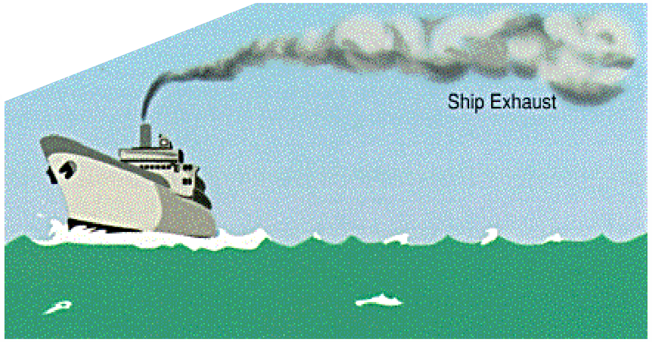
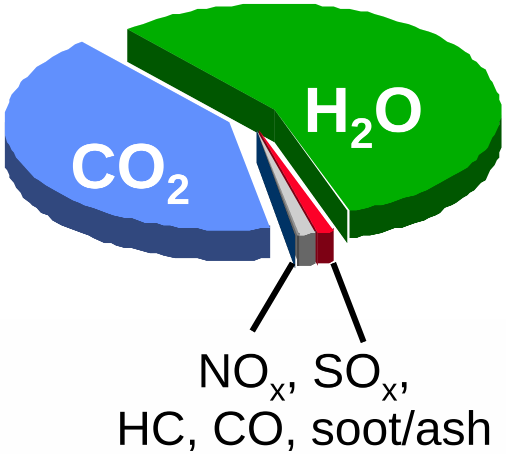
HELMHOLTZ GEMEINSCHAFT

Overview

- Introduction
- Trace Gases from Shipping
- Modification of Cloud Microphysical Paramters by Ship emissions and impact on radiation budget
- Summary & Outlook

Introduction

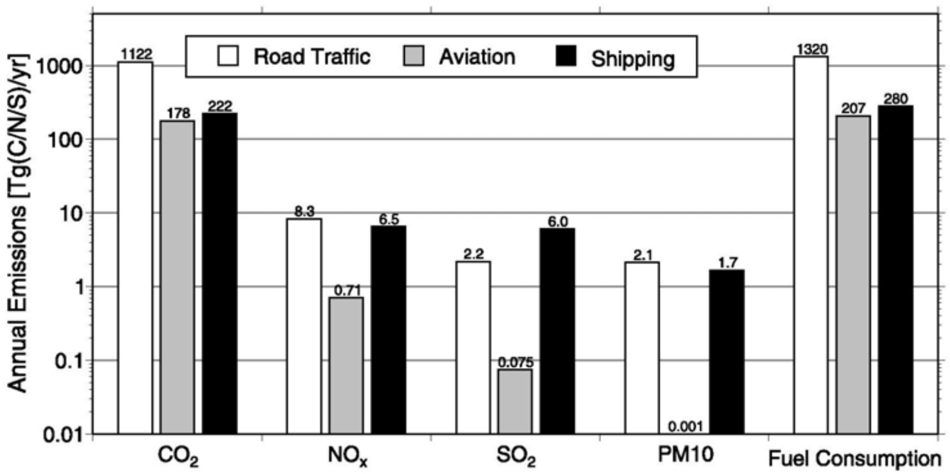


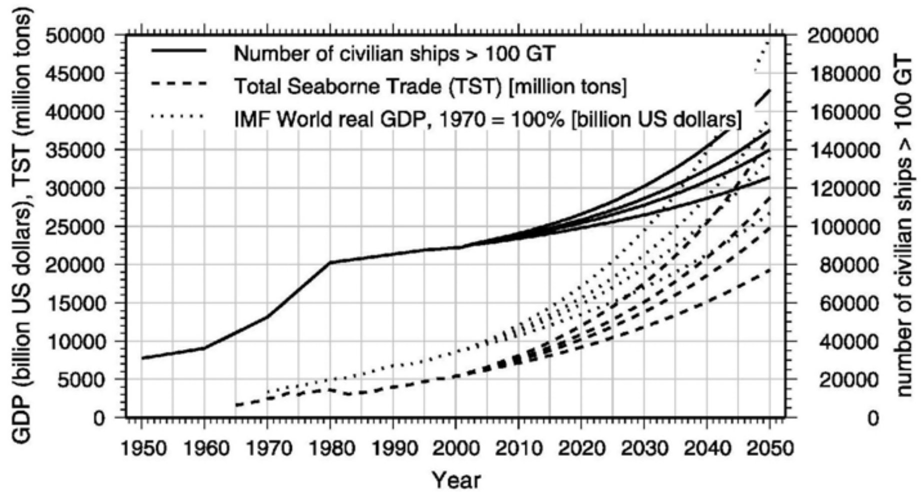


MAN B&W, 2002

- Seagoing ships emit exhaust gases and particles into the marine boundary layer and significantly contribute to the total budget of anthropogenic emissions.
- Emissions of ozone precursors, like nitrogen oxides (NO_x), carbon monoxide (CO) and unburned hydrocarbons (HC) contribute to the formation of ground-level ozone, which may damage human health and vegetation, and which changes the radiative budget as ozone is radiatively active.
- In addition, SOx and particles contribute to the cloud formation and/or modify clouds, thereby affecting the Earth radiation budget.

Magnitude and Expected Trends in Ship Emissions





- Emissions from ships are already now comparable to emissions from the other transport sectors.
- Global Shipping is assumed to significantly grow during the next decades.
- Despite their relative importance, ship emissions are currently one of the least regulated sources of anthropogenic emissions.

Eyring et al., *JGR*, 2005

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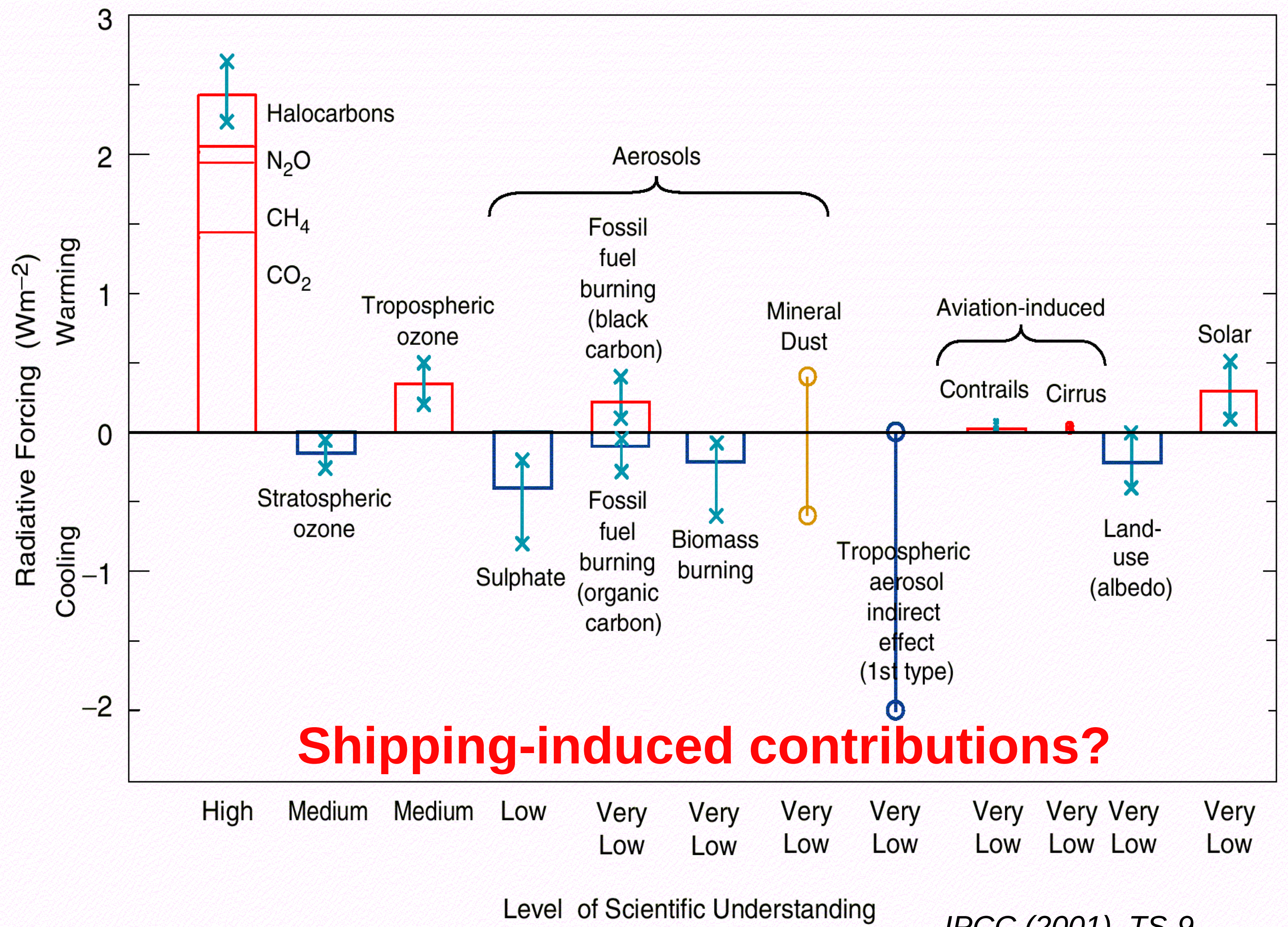
Anthropogenic Radiative Forcing



IPCC (2001), TS-9

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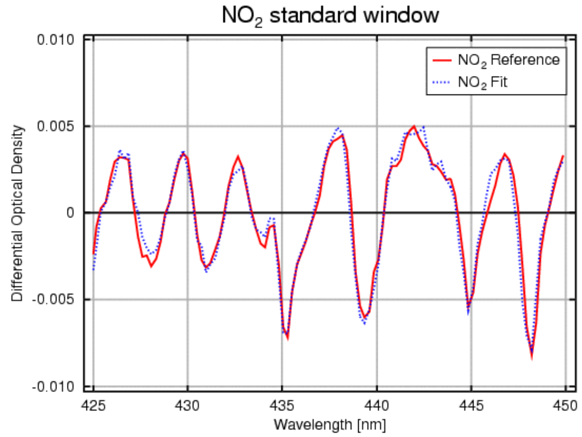
Tropospheric NO_2 Data Analysis



Spectral data analysis:

- DOAS using TOA reflectance data (here: SCIA)
- 425 - 450 nm fitting window

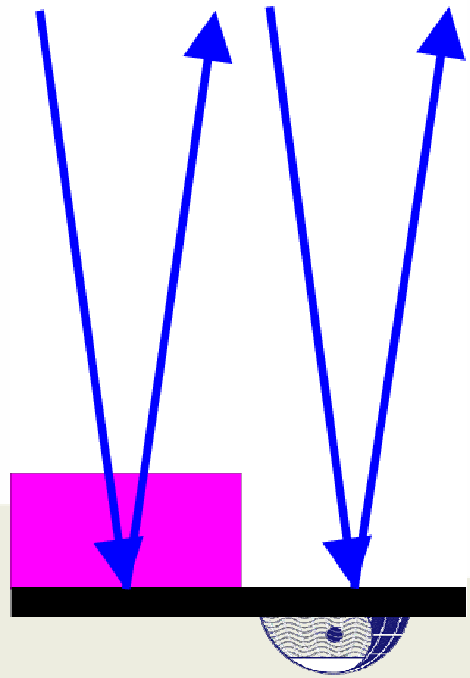
Stratospheric Columns

- stratosphere separated by measurement over pacific (“clean” troposphere), the so-called reference sector
- Assumption: stratospheric NO_2 longitudinal homogeneous

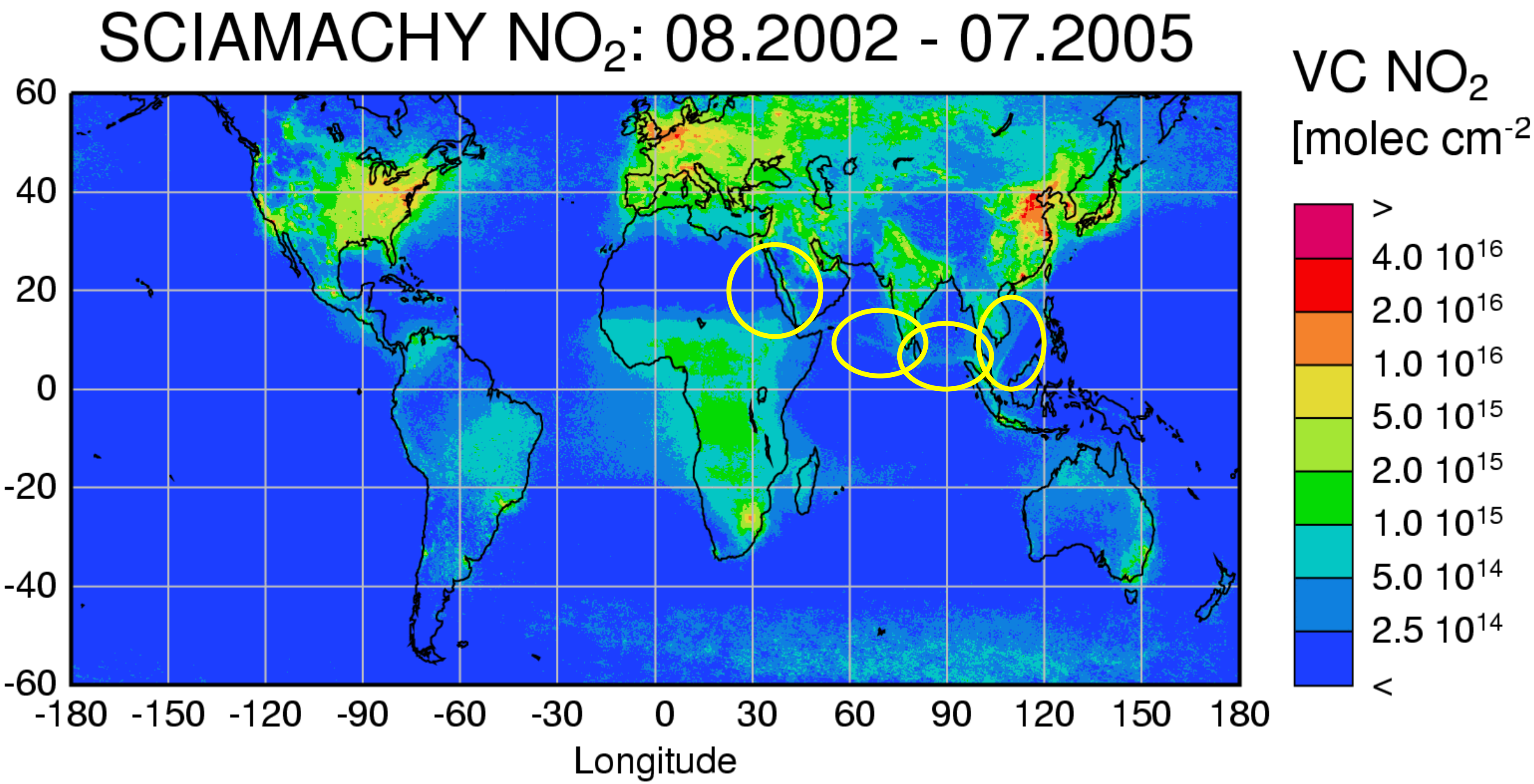
Tropospheric Columns:

- Tropospheric column = total column – stratospheric column (Pacific reference sector)
- Trop. AMF simulated with RTM
- simple cloud threshold only

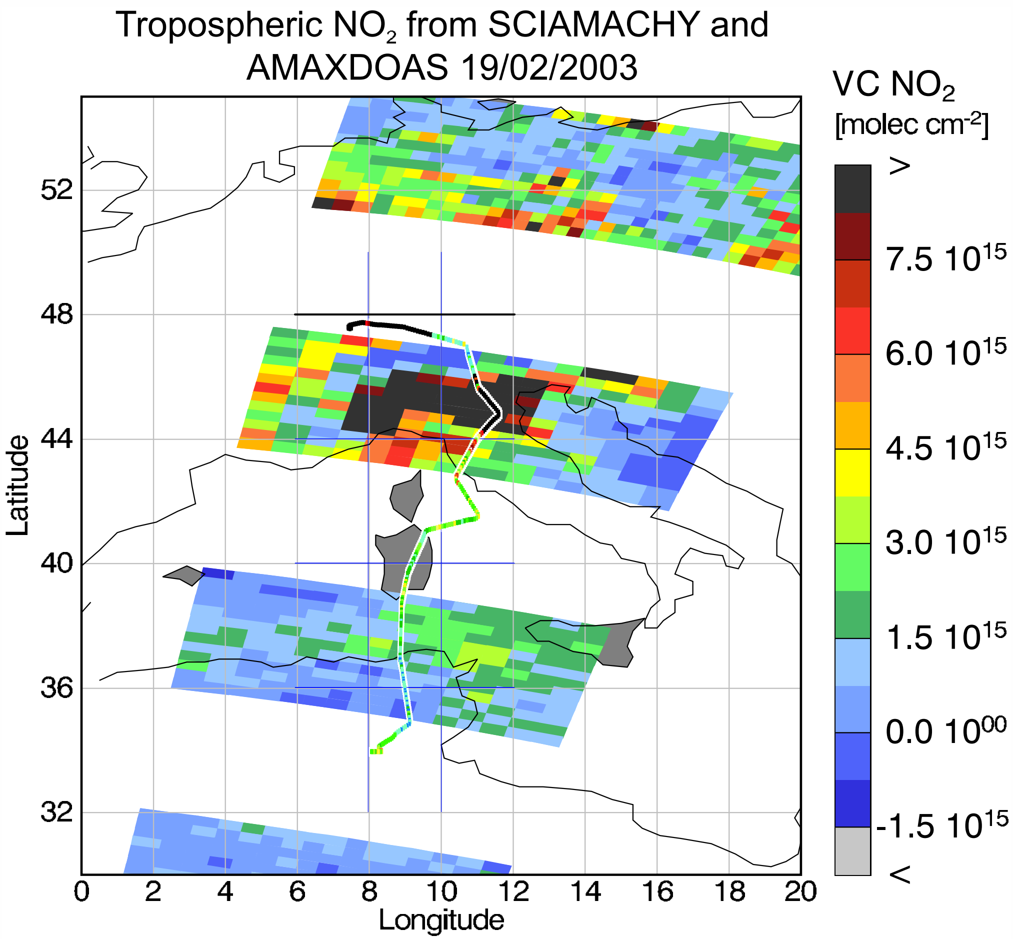
Reference Sector

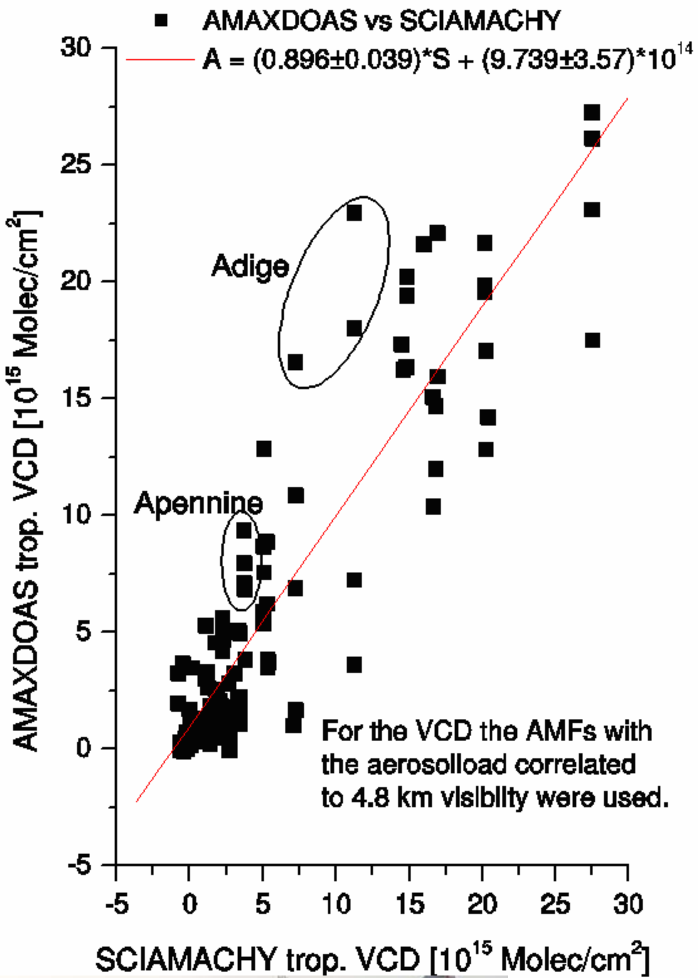


SCIAMACHY Tropospheric NO_2



Validation Examples: Airborne DOAS





Heue et al., 2004

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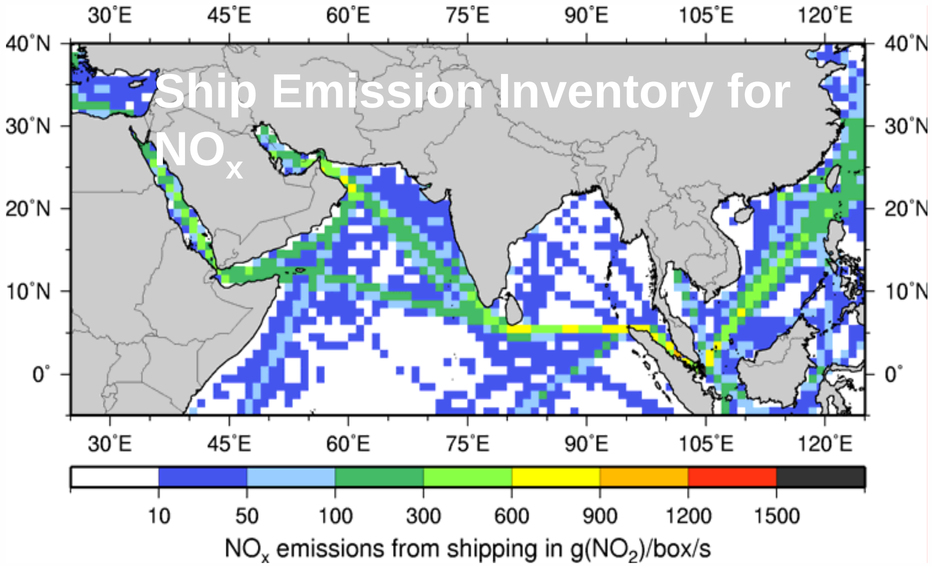
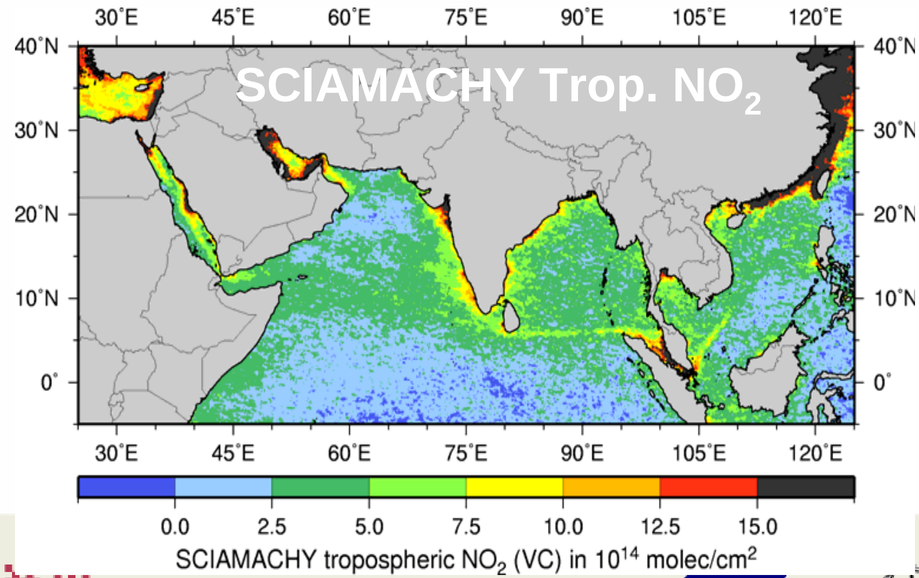
Ship Emission Inventory for NO_x and NO_2 Satellite Measurements



Emissions along ship routes from inventories

- Global Vessel Traffic Densities from AMVER *(Endresen et al., 2003)*
- Absolute emission scaled to 6.87 Tg(N)yr^{-1} *(Corbett&Köhler, 2003)*
- Global NO_x Inventory (Eyring et al., 2004)

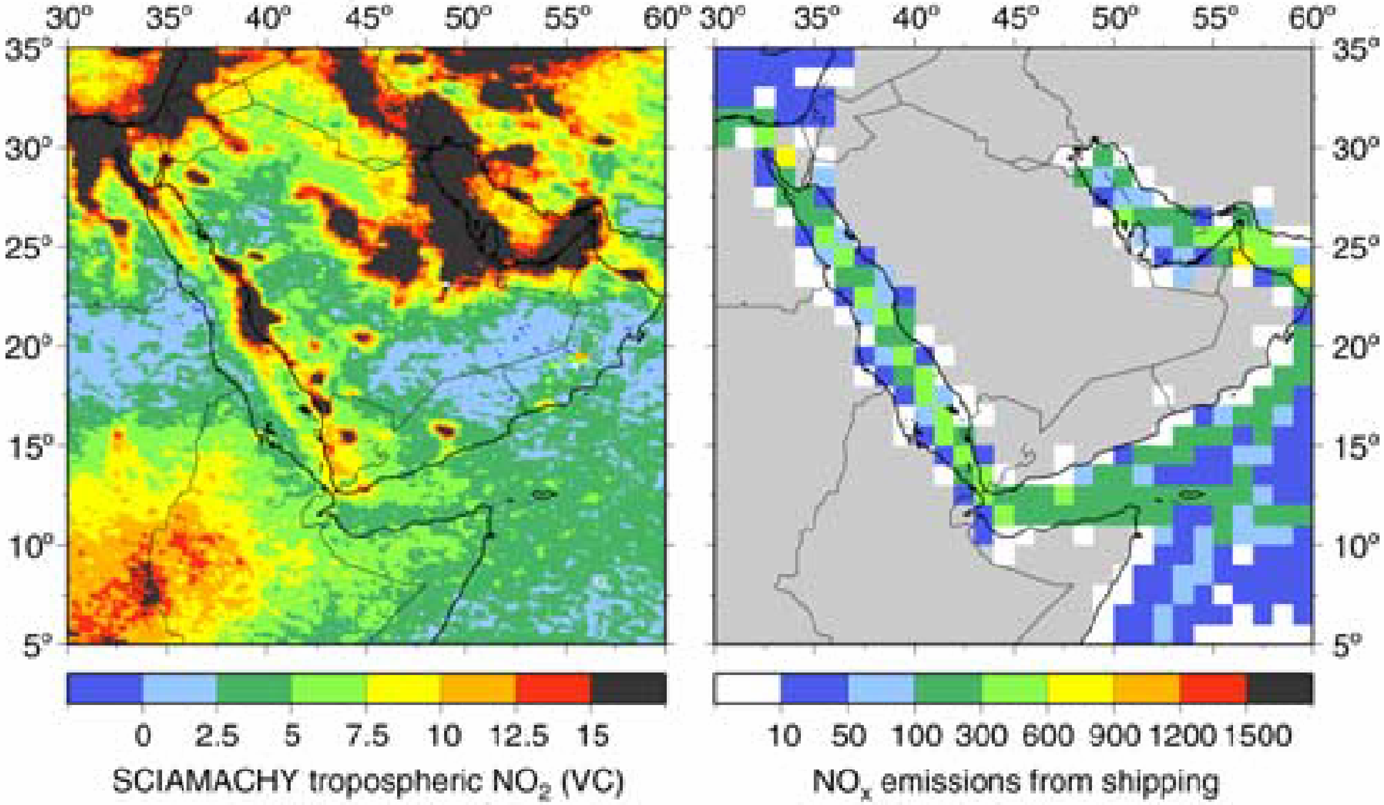


Ship routes seen in SCIA trop. NO2

- average August 2002 – April 2004
- moderate cloud filter (30%)
- trop. AMF: albedo 0.04, maritime aerosol
- ship routes clearly visible
- transfer of measured NO_2 and NO_x from emission inventories needs photo-chemical modelling

A. Richter et al., Satellite Measurements of NO2 from International Shipping Emissions, *Geophys. Res. Lett.*, **31**, L23110, doi:10.1029/2004GL020822, 2004

Red Sea



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Comparing emissions with columns

- **Assumption: $OH + NO_2 + M$ is the only loss process for NO_x,**
  - **second order reaction rate coefficient for the boundary layer is 2.5 x10^{-11} cm^3 $mol.^{-1}$ s^{-1} [Sander et al., 2000],**
  - **OH concentration: 1.5x10^6 mol. cm^{-3} in the Red Sea area (approx. 2x10^6 molecule cm^{-3} for the tropical regions) [Song et al., 2003],**
  - **first order loss of NO_x is around 3.75x10^{-5} s^{-1} (lifetime: 7 hrs)**
- **emission flux from SCIAMACHY NO_2 columns of 5.5x10^{14} mol. cm^{-2} on a 1°x1° grid: $P_{NOx,SCIAMACHY}$ = 2.0x10^{10} mol. cm^{-2} s^{-1} (inventory: 3.4x10^{10} mol. cm^{-2} s^{-1}).**

Shipping lane	Latitude Longitude (Start) to Latitude/Longitude (End)	Mean Inventory Estimate	Assumed Lifetime	SCIAMACHY Estimate and Upper and Lower Limits
		molecule cm^{-2} s^{-1}	h	molecule cm^{-2} s^{-1}
Red Sea	17.5°N 32°E to 30°N 44°E	3.4e+10	7.4	2.0e+10 (1.3..5.3e+10)
Indian Ocean West	5°N 44°E to 14°N 78°E	2.3e+10	5.6	< 1e+10 (0.7..2.3e+10)
India to Indonesia	4°N 78°E to 7°N 98°E	7.1e+10	5.6	2.8e+10 (1.8..7.5e+10)
East of Indonesia	2°N 105°E to 8°N 110°E	6.2e+10	5.6	2.7e+10 (1.8..7.2e+10)

Main Factors Determing the Errors on emissions

- NO_2 columns errors:
  - spectral fit error: 10%.
  - airmass factor error: 25% (cloud contamination, possible aerosol effects and the uncertainty in the boundary layer height)
  - subtraction of stratosphere and background values: 20%
  - Total error (assuming independent errors): 34%.
- NO_2 liftetime:
  - the instantaneous NOx lifetime in a plume depends on NOx concentration and will be short (1-2 hrs) right after emission but increase to background values of around 7 – 10 hrs as the plume evolves (Song et al. 2003). Sat. Obs weighted towards aged plume.
  - Lifetime estimate from satellite scene itself (Beierle et al. 2004): shape of plume and average wind speed was used to derive an effective lifetime of NO_2 of 3.8 h and 8.5 h for summer and winter, respectively, in agreement with the 5.6 to 7.4 hours used here.
- In total, an uncertainty of up to a factor of 2 remains, needs to be minimised by plume modelling in combination with 3D chemical model

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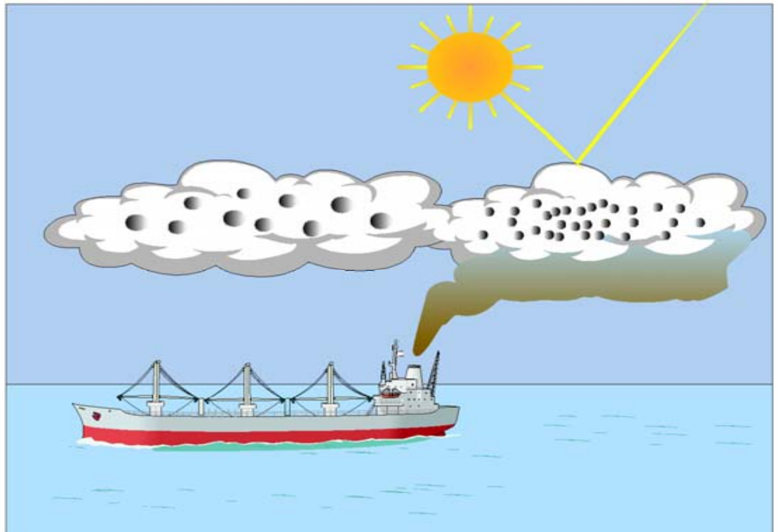
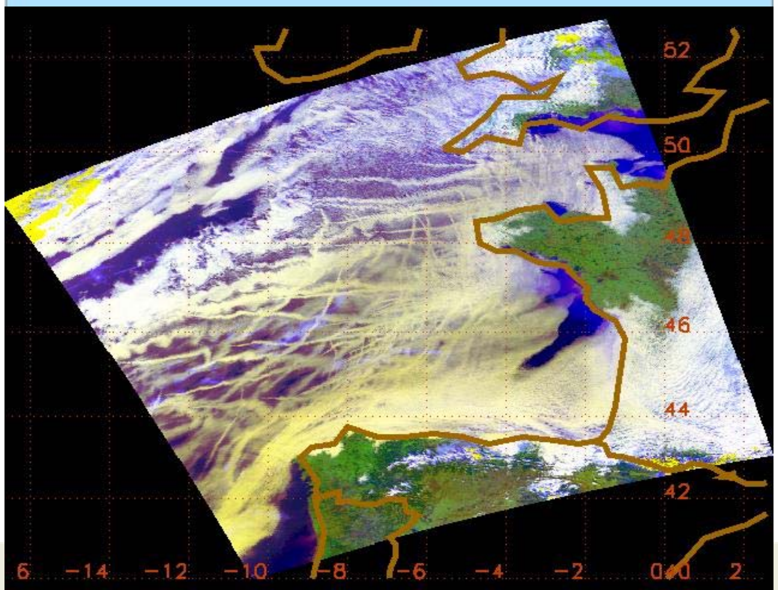
Cloud modifications by ship emissions





AVHRR (1, 2, 6), 2003/01/27, 13:30 UTC

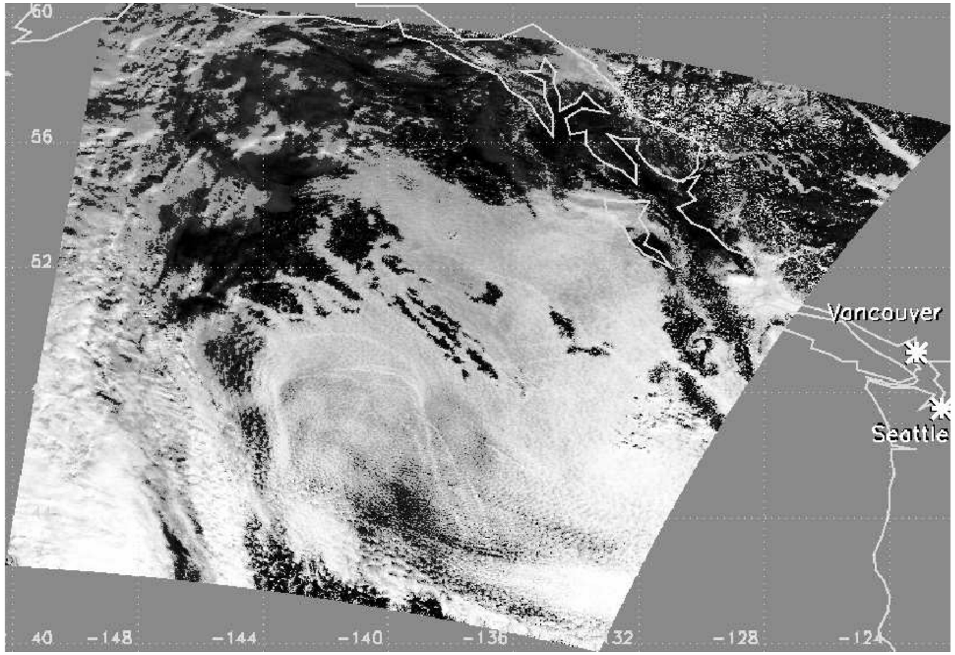
The “normal” maritime boundary layer contains only a small amount of aerosol particles, which can act as cloud condensation nuclei (CCN)

Ship emissions contain particles, which are able to act as CCN, e.g. a large amount of SO_2

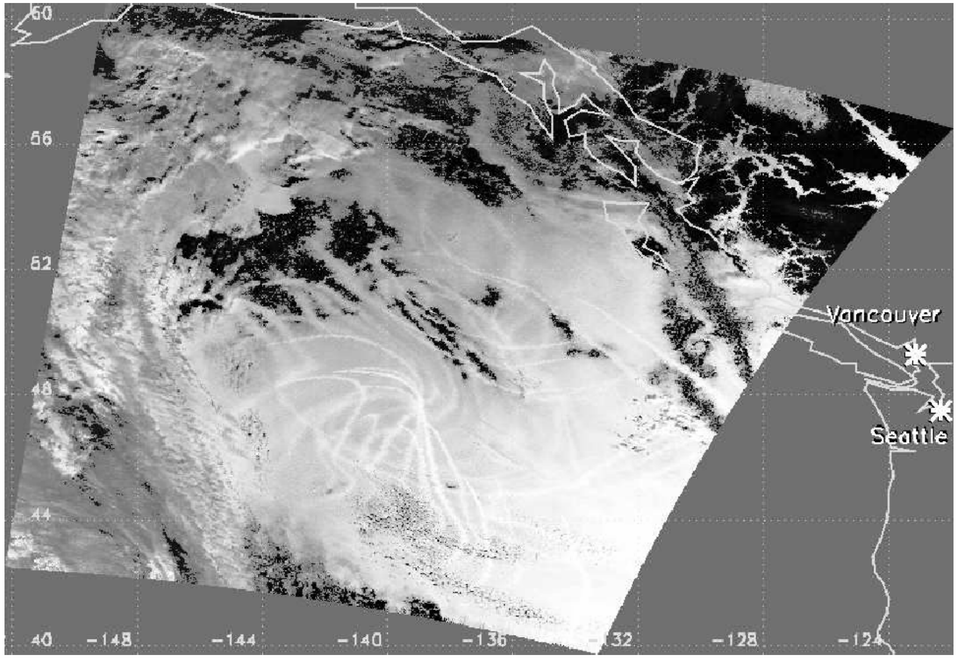
For low stratiform clouds (< 1500 m), the emissions are able to reach the cloud

The increased amount of CCN changes the droplet size distribution towards smaller particle radii and increases the droplet number (Twomey, 1977)

MODIS/TERRA, 10th Februar 2003

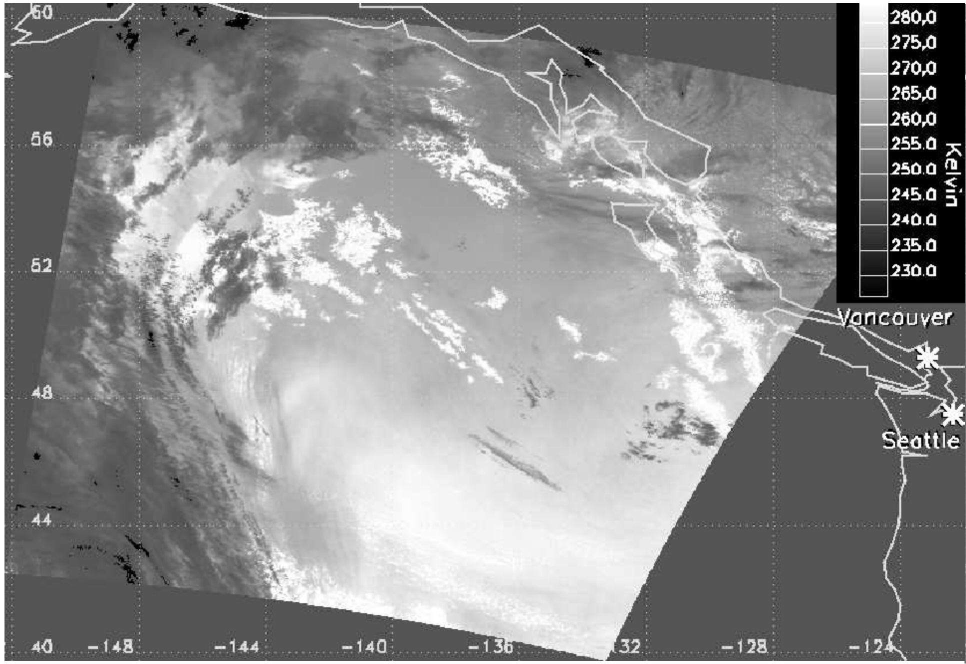


Reflectance in 0.85 µm channel

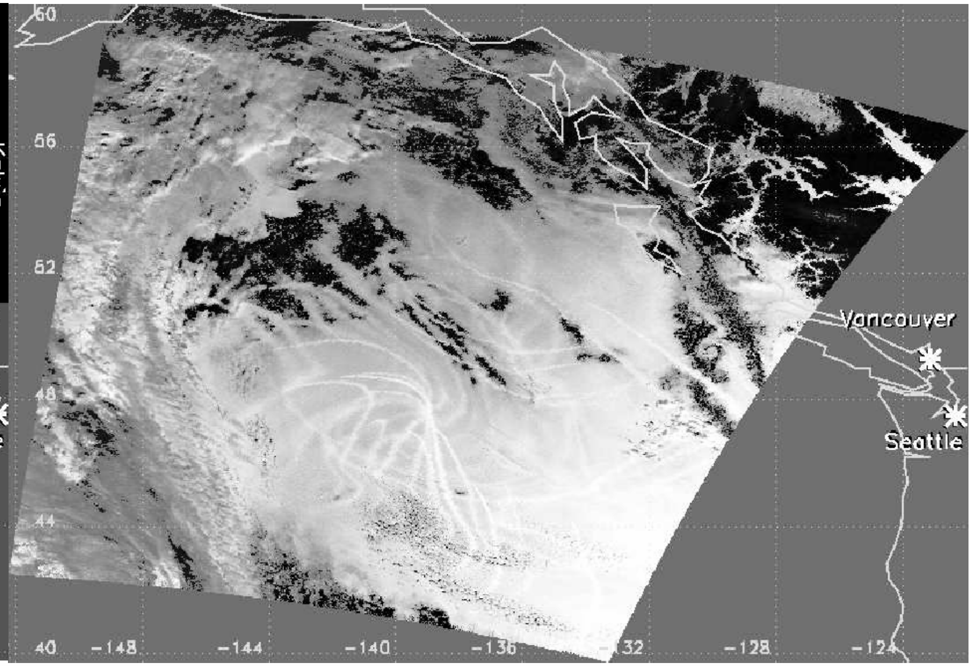


Reflectance in 2.13 µm channel

MODIS/TERRA, 10th Februar 2003



Scene Temperature from 11 µm channel



Reflectance in 2.13 µm channel

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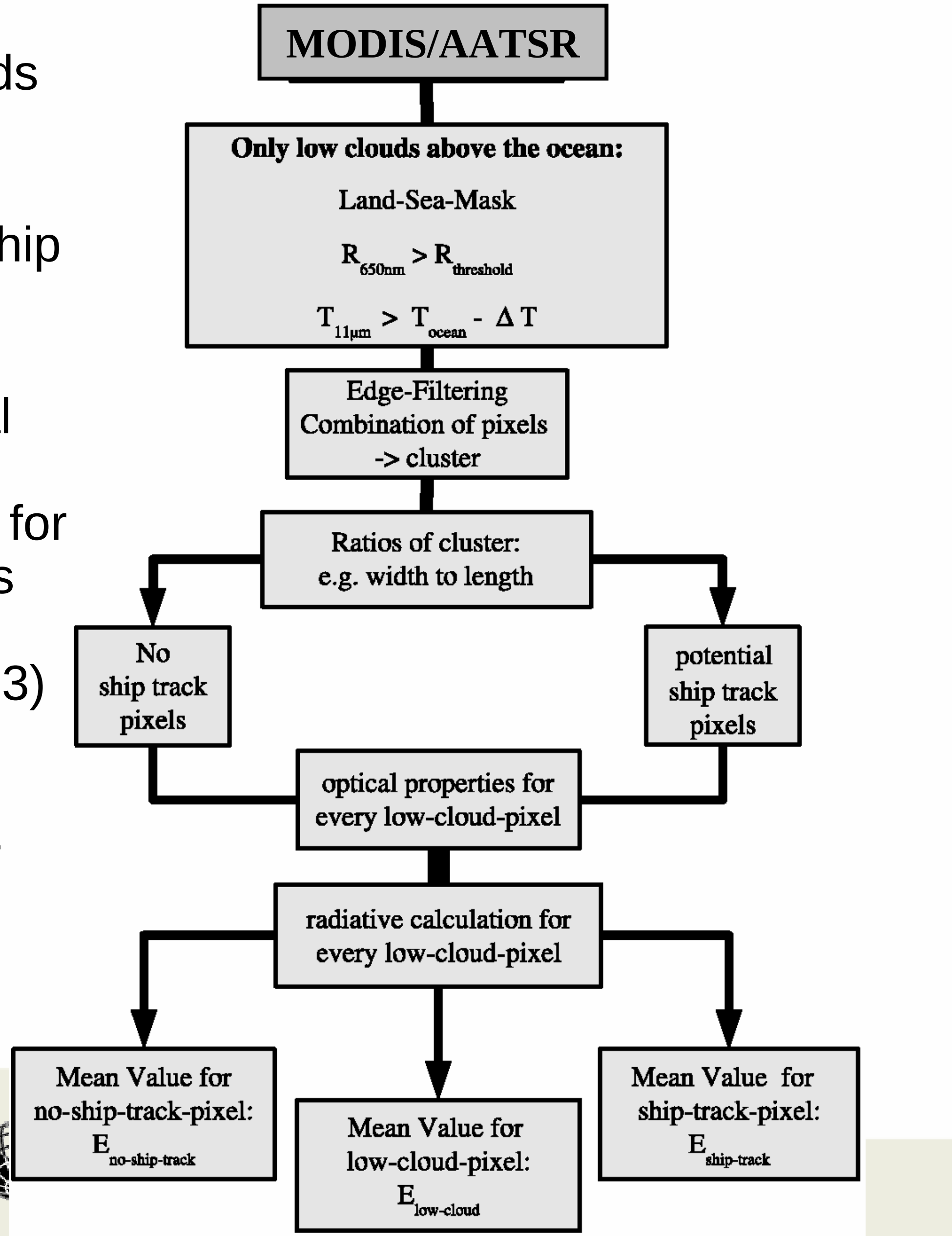
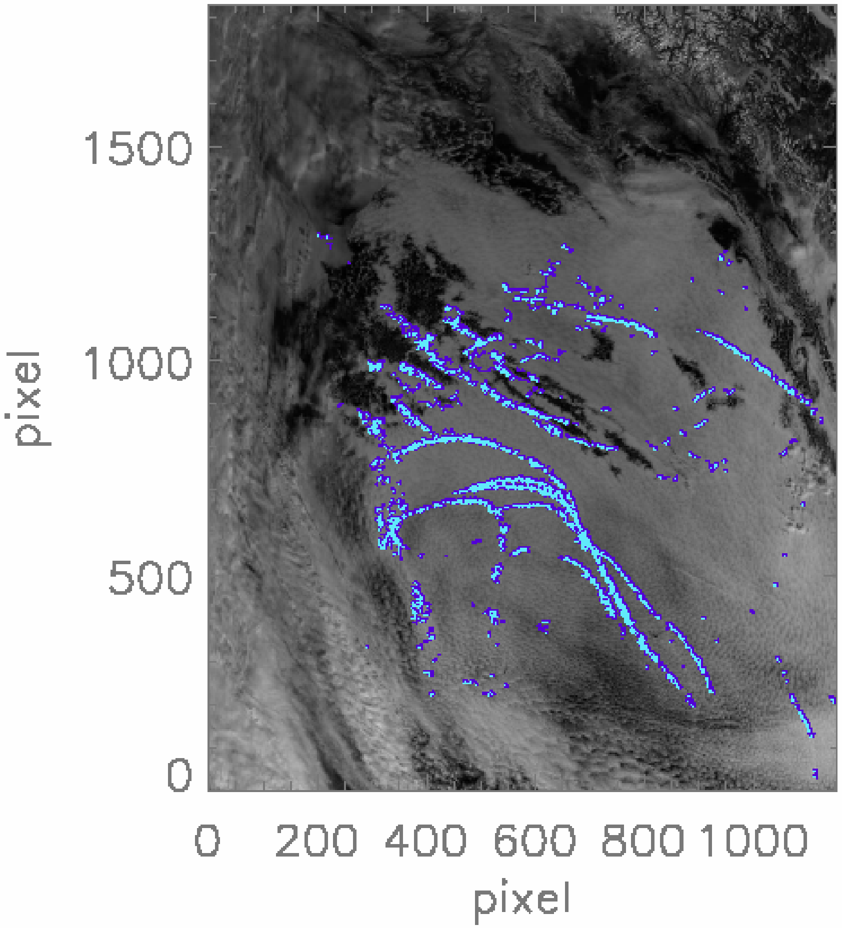
Methodology

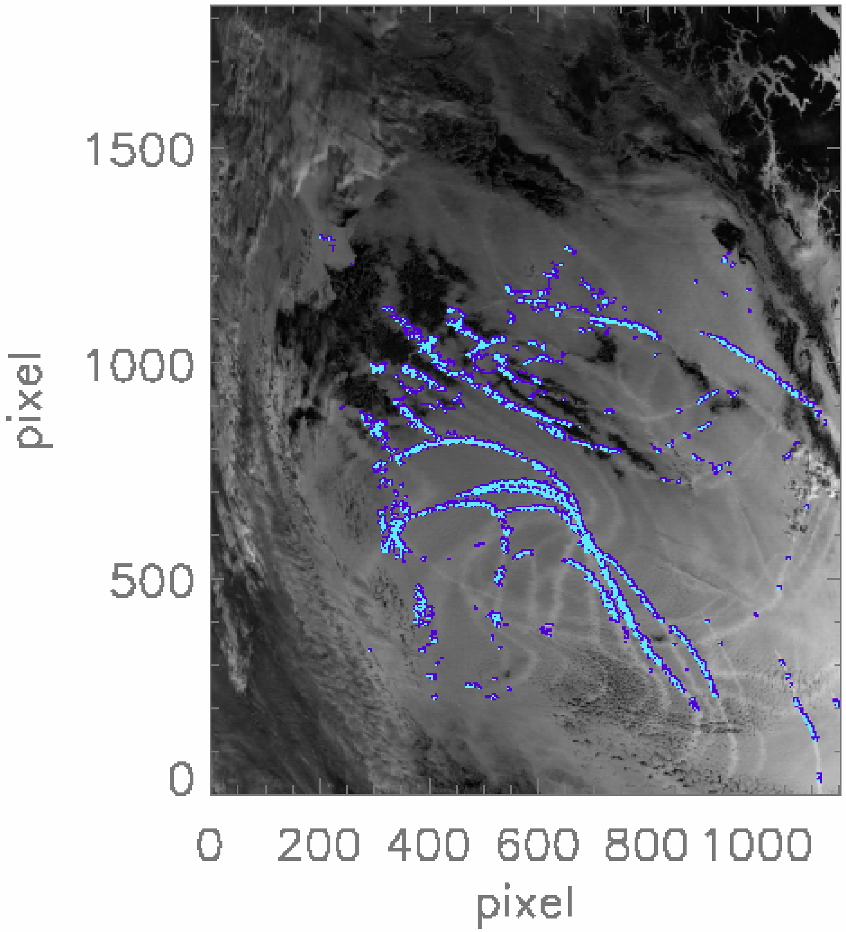
- Identification of low stratiform clouds over oceans (0.65 µm and 11µm channels)
- Use pattern recognition to derive ship track mask (0.85 and 2.13 µm channels)
- Calculate optical properties (optical thickness, effective radius, liquid water path, number concentration) for ship track and non-ship track pixels (0.85 and 1.6 µm channels) using SACURA (Kokhanovsky et al., 2003)
- Simulate radiation (short- and longwave) using derived optical properties using libRadtran (Mayer and Kylling, 2005)



Ship Track Mask



Reflectance in 0.85 µm channel



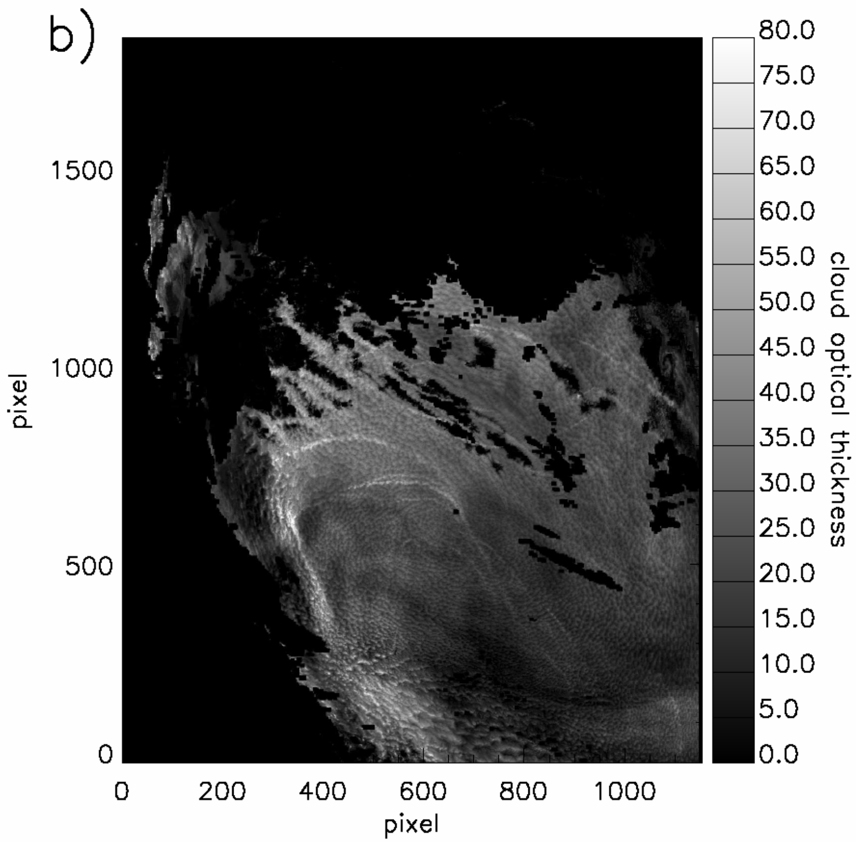
Reflectance in 2.13 µm channel

SACURA

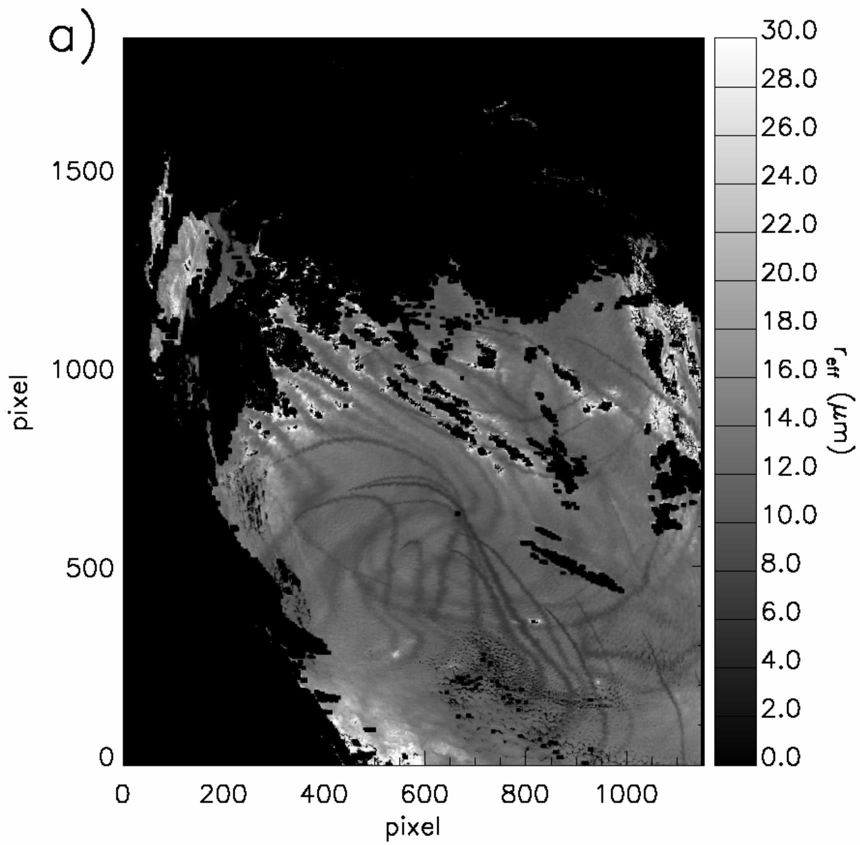
- Semi-analytical code to derive cloud parameters from reflectance measurements
- Assumes single-scattering albedo close to 1
- Quick, but increasing errors for small optical thicknesses (< 5)
- In this study for optical thickness < 5 LUT appraoch based on libRadtran simulations was used.
- Albedo: 0.03 @ 0.85 µm, 0 @ 1.6 µm
- Parameters derived, assuming vertically homogenous clouds:
  - Effective Radius
  - Optical Thickness
  - Liquid Water Path
  - Droplet number concentration:
    - effective radius + cloud optical thickness + assuming a gamma droplet size distribution (Deirmendjian 1969) + vertical homogeneous cloud of a thickness of 500m

Cloud optical properties of clouds modified by ship emissions

optical thickness



effective radius (µm)



⇒Increased optical thickness and decreased effective radius in ship tracks

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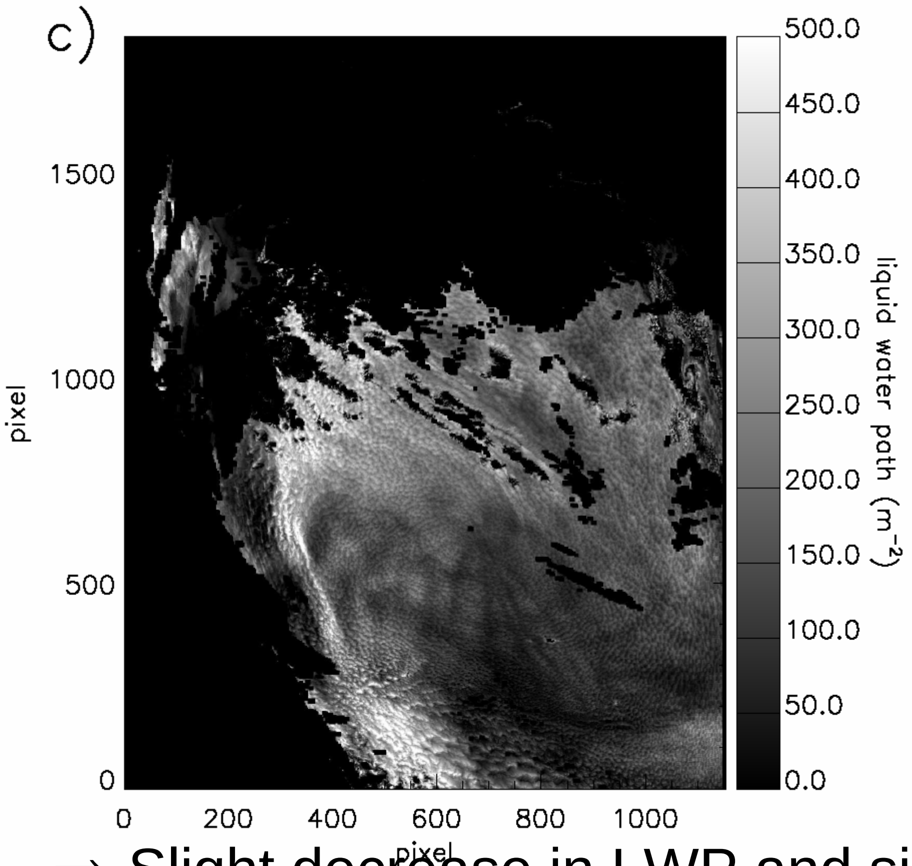
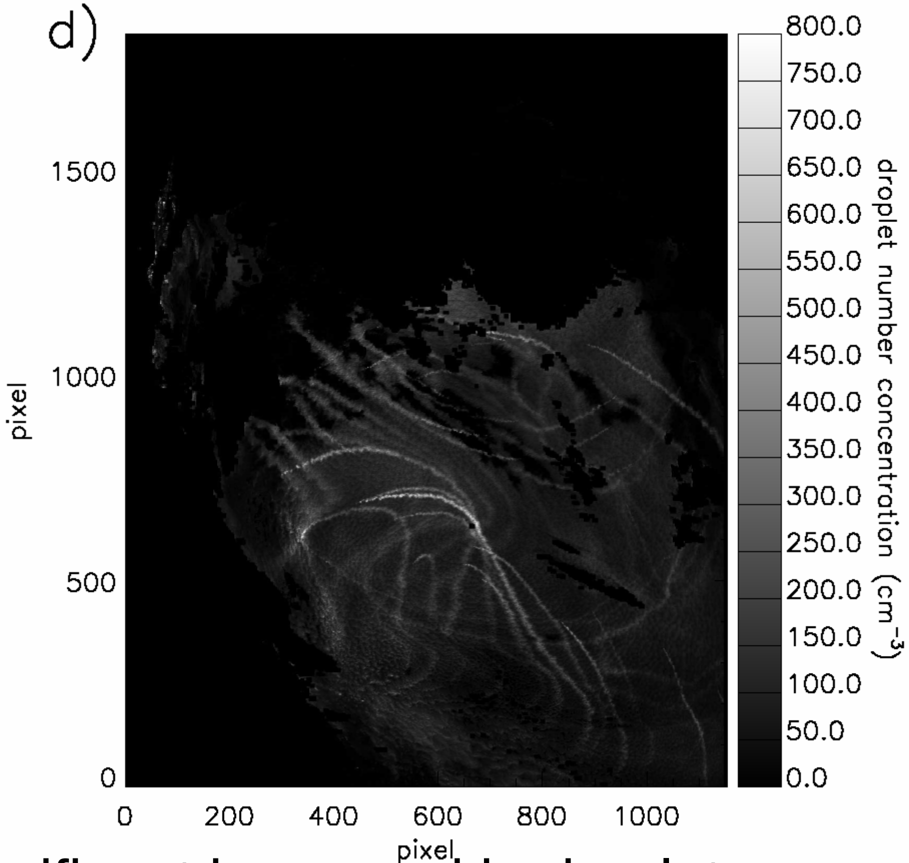
Cloud optical properties of clouds modified by ship emissions

liquid water path LWP (m^{-2}) droplet concentration N (cm^{-3})





⇒ Slight decrease in LWP and significant increased in droplet concnetrationsin ship tracks

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Changes of cloud parameters by ship emissions

	All low-cloud-pixel	no-ship-track-pixel	Only ship-track-pixel
All low-cloud-pixel			
effective radius (µm)	13.0 (*4.0*)	13.2 (*4.0*)	10.1 (*2.5*)
MODIS Standard Product		13.2	10.6
optical thickness	21.4 (*11.1*)	20.7 (*10.4*)	34.6 (*14.5*)
MODIS Standard Product		17.8	29.8
liquid water path (gm^{-2})	174 (*122*)	172 (*122*)	227 (*120*)
MODIS Standard Product		178	244
droplet number (cm^{-3})	85 (*61.7*)	79 (*82.8*)	210 (*112.6*)

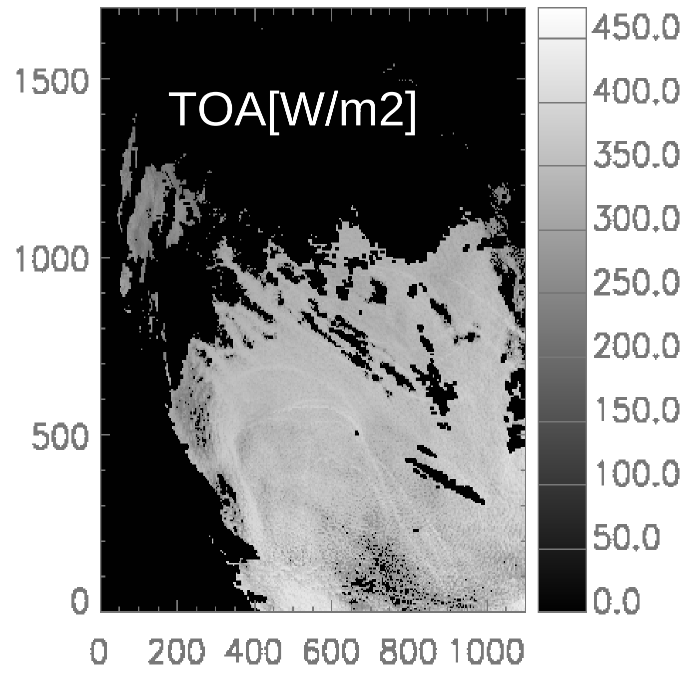
- Retrieval consistent with MODIS standard products, optical thickness slightly unerestimated by SACURA (see Nauss et al. 2005)
- Decrease of effective radius, due to CCN
- Increase of optical thickness due to increased scattering
- Increase in droplet number concentration N (more CCN inside the ship track)
- Increase in Liquid Water Path, not significant for smaller scene
- Results consistent with findings from MAST campaign

Change in radiance due to modified clouds by ship emissions

Calculate surface and TOA radiance with cloud parameters derived above taking into account the solar zenith angle dependence.

For specific scene and with a scene average SZA of 63° (all low cloud – no-ship-track px.)
Impact on shortwave surface: -2.1 W/m2
Impact on shortwave TOA: 2.0 W/m2
Impact on longwave TOA: -0.4 W/m2

Total TOA: 1.6 W/m2



Ship Tracks result in a cooling 1.6 W/m2 for the specific scene, but was is the global impact?

Summary and Outlook

- Ships globally emit 3.8% of all anthropogenic CO_2 (23% of total CO_2 from transport), 8% of NO_x emissions (14% of transport) (Eyring et al. JGR, 2005).
- Measured increase of NO_2 along major ship routes (*Richer et al., GRL, 2004*) will allow verification of emission inventories.
- Measured modification of optical and micro-physical parameters of clouds due to ship emissions will allow to estimate the contribution to the radiative forcing, for a specific scene a cooling of 1.6 W/m2 is estimated (Schreier et al. 2005). Global estimate in preparation.
- Use of satellite data allows to assess the global impact.

➔ Project demonstrates that ship emissions impact on the chemical composition of the atmosphere and on the radiation budget.

➔ Integrative study with a coupled-chemistry climate is progressing, to consistently assess the overall impact

Using AATSR-Data for global estimation

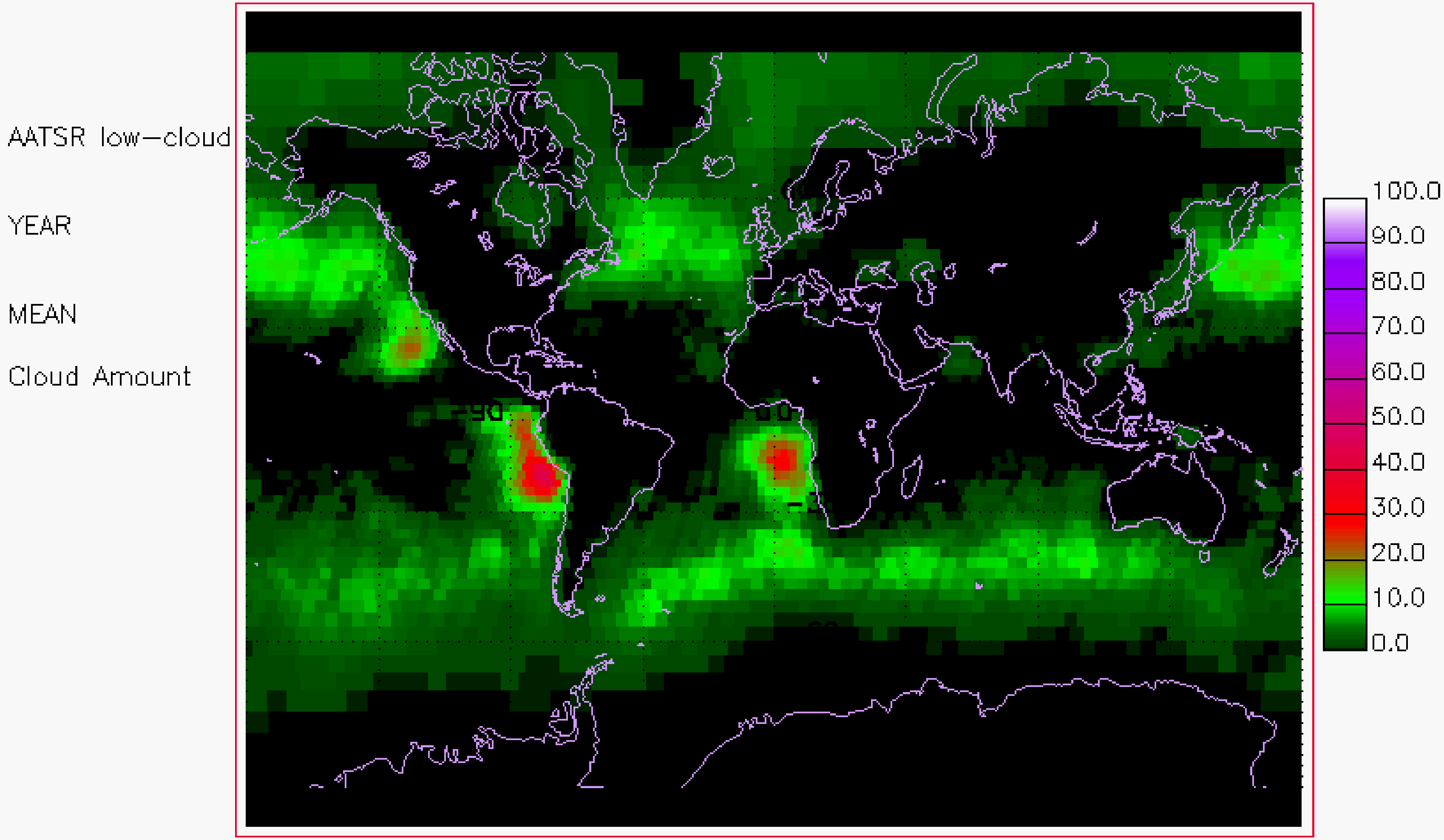
Find low clouds over ocean susceptible for ship tracks in Satellite-Data

looking for ship tracks in this data

Calculate changes in cloud properties

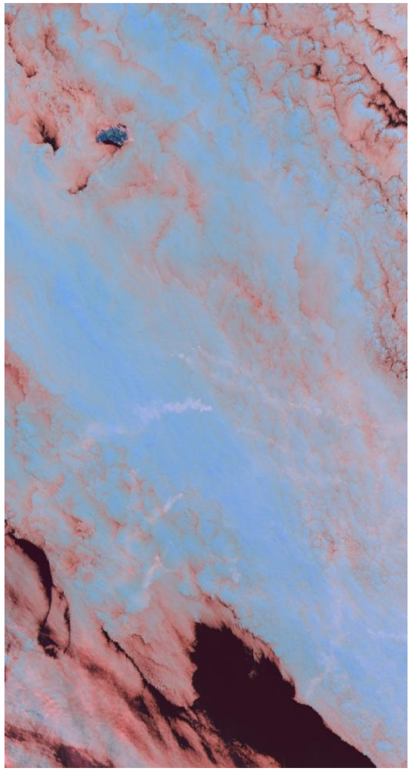
Estimate global radiation effect

Regions with low clouds susceptible for ship tracks from AATSR



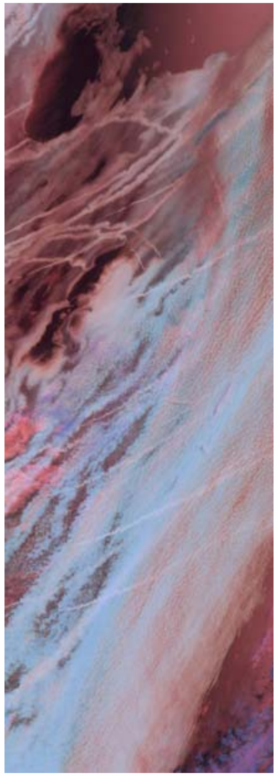
Many types of ship tracks are found in the data ….

barely visible in NIR-pictures



visible even in VIS-channels

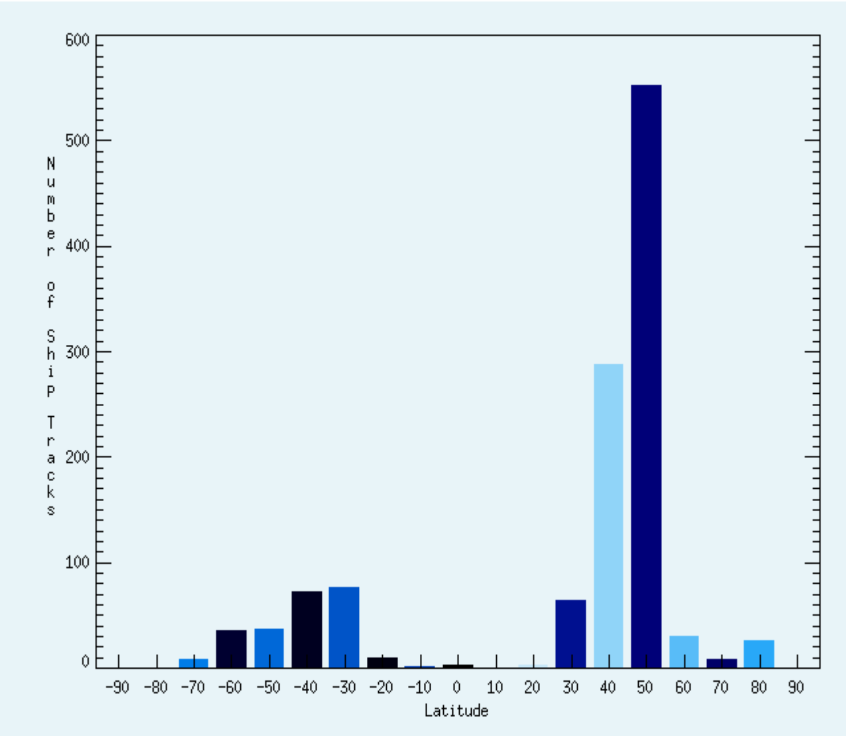
both...



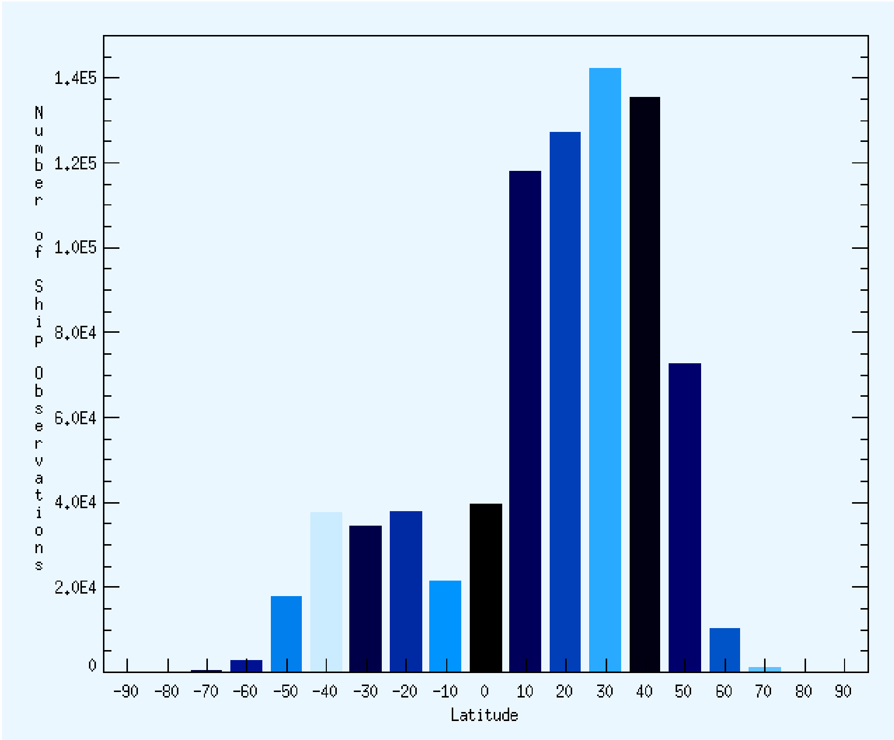
Systematic detection of ship tracks is challenging...

Preliminary Result: Latitudinal Distribution of identified ship tracks

Number of identified ship tracks



Vessel traffic density



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