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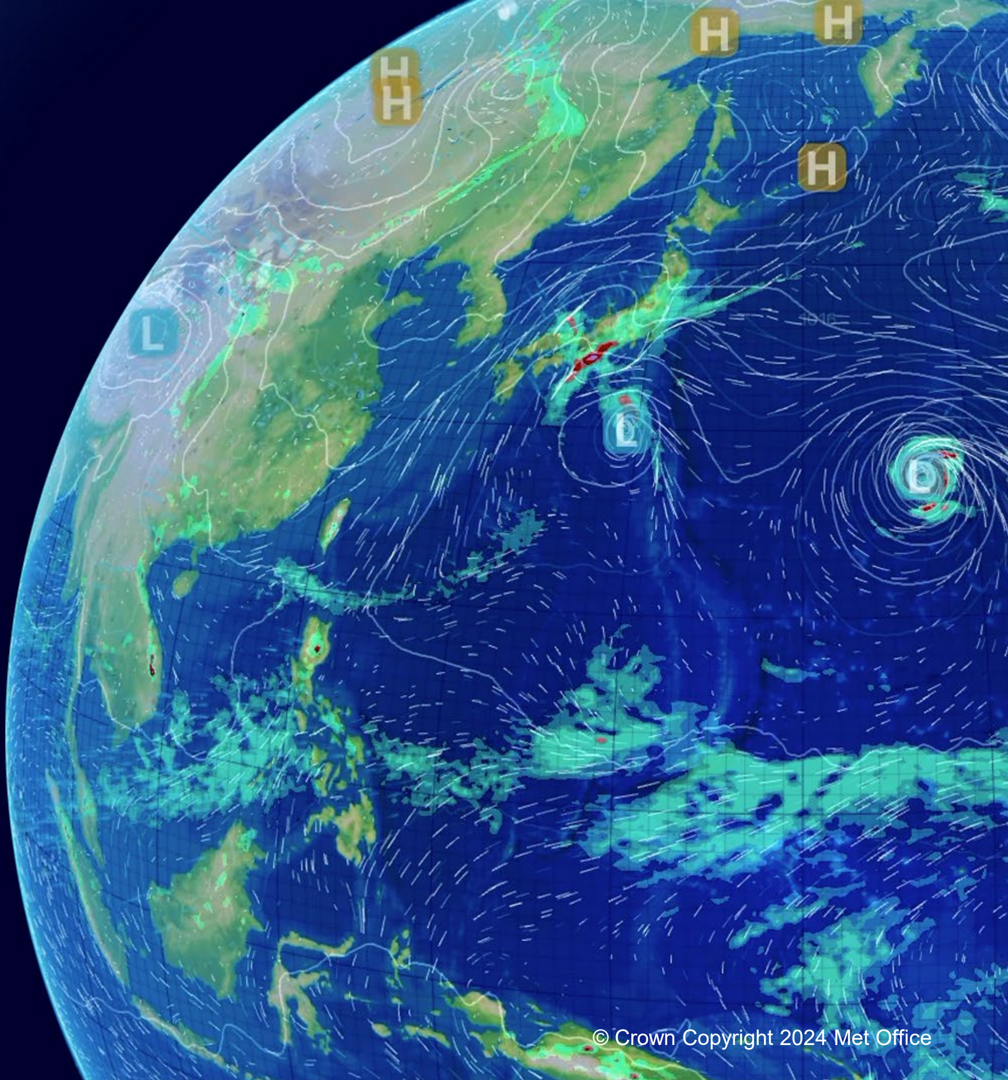
Infrared emissivity modelling

Stu Newman, Ed Pavelin, Brett Candy and Chawn Harlow

NWP SAF Workshop on Satellite Observations of the Earth System Interfaces, ECMWF, 19-22 November 2024



Infrared emissivity modelling

Part 1 – forward modelling the ocean IR emissivity

Part 2 – estimation of land surface IR emissivity

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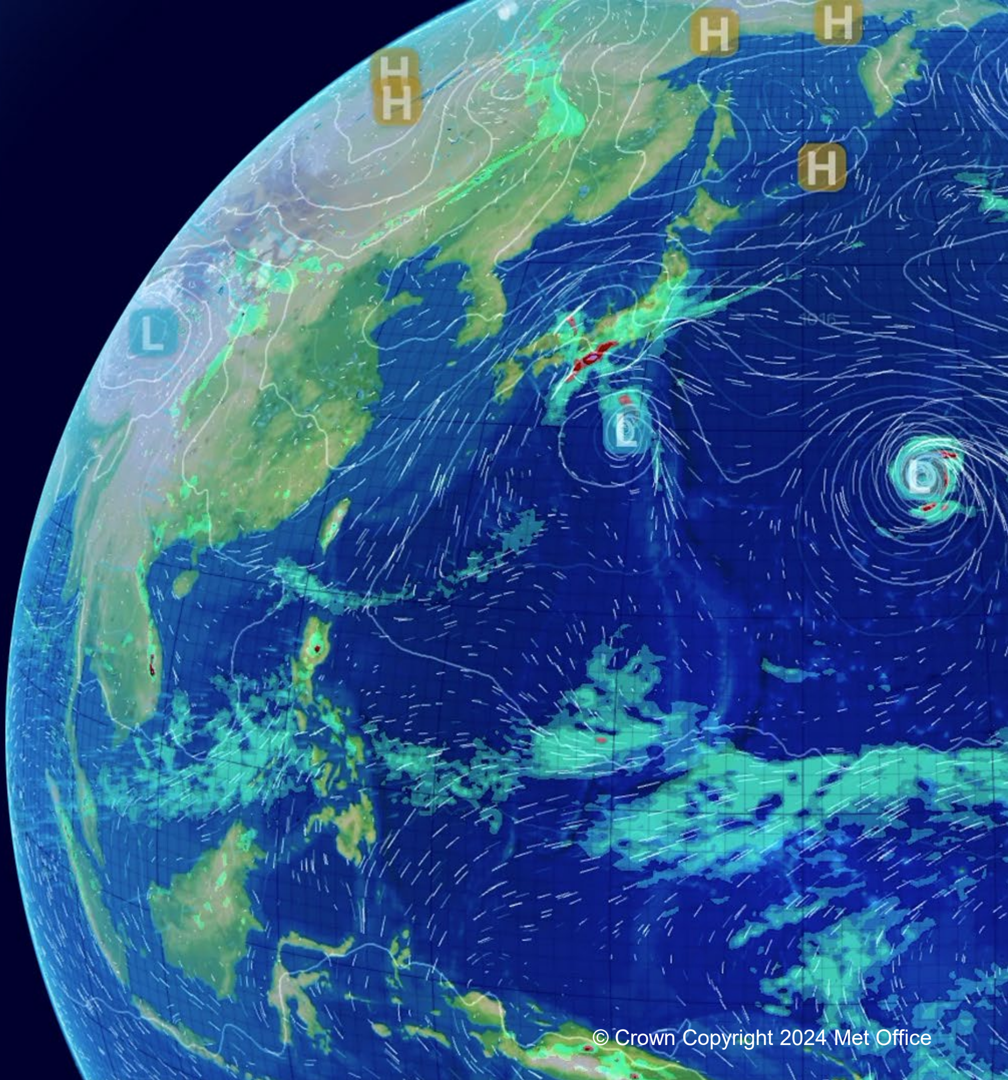
Part 1 – forward modelling the ocean infrared emissivity



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IR ocean emissivity modelling: wave facets

Fresnel equations: reflectance ρ (emissivity ε) for a planar surface as a function of complex refractive index n and view angle χ w.r.t. surface normal

$$\gamma_{\parallel} = -\frac{n\cos\chi - \cos\chi'}{n\cos\chi + \cos\chi'}$$

$$\gamma_{\perp} = \frac{\cos\chi - n\cos\chi'}{\cos\chi + n\cos\chi'}$$

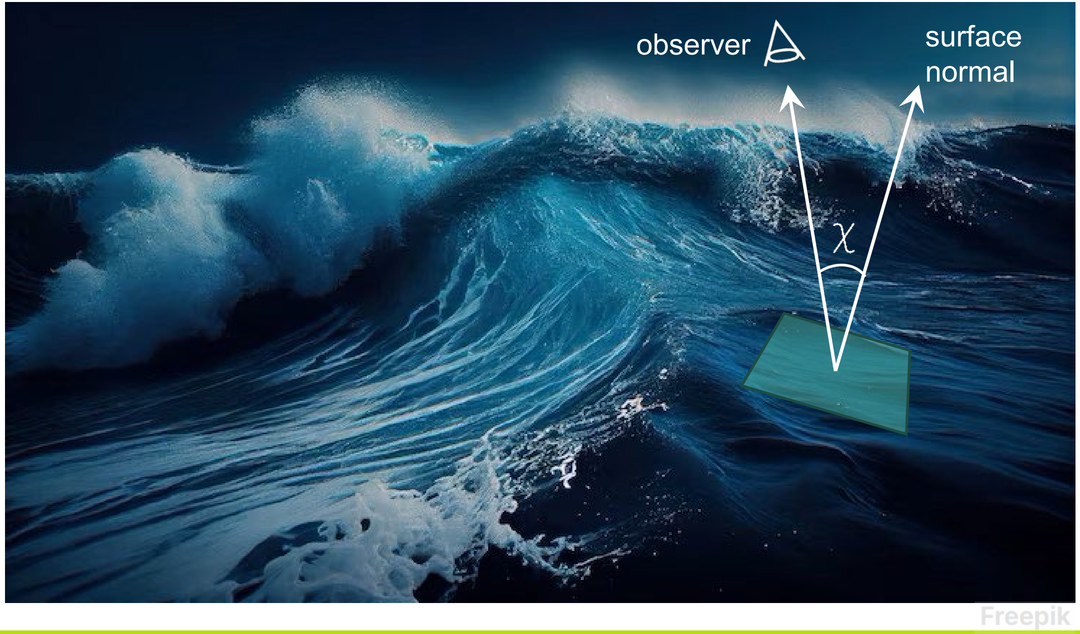
$$\sin\chi' = (1/n)\sin\chi$$

$$\rho(n,\chi) = \left(|\gamma_{\parallel}|^2 + |\gamma_{\perp}|^2\right)/2$$

$$\epsilon(n,\chi) = 1 - \rho(n,\chi)$$

K. Masuda et al., https://doi.org/10.1016/0034-4257(88)90032-6

- Geometric optics regime
- Model emissivity of individual wave facets (Fresnel equations) for
  - a given orientation angle
  - spectral complex refractive index
- Integrate emission over modelled probability distribution of wave slopes
- Account for proportion of foam and its emission



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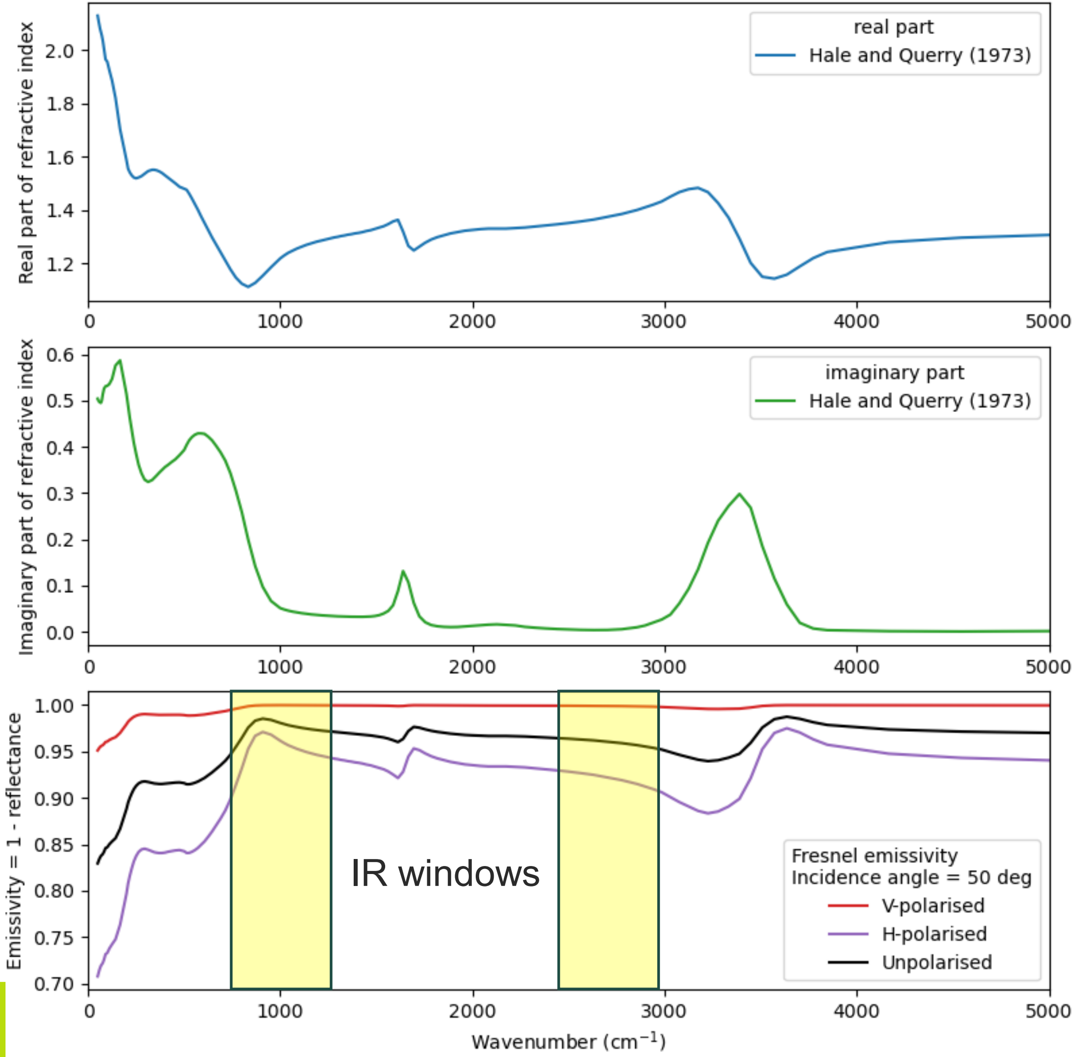
IR emissivity modelling

- Make use of tabulated complex refractive index (or permittivity) of (sea)water
- Fresnel equations for flat surface emissivity
- Emissivity polarisation dependence for incidence angles > 0º – we typically assume IR radiometers do not have polarisation sensitivity and use the average of polarised emissivity components



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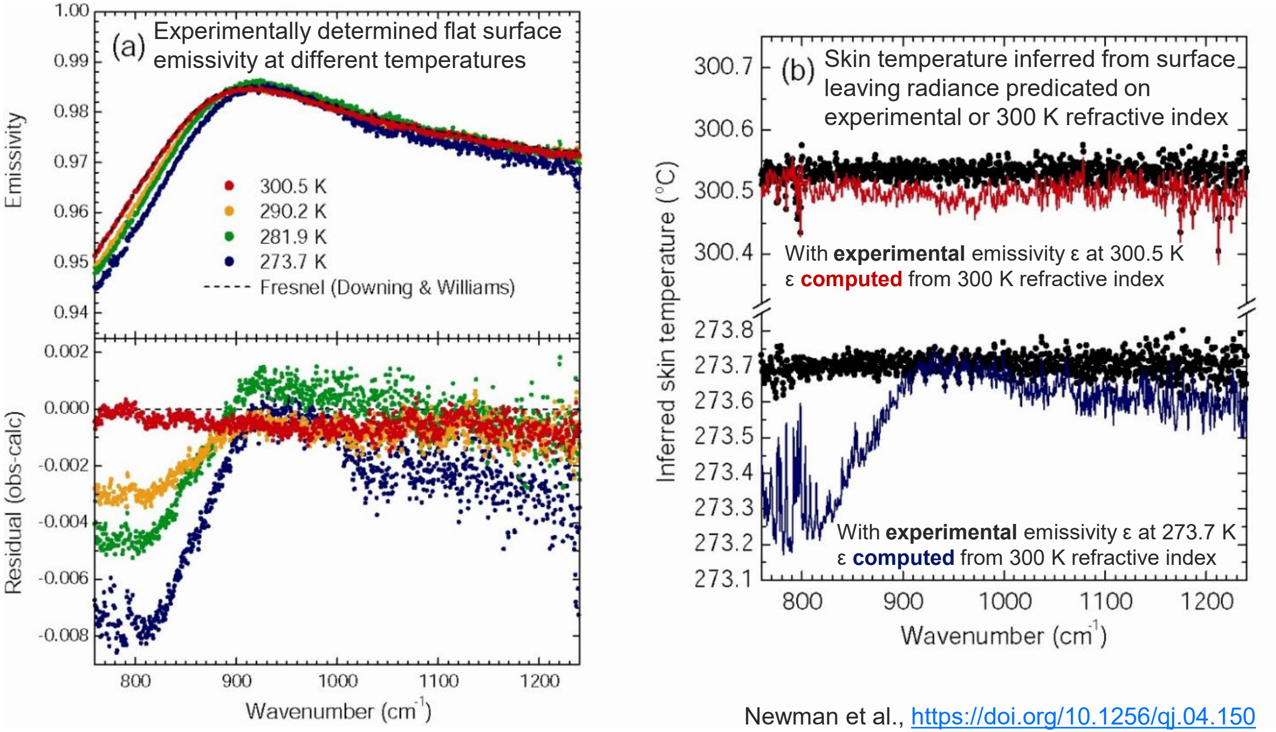
IR ocean emissivity

Errors in retrieved SST of up to 0.5 K can result from neglecting refractive index temperature dependence

- In the mid-IR it is important to correct pure water complex refractive index for effects of temperature as well as salinity
- Experimentally retrieved emissivity for pure water departs from room temperature (300 K) laboratory data with decreasing temperature near 800 cm^{-1}



Newman et al., https://doi.org/10.1256/qj.04.150

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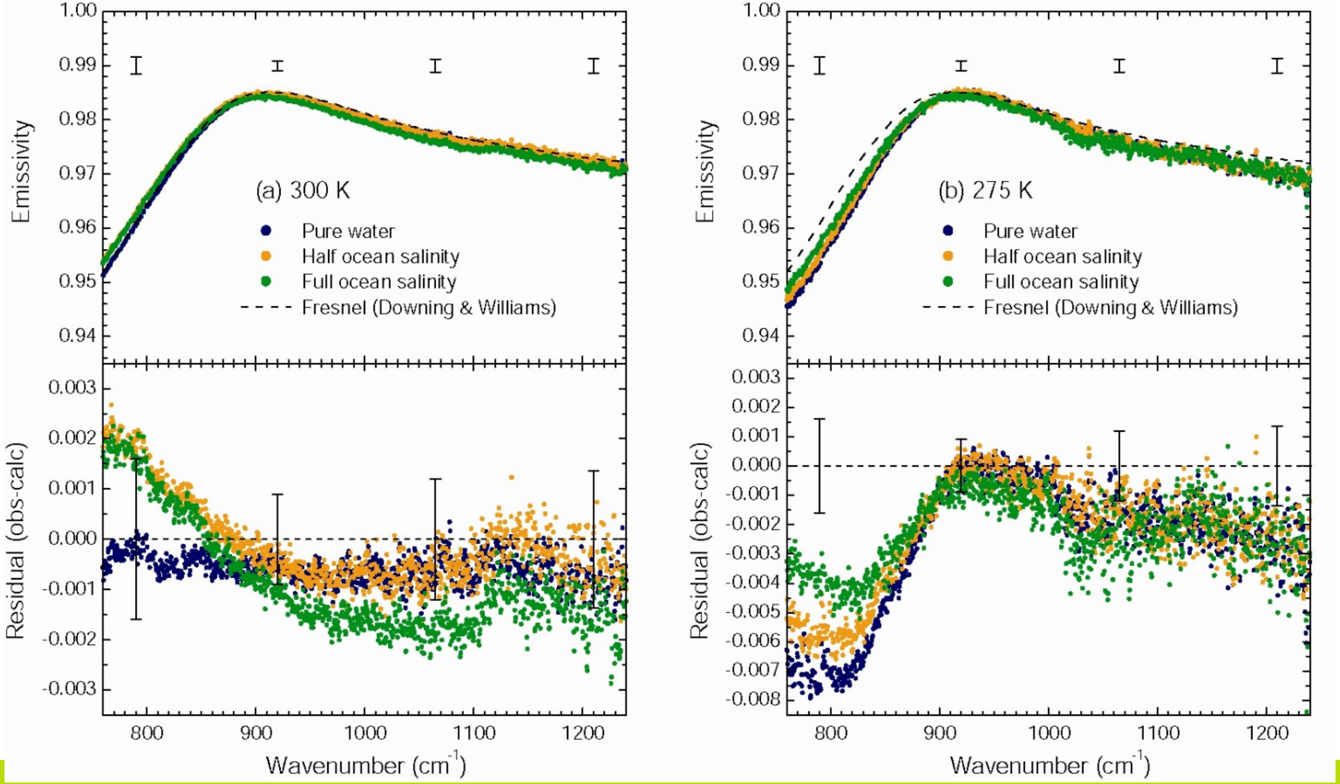
IR ocean emissivity

- Corrections of pure water complex refractive index for salinity are smaller than for temperature
- Typically we correct for standard ocean salinity of 35 g/l



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IR emissivity modelling: wave slope probabilities

- Models integrate over a probability distribution function describing the tilts of the facets of the sea surface
- It is common to model mean square slope as a linear function of 10 m wind speed

Mean square slopes upwind (m_u) and crosswind (m_c)

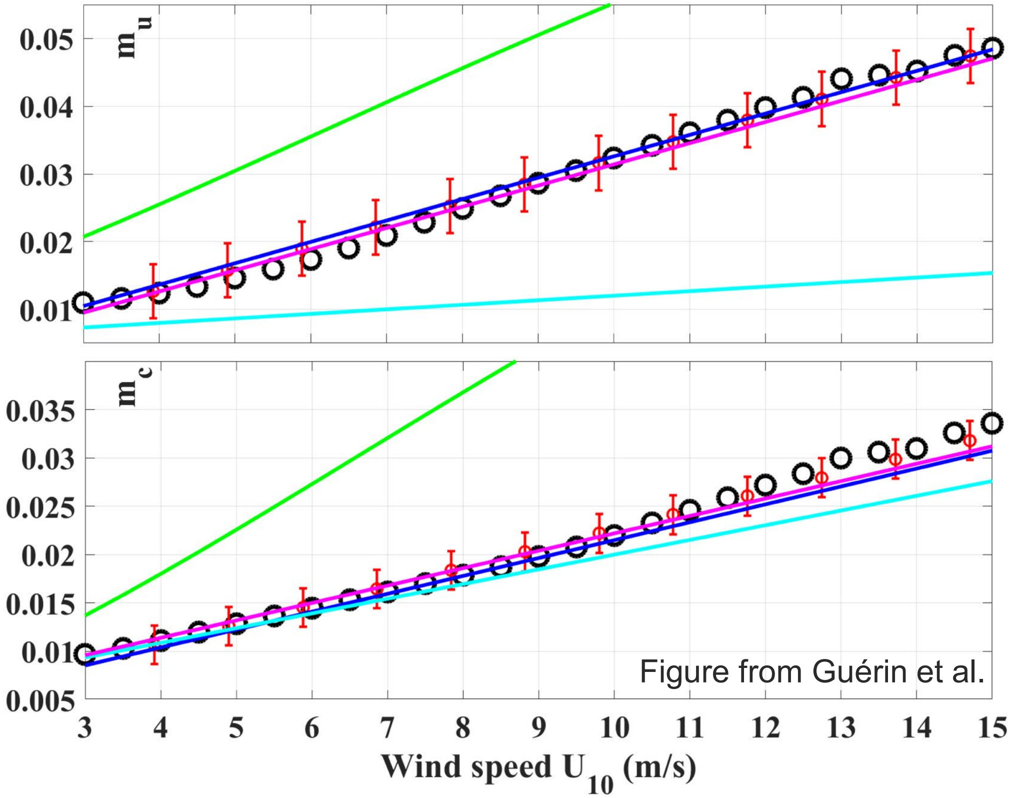


Figure from Guérin et al.

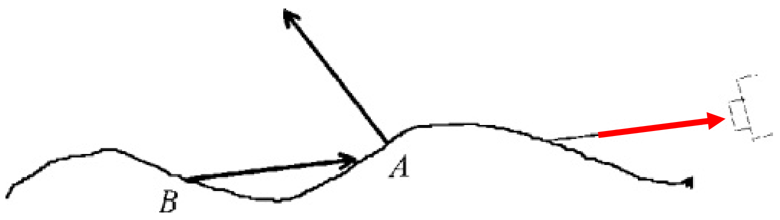
Figure legend:

- Guérin et al., https://doi.org/10.1016/j.rse.2023.113508
- Cox and Munk, https://doi.org/10.1364/JOSA.44.000838
- Mermelstein et al., https://doi.org/10.1364/AO.33.006022
- Ebuchi and Kizu, https://doi.org/10.1023/A:1021213331788
- Bréon and Henriot, https://doi.org/10.1029/2005JC003343
- Lenain et al., https://doi.org/10.1175/JPO-D-19-0098.1

IR emissivity modelling: integration over wave slopes

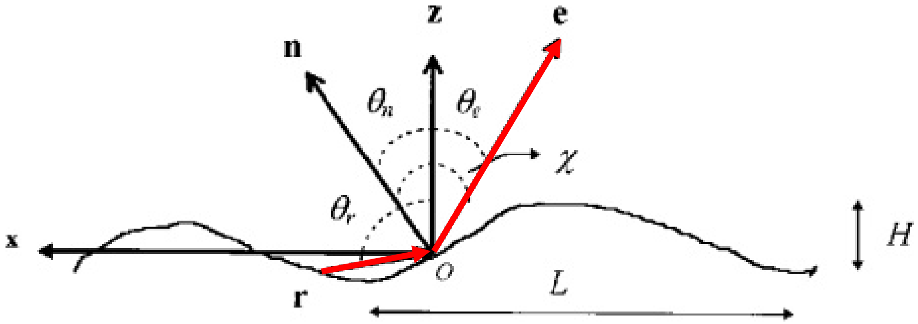
- Wave shadowing

Waves can block some sea surface emission from reaching the sensor



- Surface-emitted surface-reflected (SESR) emission

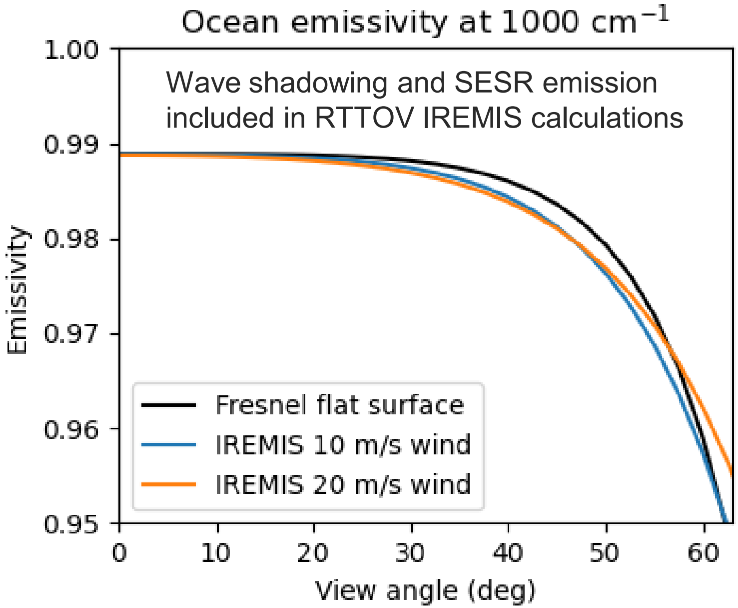
Include probability of reflected radiance originating from the sea surface rather than the sky



Figures from Wu and Smith, https://doi.org/10.1364/AO.36.002609

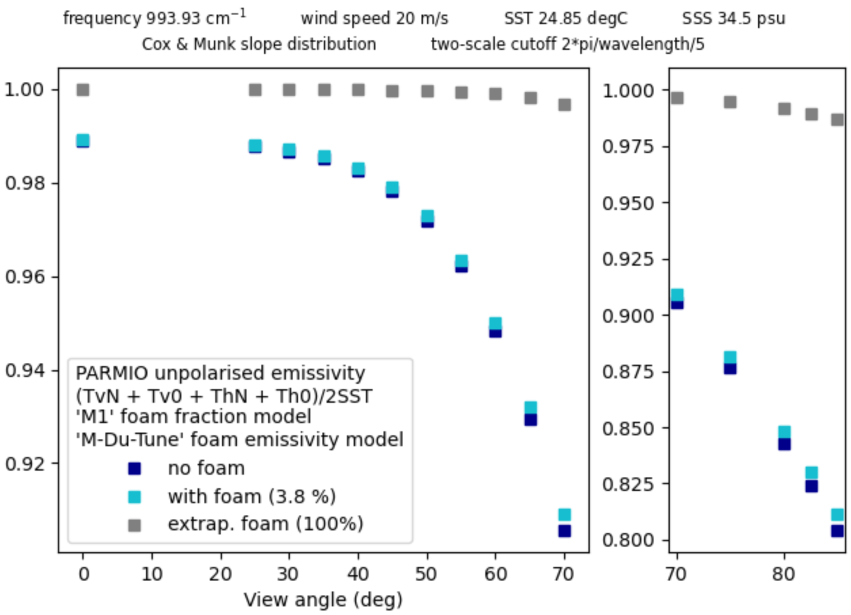
IR emissivity modelling: integration over wave slopes

- Modelled emissivity for roughened sea surface departs from Fresnel flat surface values for larger view angles and higher surface wind speeds



IR emissivity modelling: effects of foam coverage

- Presence of foam at higher surface wind speeds is often neglected in IR ocean emissivity models
- Studies in the literature suggest the IR emissivity of foam is similar to or slightly higher than that for seawater
- Passive and Active Reference Microwave to Infrared Ocean (PARMIO) reference model includes modules for foam coverage fraction and foam emissivity – this is optimised for the microwave (Magdalena Anguelova)



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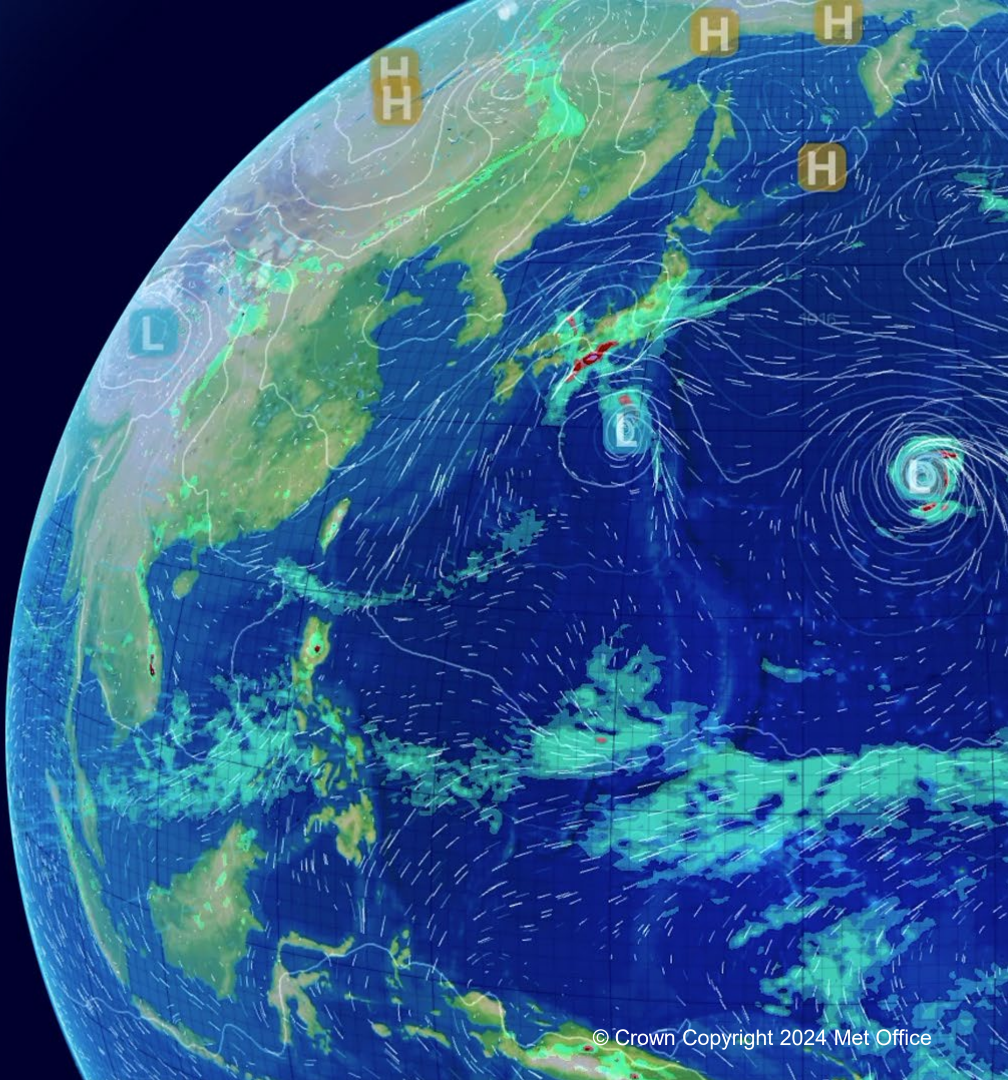
IR ocean emissivity models

- IREMIS in RTTOV (since version 12, Marco Matricardi and James Hocking)
  - ❑ Complex refractive index of seawater, including temperature and salinity dependency
  - ❑ Wind speed dependent wave slope statistics taken from Ebuchi and Kizu, https://doi.org/10.1023/A:1021213331788
  - ❑ Integration over wave slopes, including shadowing and SESR, due to Masuda, https://doi.org/10.1016/j.rse.2006.04.011
  - ❑ Foam emissivity not modelled
- PARMIO reference model (ISSI team, Emmanuel Dinnat et al.)
  - ❑ Two-scale model; geometric optics treatment now updated to be similar to IREMIS and is applicable in the IR
  - ❑ Several options for slope variance of large-scale waves, such as empirical relationship of Cox and Munk, https://doi.org/10.1364/JOSA.44.000838 or wave spectrum of Durden and Vesecky, https://doi.org/10.1109/JOE.1985.1145133
  - ❑ Includes models for foam fraction and emissivity (requiring validation in the IR)

Part 2 – estimation of IR land surface emissivity



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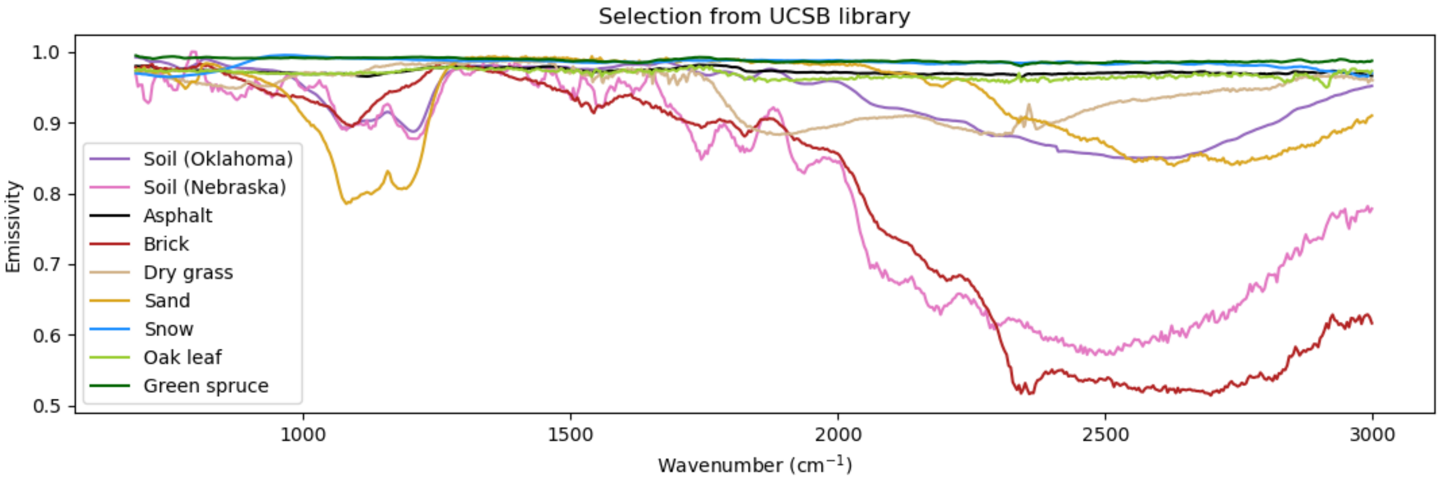
Infrared emissivity of land surfaces

- In contrast to the ocean, the land surface exhibits highly variable spectral emissivity
- Databases of laboratory measurements of natural and artificial materials are available:
  - UCSB Emissivity Library https://icess.eri.ucsb.edu/modis/EMIS/html/em.html
  - ASTER/ECOSTRESS spectral library https://speclib.jpl.nasa.gov/



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  - ASTER/ECOSTRESS spectral library https://speclib.jpl.nasa.gov/
- IR land surface emissivity atlases are available in RTTOV from work by Eva Borbas, Suzanne Seemann, Michelle Feltz (University of Wisconsin/CIMSS) and co-workers – MODIS emissivity mapped to high spectral resolution using principal components of laboratory data
  - ❑ University of Wisconsin Infrared Emissivity Atlas (UWiremis)
  - ❑ Combined ASTER MODIS Emissivity over Land (CAMEL) dataset
- Previous work at the Met Office combined upwelling and downwelling airborne measurements of IR spectral radiance (ARIES airborne interferometer) to retrieve emissivity spectra over different surfaces (assuming Lambertian reflectance)
  - For methodology see Thelen et al. (2009) https://doi.org/10.1002/qj.520

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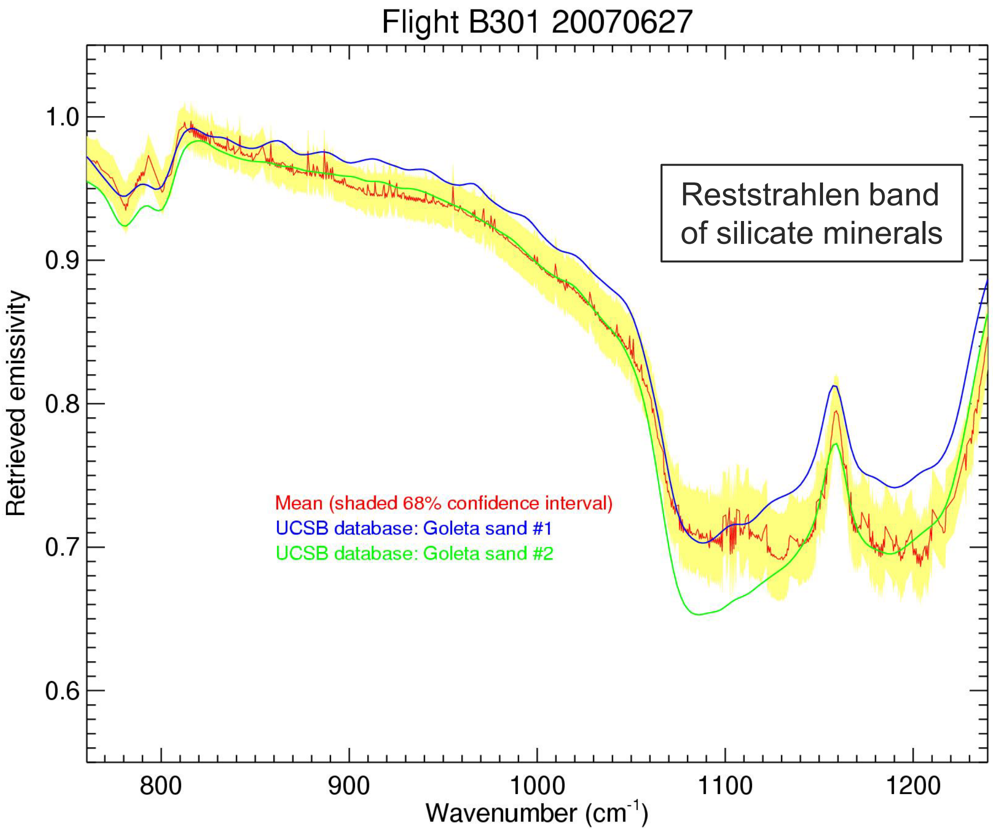
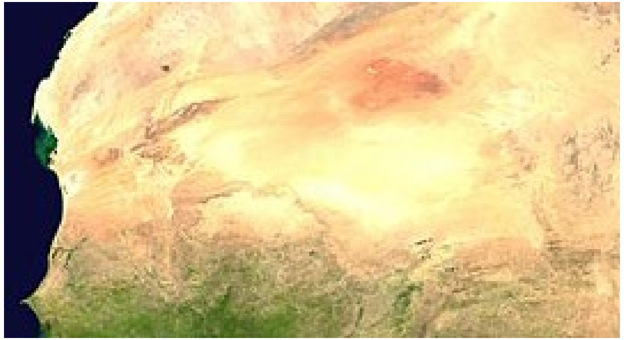
Airborne retrievals of IR emissivity

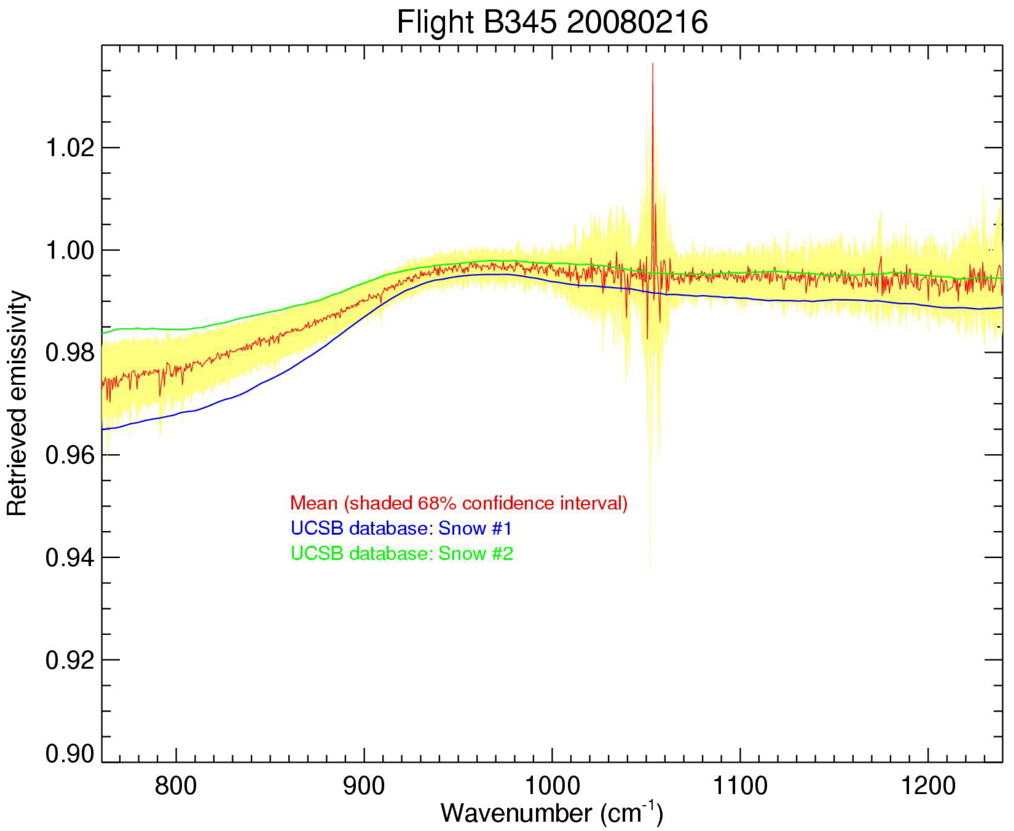


GERBILS campaign: southwestern parts of Sahara Desert

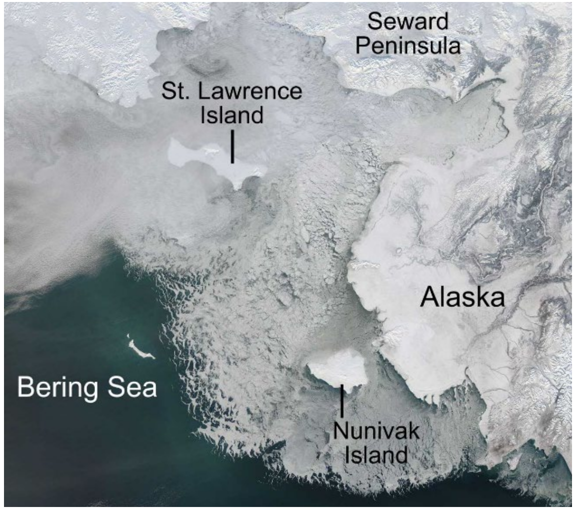


NASA/GSFC/MODIS blue marble

Airborne retrievals of IR emissivity



CLPX-II campaign: snow-covered sea ice off Alaskan coast



NASA/GSFC/MODIS/EARTH@HOME

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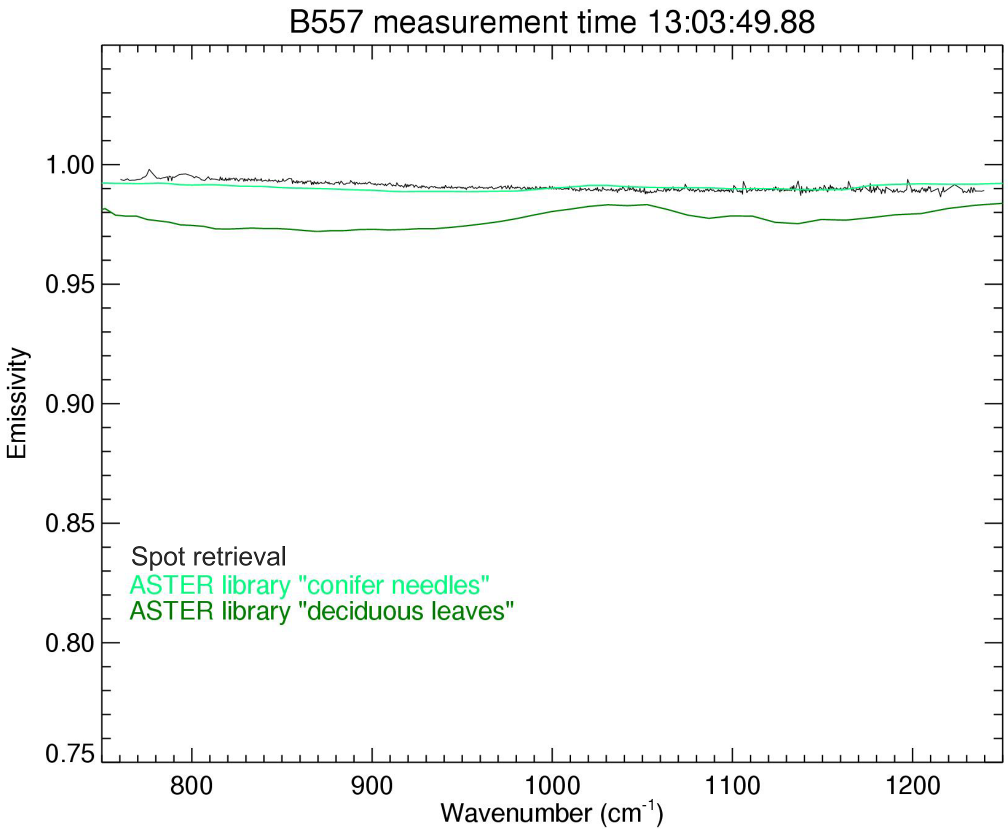
Airborne retrievals of IR emissivity



Flight over eastern England: treetops

FAAM downward facing camera

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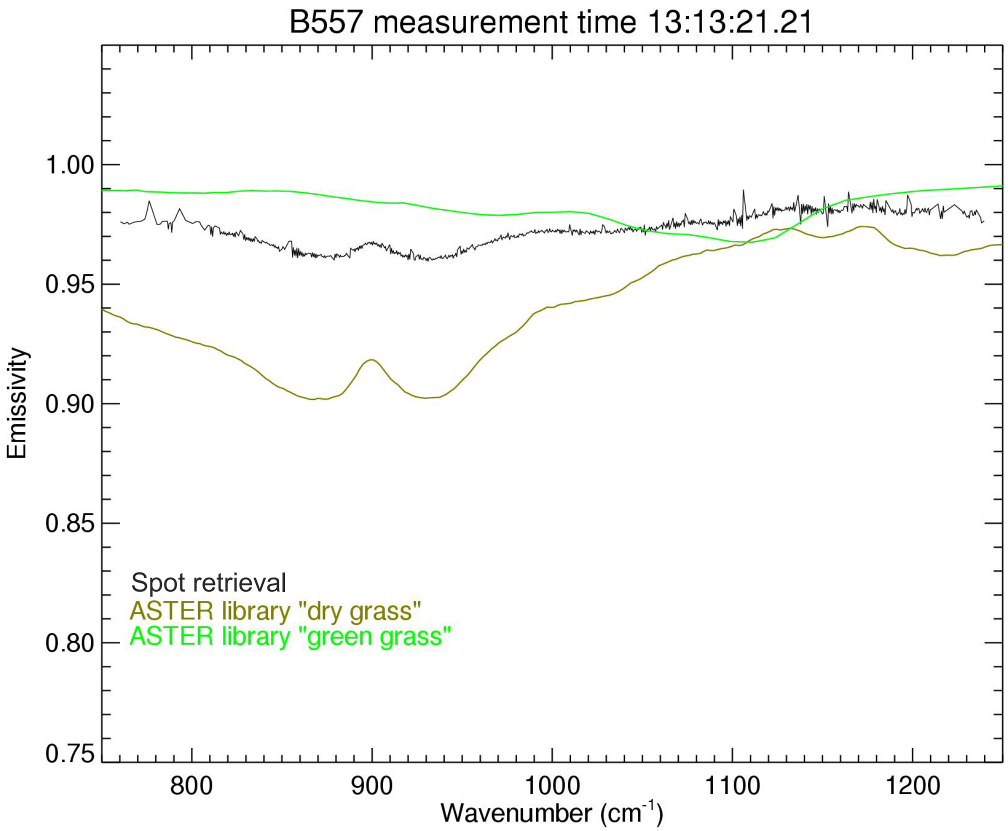
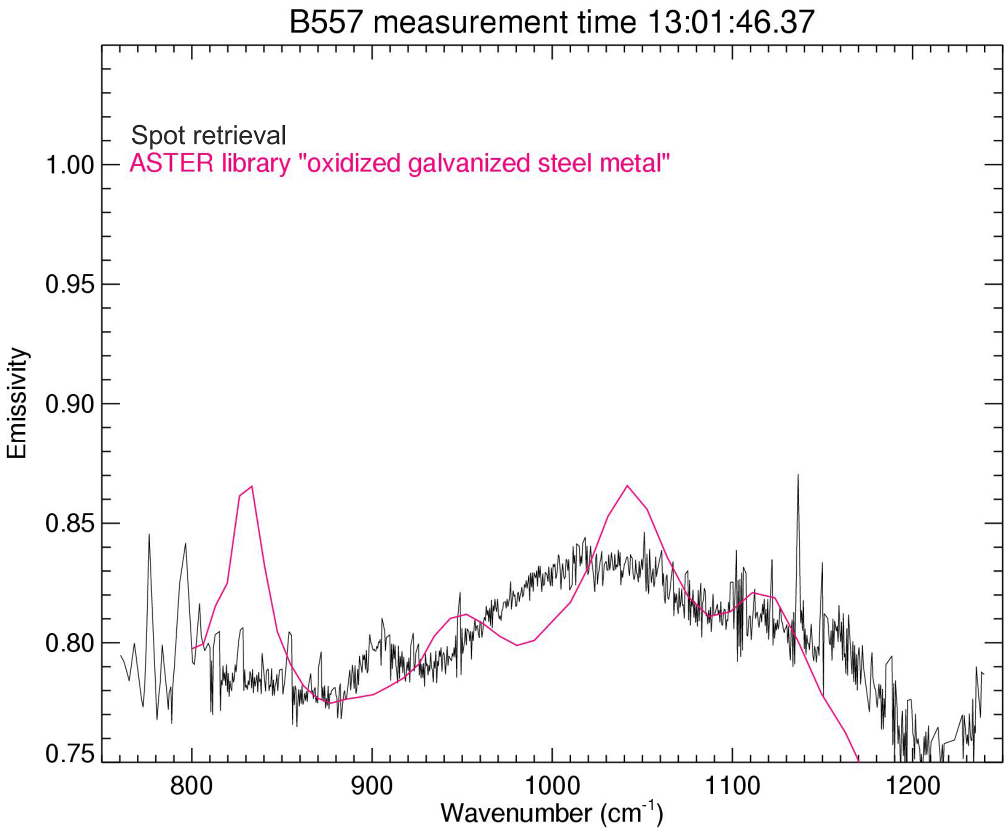
Airborne retrievals of IR emissivity



Flight over eastern England: dry arable land

FAAM downward facing camera

Airborne retrievals of IR emissivity



Flight over eastern England: sheds/buildings

FAAM downward facing camera

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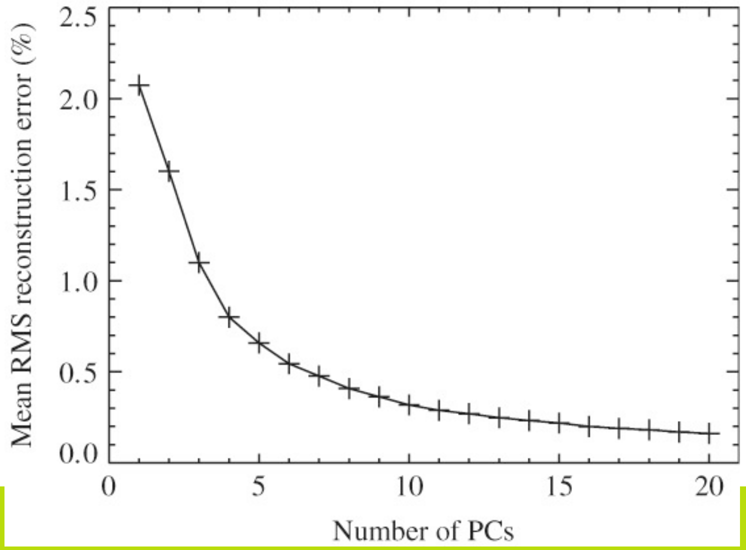
Quarterly Journal of the Royal Meteorological Society   *Q. J. R. Meteorol. Soc.* 140: 1198–1208, April 2014 B DOI:10.1002/qj.2218

RMetS
Royal Meteorological Society

Assimilation of surface-sensitive infrared radiances over land: Estimation of land surface temperature and emissivity

E. G. Pavelin* and B. Candy
Met Office, Exeter, UK

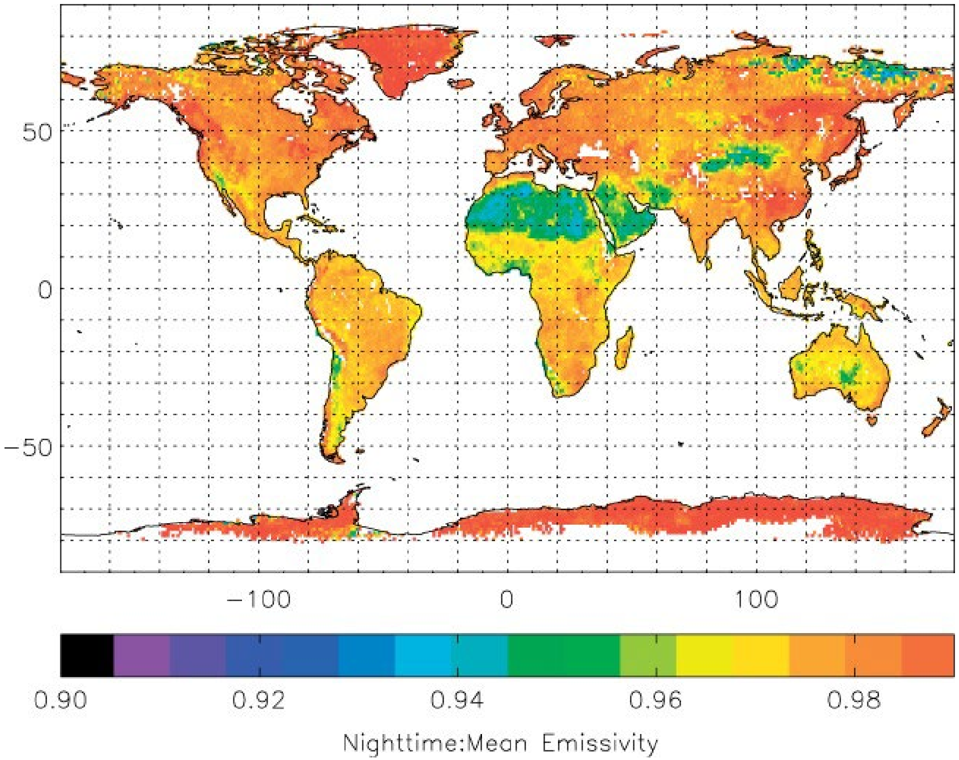
- At the Met Office satellite radiances are processed by a 1D-Var scheme (quality control; retrieval of auxiliary cloud and surface parameters) before being passed to 4D-Var
- Emissivity is retrieved in the 1D-Var as a set of leading principal components (PCs)
- Derive PCs from laboratory data (UCSB set)
- With 12 PCs the RMS reconstruction error is < 0.3%



(Ed Pavelin and Brett Candy)

IASI emissivity retrieval

- Spectral emissivity Jacobians from RTTOV transformed to be with respect to perturbations in PC weights
- Error covariance for emissivity PCs is derived from the covariance matrix of the training dataset PCs
- Skin temperature retrieved simultaneously, background error set to 5.0 K globally
- 1D-Var initialised with atlas data in RTTOV as first guess
- Emissivity passed to 4D-Var for use in forward calculation



Monthly mean (February) retrieved surface emissivity at 10.4 μm (night-time only IASI scenes)

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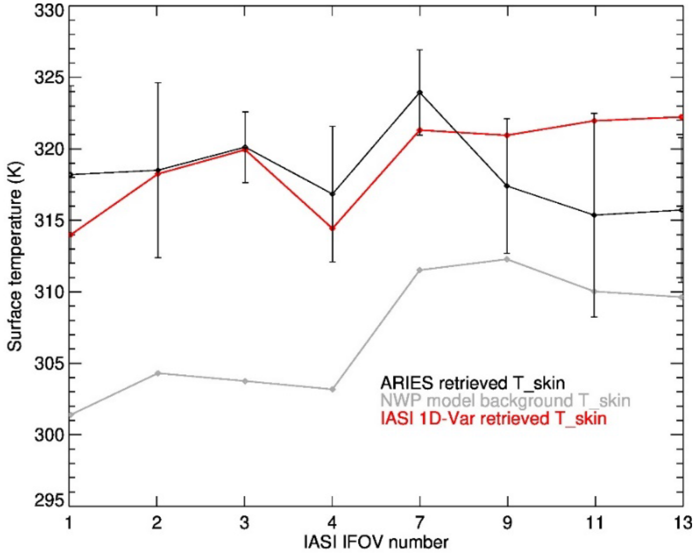
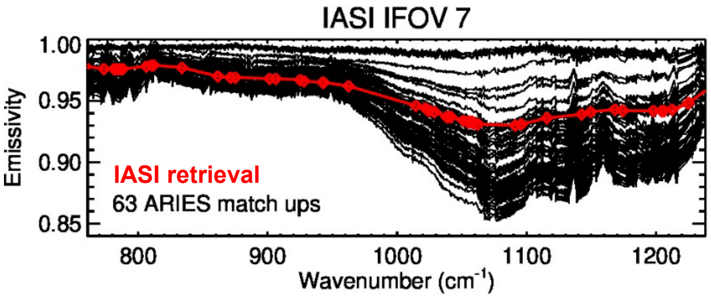
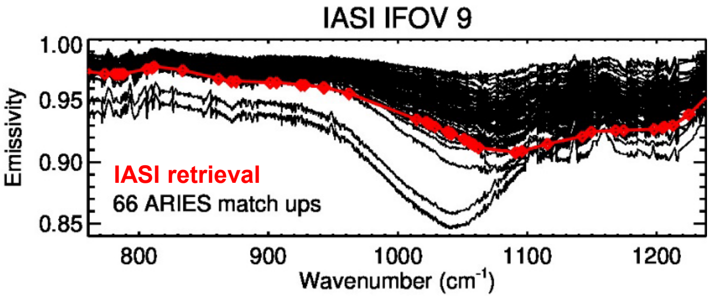
Airborne validation of IASI retrievals

Semi-Arid Land Surface Temperature and IASI Calibration Experiment (SALSTICE) in Southeastern Arizona in 2013

- Scene inhomogeneity makes validation challenging
- Large model skin temperature biases over arid regions
- Daytime rejections for surface-sensitive channels (those peaking below 400 hPa) due to larger uncertainties in retrieved emissivity and skin temperature







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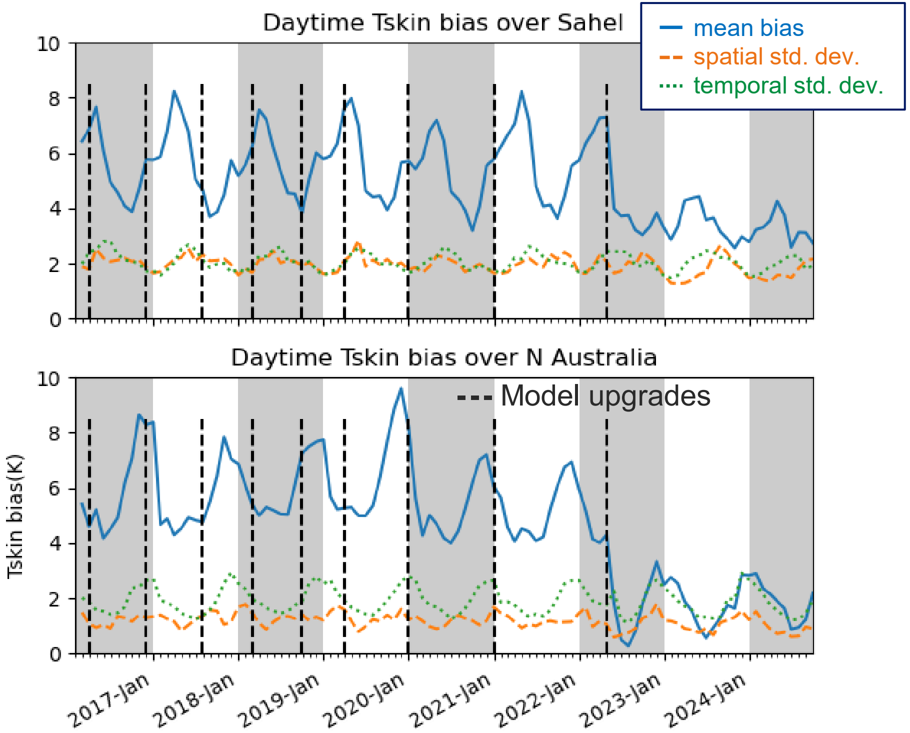
Monitoring land surface temperature model biases

- IASI retrievals can be used to monitor background skin temperature
- Recent Met Office model upgrades have resulted in reduced land surface temperature biases
- Currently, retrieved emissivity and skin temperature are passed as fixed variables to 4D-Var at the Met Office



(Chawn Harlow)

Infrared emissivity modelling: summary

IR ocean emissivity

- Geometric optics approach
- We need an accurate knowledge of the spectral optical properties of seawater
- Rough ocean modelled via probability distribution function of wave slopes
- Emissivity of foam is similar to that of seawater (contribution is often neglected)

IR land and sea ice emissivity

- IR emissivity over land is highly spatially variable for different scene types
- Sources of emissivity information include laboratory spectra and retrievals from spaceborne sensors
- IR emissivity atlases can be used e.g. as a first guess as in Met Office 1D-Var – possibility of extending land approach to sea ice

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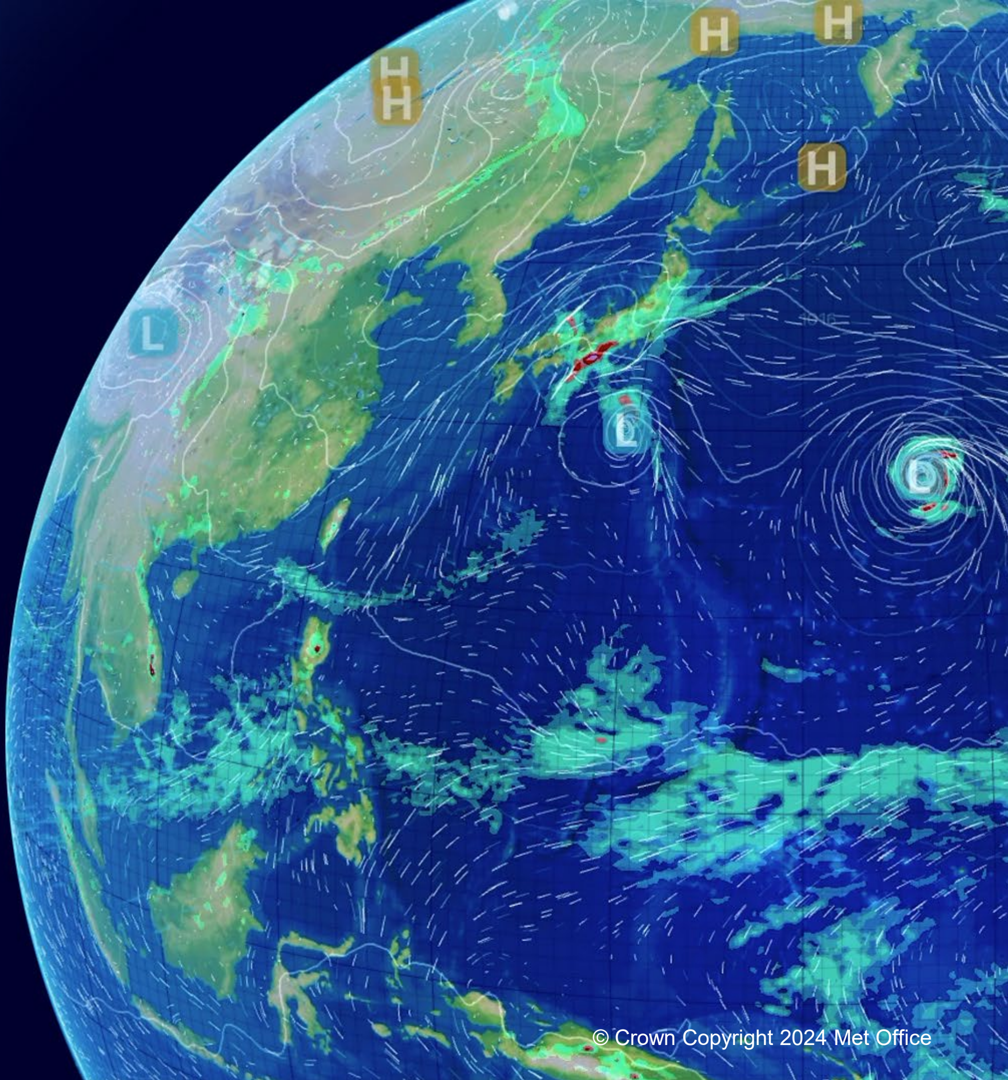

Thanks for listening

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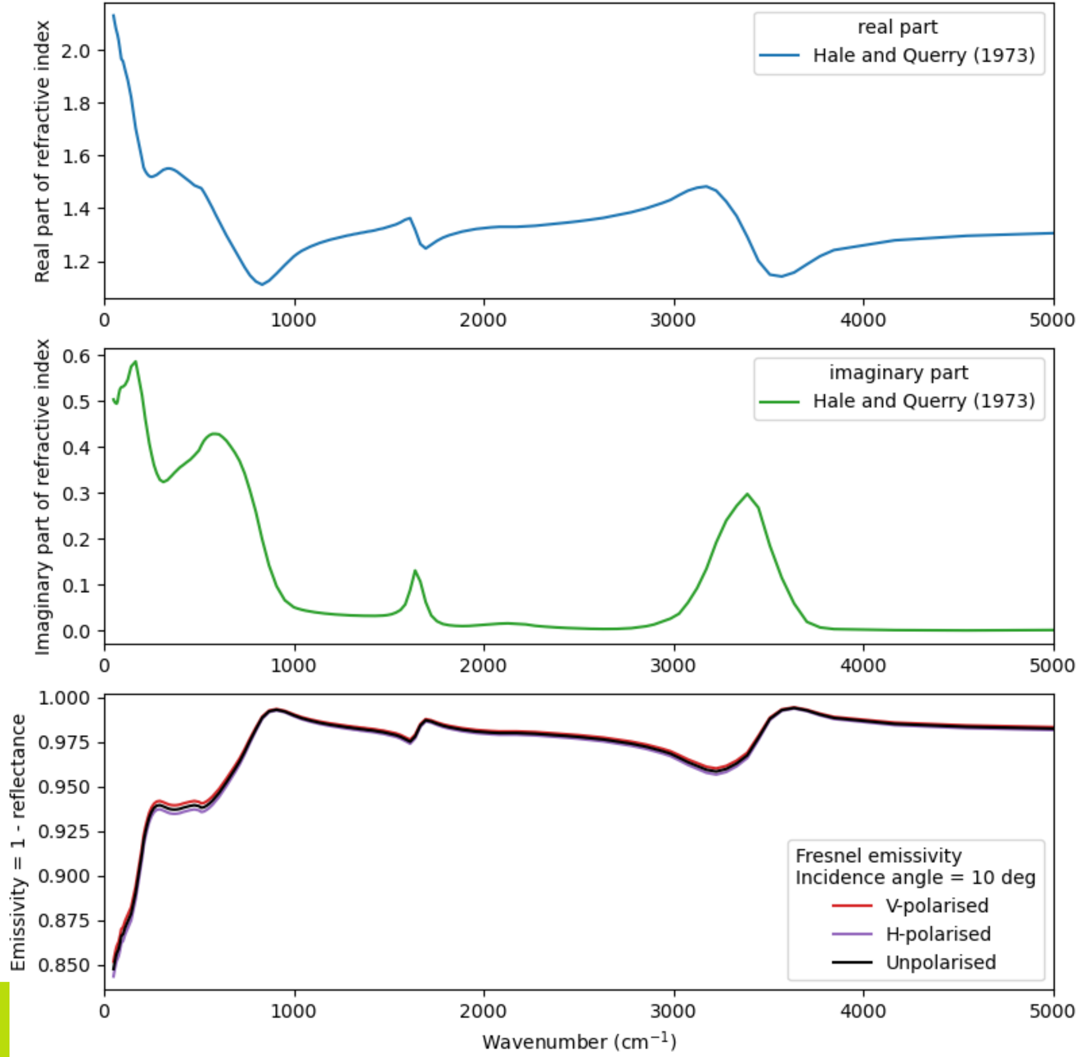
Additional slides

IR emissivity modelling

- Fresnel relationship: at near-nadir incidence angle the V- and H-polarised emissivity spectra are very similar (identical for an incidence angle of 0º)



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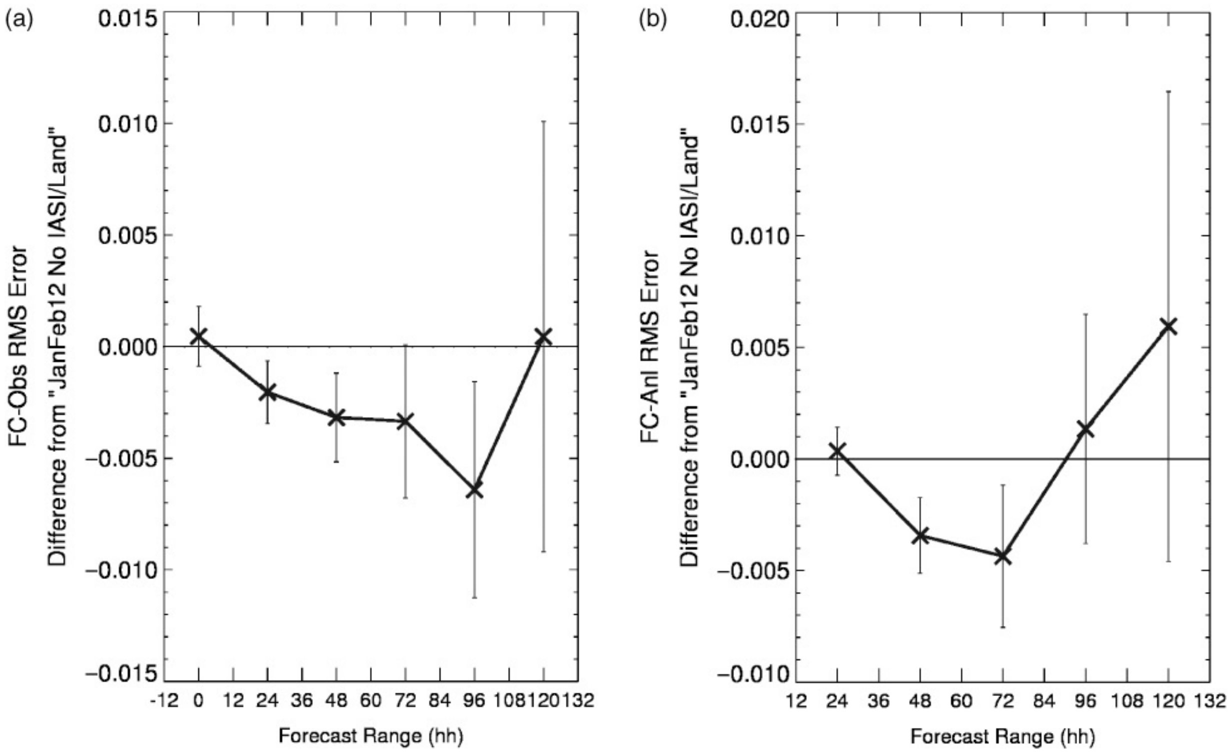
Impact of assimilating low-peaking IASI channels over land on the near-surface temperature forecast

- Left: change in RMS surface temperature forecast difference from surface observations (trial versus control)
- Right: change in RMS surface temperature forecast difference from analyses (trial versus control)



Pavelin and Candy, https://doi.org/10.1002/qj.2218

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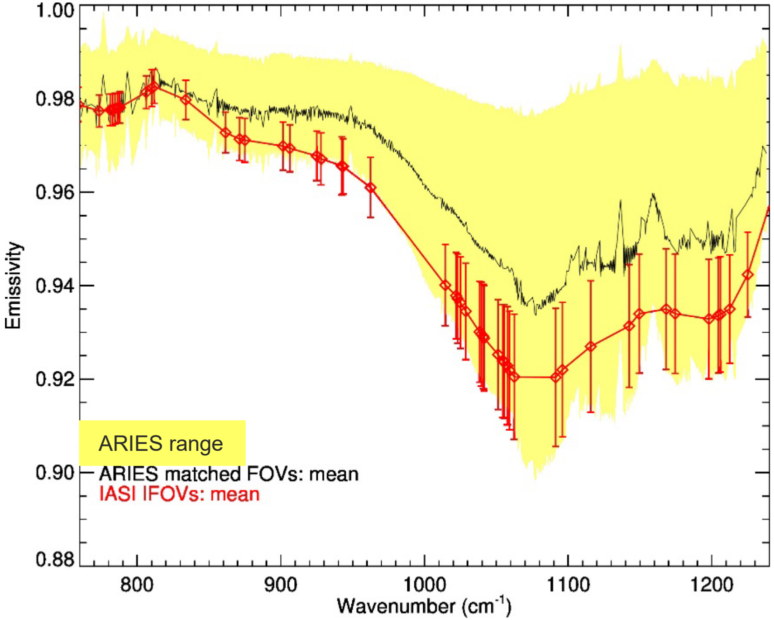
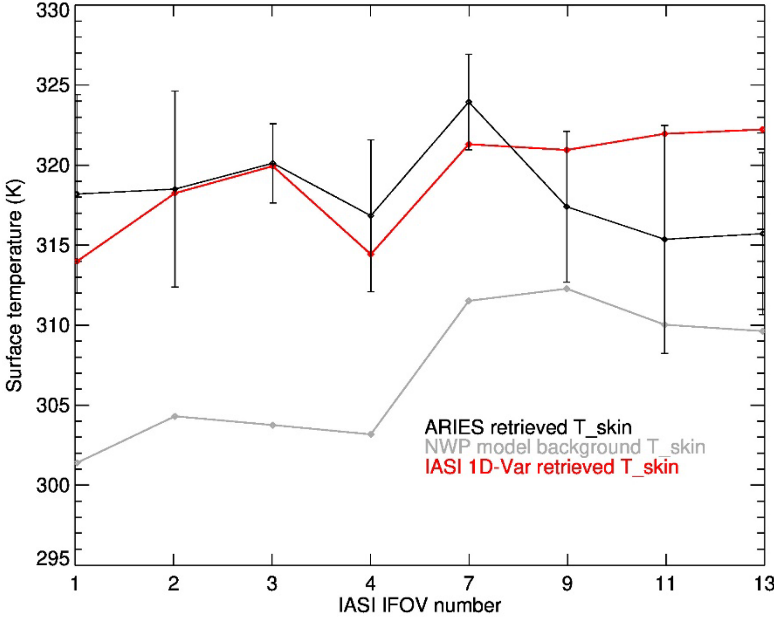
Airborne validation of IASI retrievals (SALSTICE)

- Matched IASI fields of view (8) with ARIES linear transects





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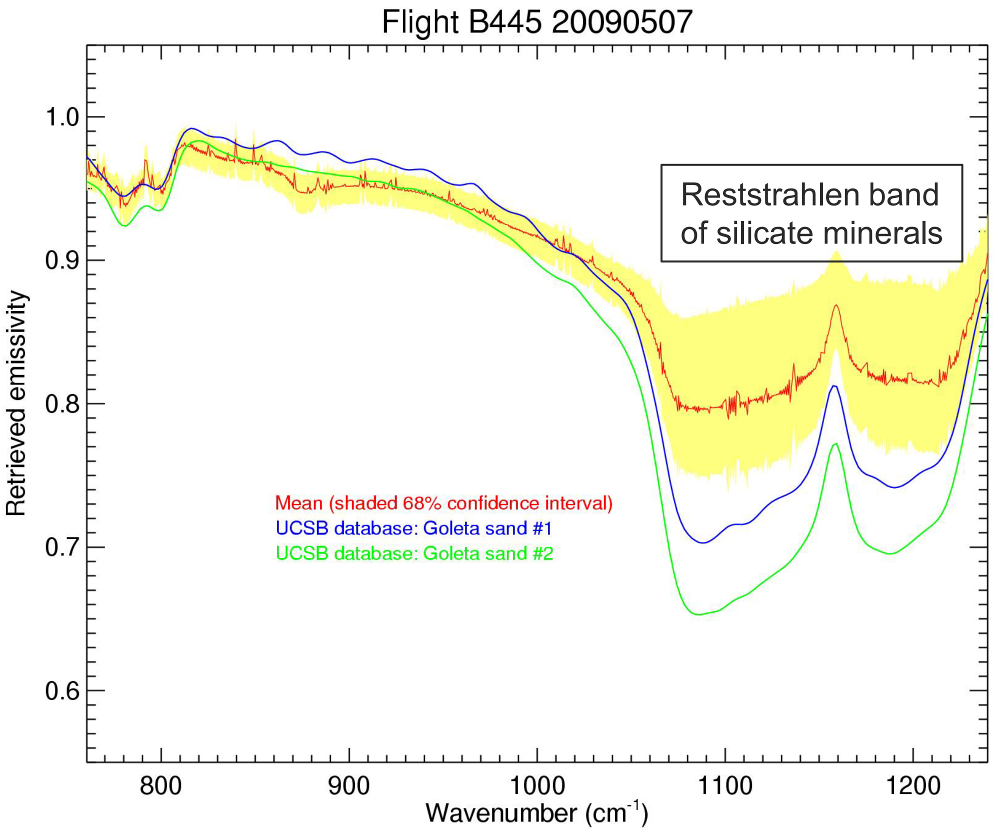
Airborne retrievals of IR emissivity



ARIES airborne interferometer

MEVEX campaign: Oman

NASA/GSFC/MODIS blue marble