Coupling through the observation operator

Alan Geer

Thanks to: Patricia de Rosnay, Yoichi Hirahara, Katrin Lonitz, Niels Bormann, Phil Browne, Steffen Tietsche, Stephen English, Cristina Lupu

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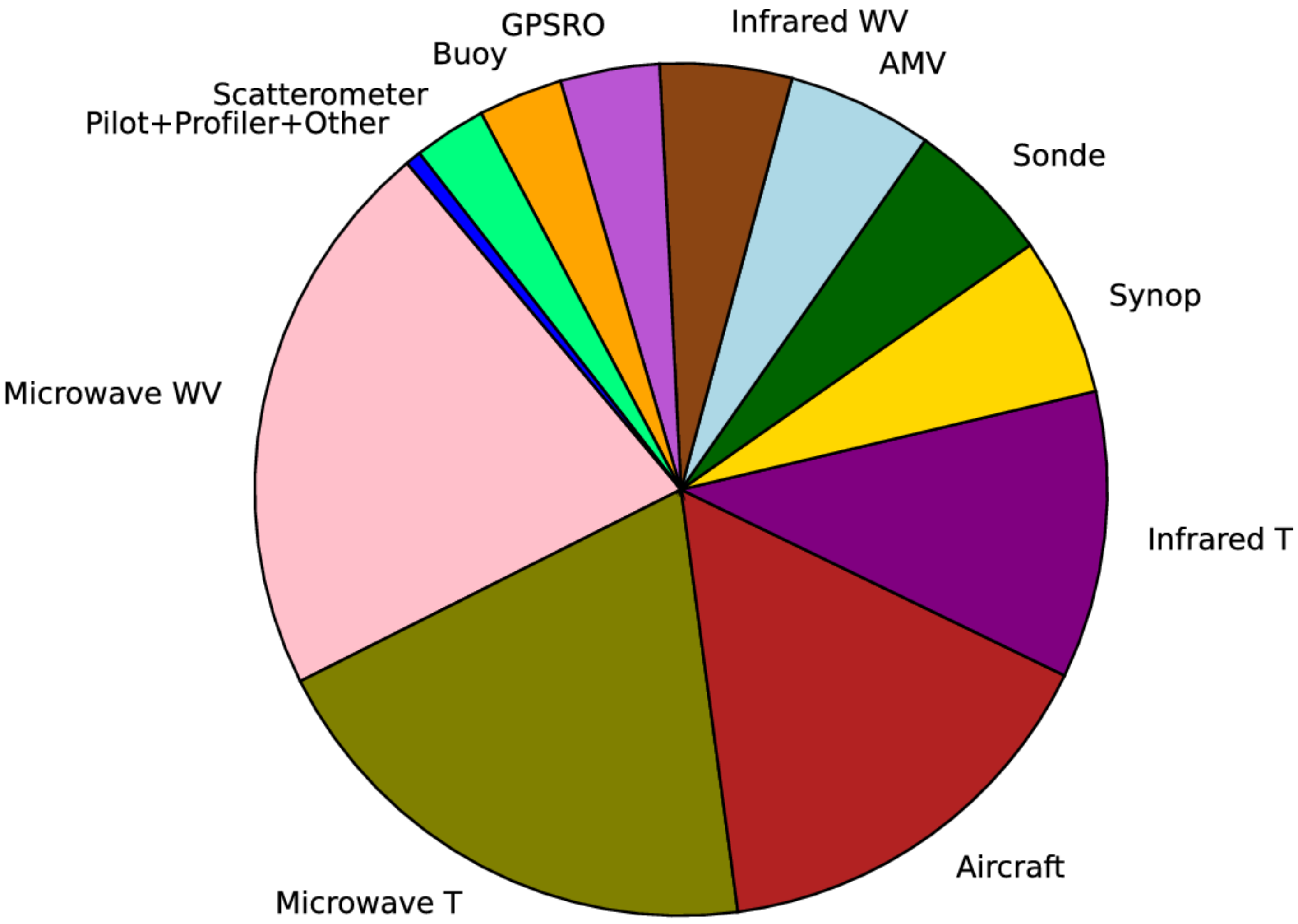
ECMWF

ECMWF FSOI February 2018: 70% of 24h forecast impact comes from satellite data



Ancient ECMWF history

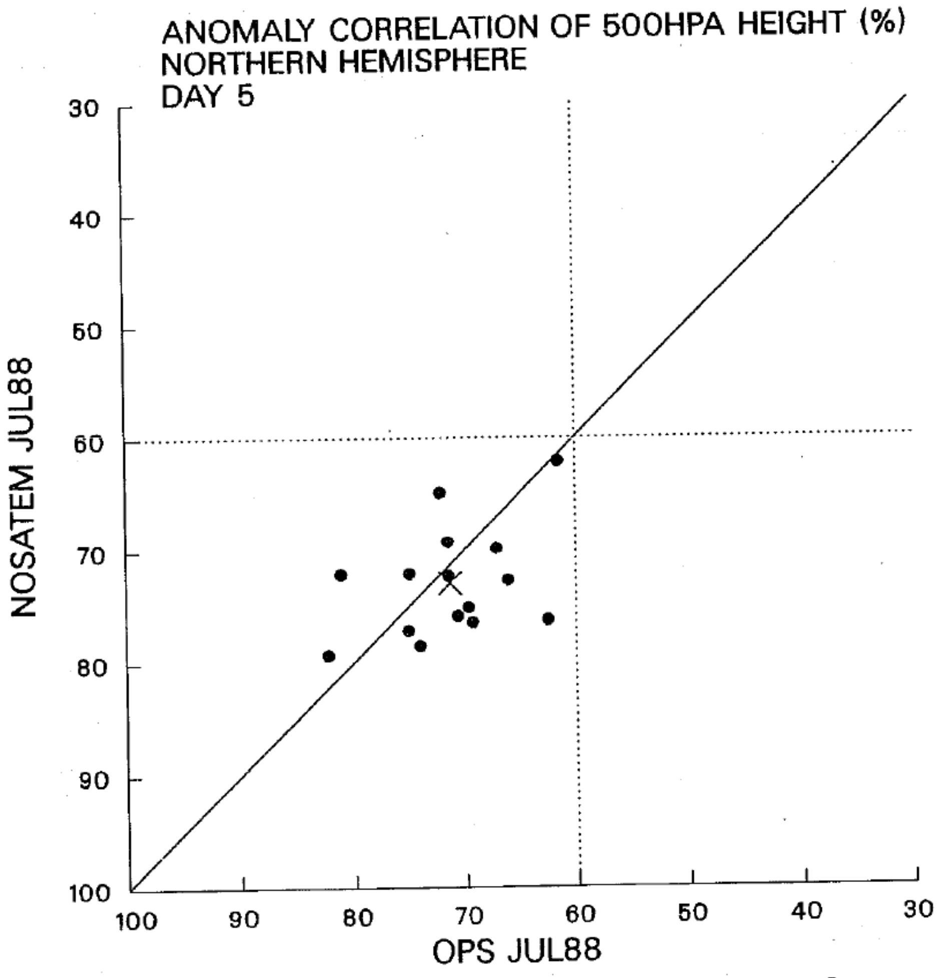
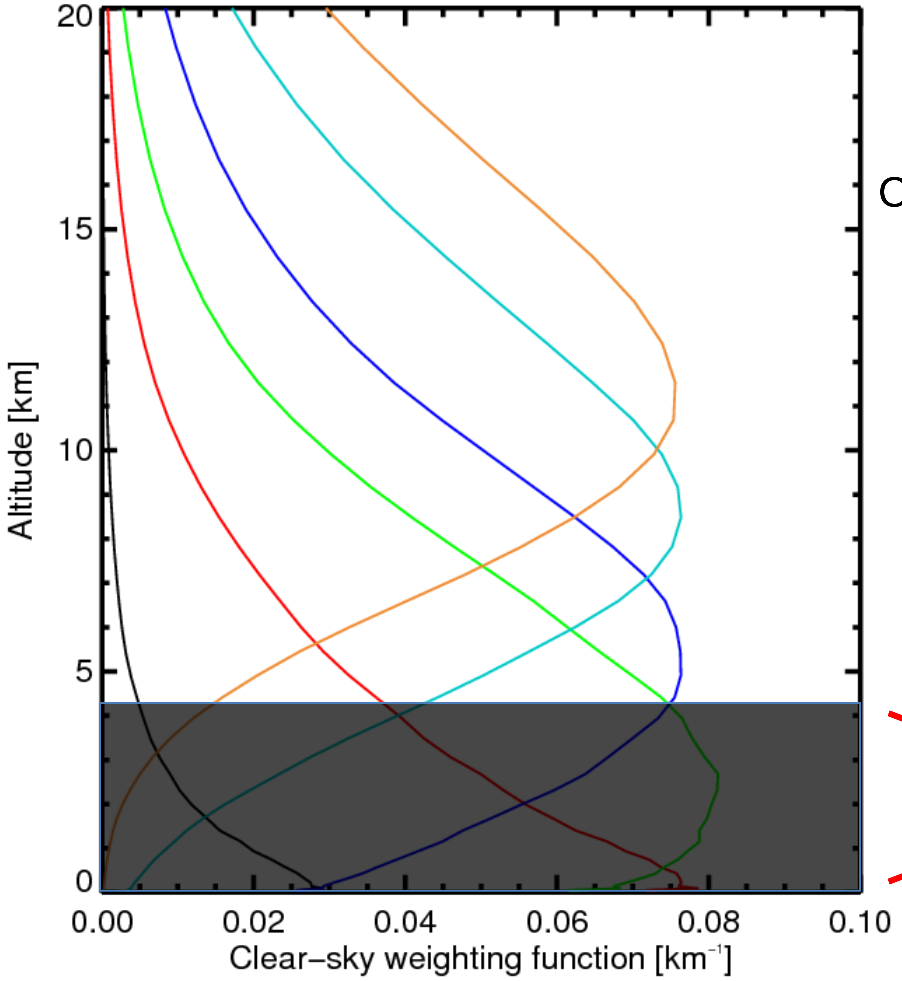


Fig. 3 Scatter diagrams comparing the anomaly correlation of operational forecasts (horizontal axis) and "NO-SATEM" forecasts (vertical axis), for 15 cases in February 1987.

Pailleux et al. (1989, TM159)

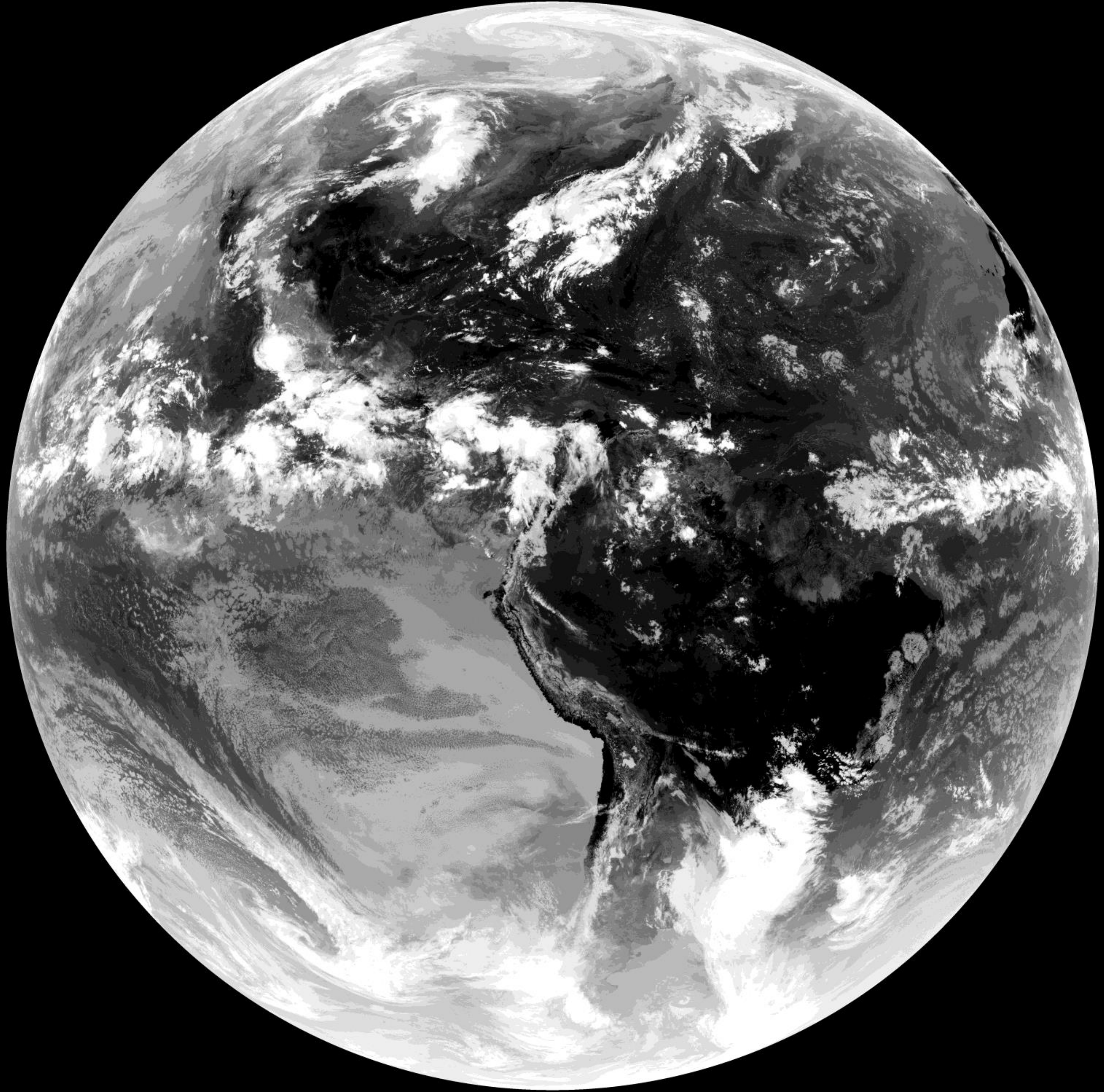
AMSU-A clear-sky weighting functions

(Channels 8-14 don’t see surface – not shown)



Channel	Transmittance surface to space
7	0%
6	0%
5	5%
4	19%
3	56%
2	92%

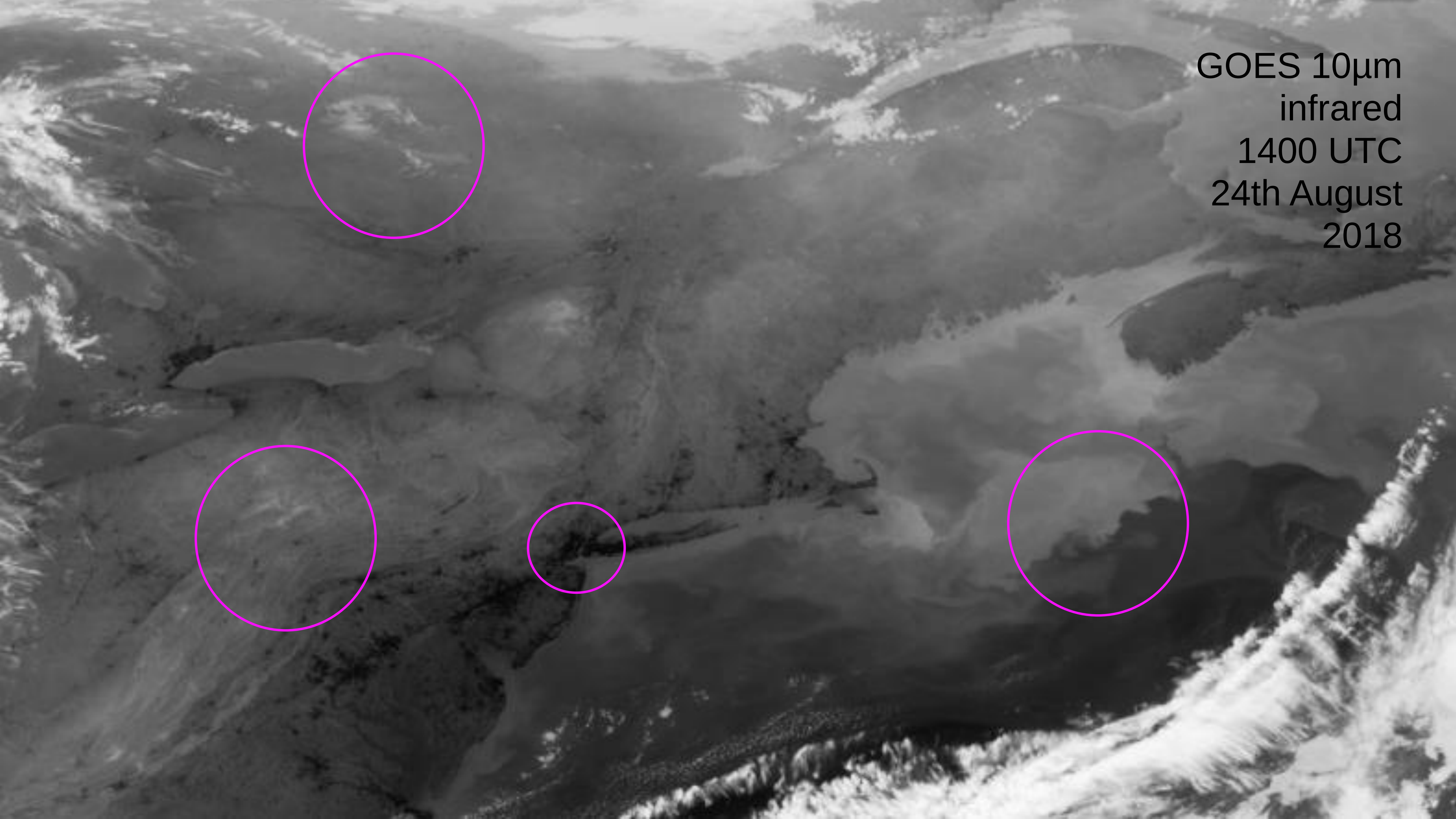
What is a satellite observation?

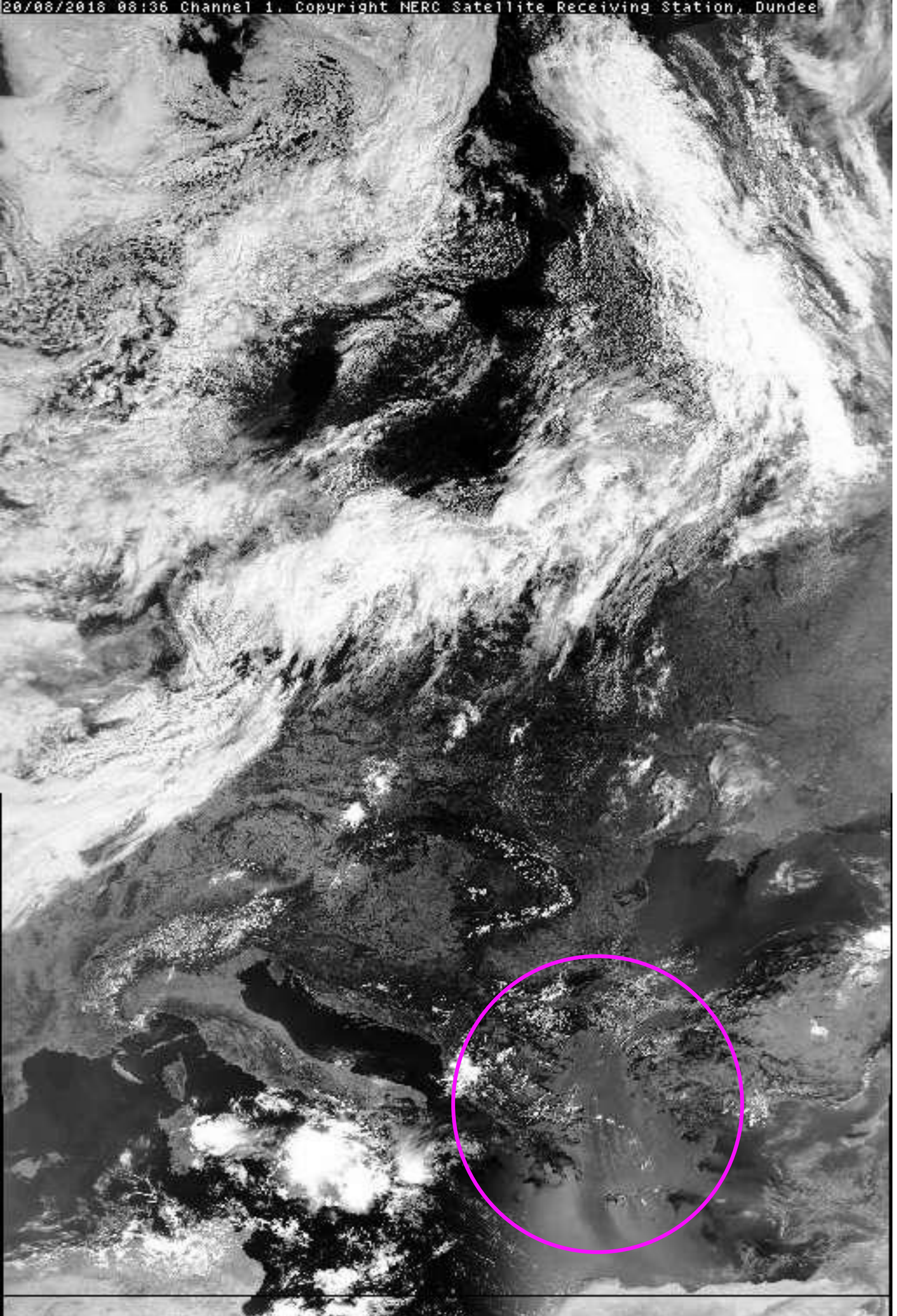


GOES 10µm
infrared
1400 UTC
24th August
2018

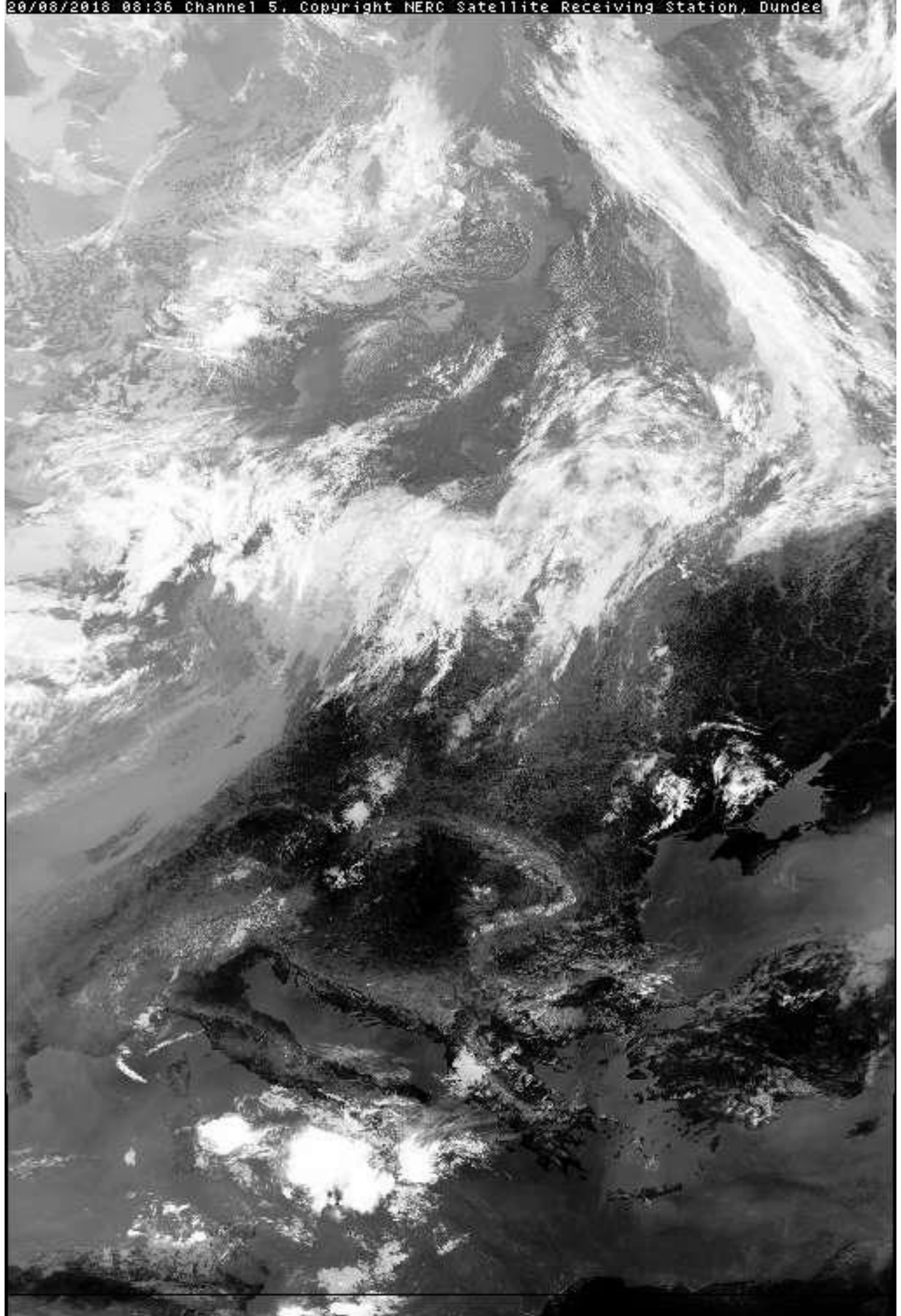

GOES 10µm
infrared
1400 UTC
24th August
2018


GOES 10µm
infrared
1400 UTC
24th August
2018


GOES 10µm
infrared
1400 UTC
24th August
2018



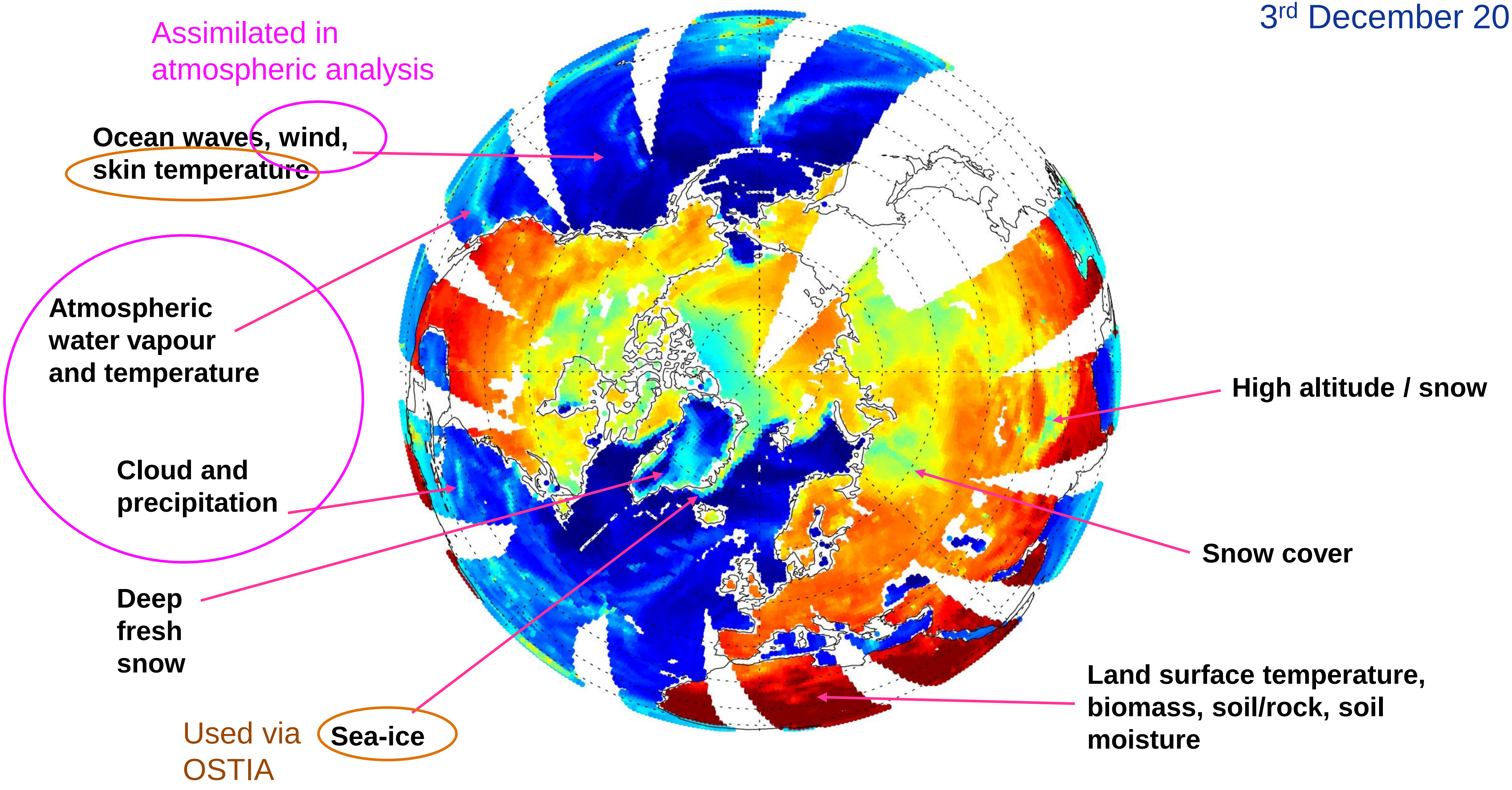
0.6µm
VIS

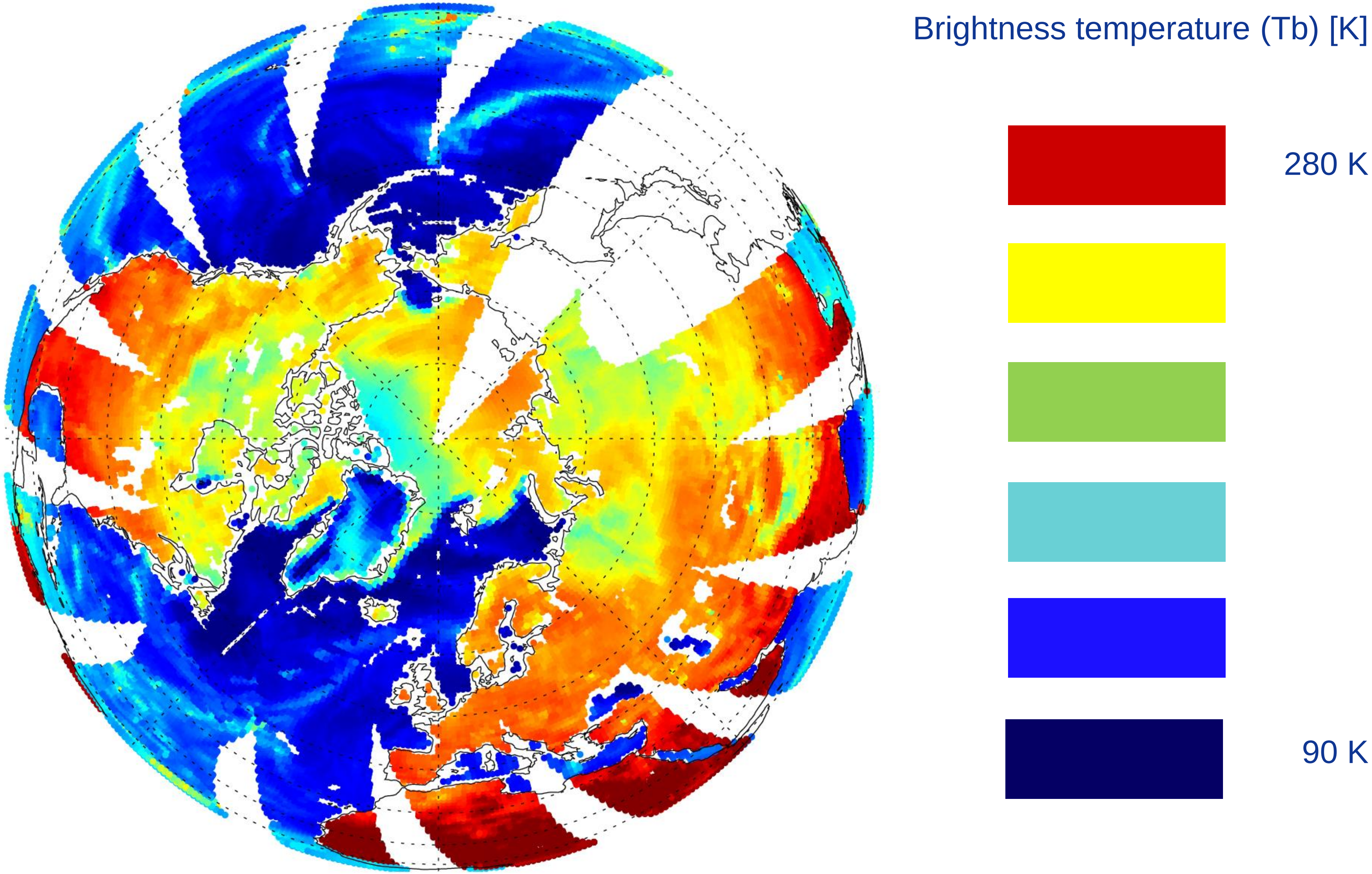


12µm
IR

AVHRR
20th
August
2018

SSMIS F-17 channel 13 (19 GHz, v)
Microwave brightness temperatures
3rd December 2014




Brightness temperature (Tb) [K]
280 K
90 K

All-sky, all-surface microwave radiance observation

$$y = H \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_{\dots} \end{pmatrix}$$

Atmospheric temperature, water vapour, wind, cloud, precipitation

Skin and substrate temperature and moisture

Ocean wind, waves, foam

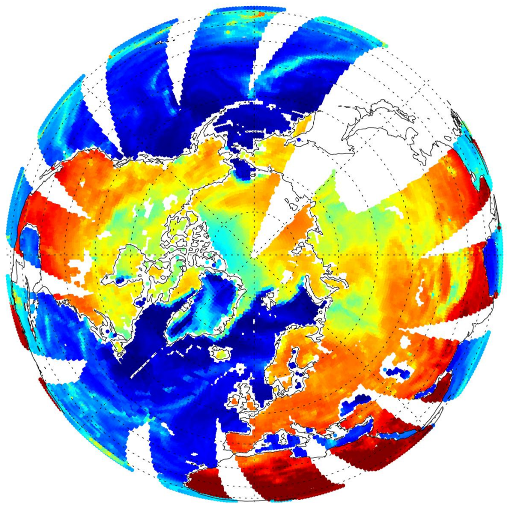
Sea-ice

Snowpack

Ice

Vegetation

Soil

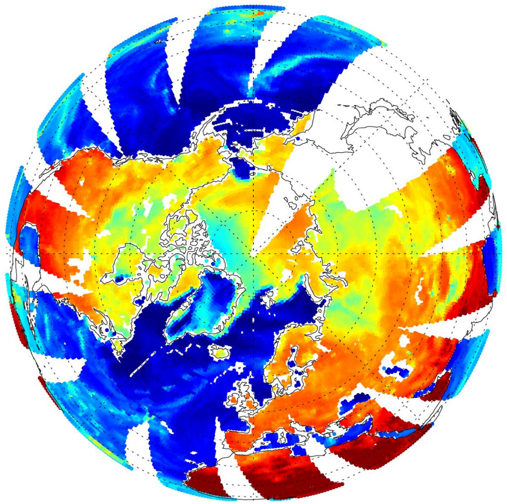


Atmospheric temperature,
water vapour, wind, cloud,
precipitation

Skin and substrate temperature
and moisture
Ocean wind, waves, foam
Sea-ice
Snowpack
Ice
Vegetation
Soil

$$\begin{bmatrix} \delta x_1 \\ \delta x_2 \\ \delta x_3 \\ \delta x_4 \\ \delta x_5 \\ \delta x_{....} \end{bmatrix} = \mathrm{H}^T \delta \mathrm{y}$$

All-sky, all-surface
microwave radiance
observations



Approximations:

- Local linearity of observation operator and model
- Gaussian errors

$$\mathrm{x}_a = \mathrm{x}_b + \mathrm{B}\mathrm{M}^T\mathrm{H}^T(\mathrm{H}\mathrm{M}\mathrm{B}\mathrm{M}^T\mathrm{H}^T + \mathrm{R})^{-1}(\mathrm{y}^o - H(M(\mathrm{x}_b)))$$

Analysis (x_a)

Background (x_b)

Linearised and adjoint models (M^T, M)

Background departure ($\mathrm{y}^o - H(M(\mathrm{x}_b))$)

Background errors (B)

Observation errors (R)

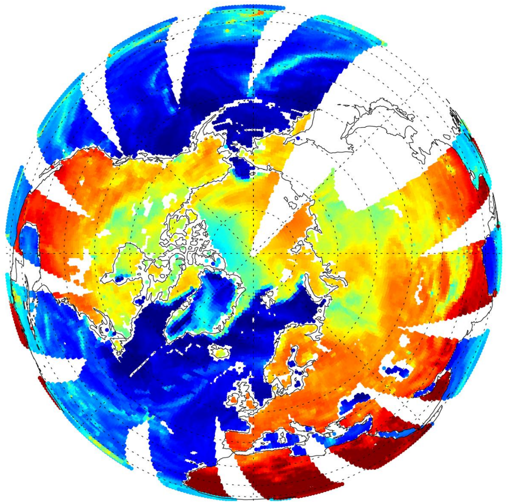
Observation (y^o)

Forecast model (M)

Weighting of background departures in observation space

$$x_a = x_b + \underbrace{BM^T H^T}_{\text{Mapping and weighting into analysis space}} \overbrace{(HMBM^T H^T + R)^{-1}(y^o - H(M(x_b)))}$$

Mapping and weighting into analysis space



Atmospheric temperature, water vapour, wind, cloud, precipitation

Skin and substrate temperature and moisture
Ocean wind, waves, foam
Sea-ice
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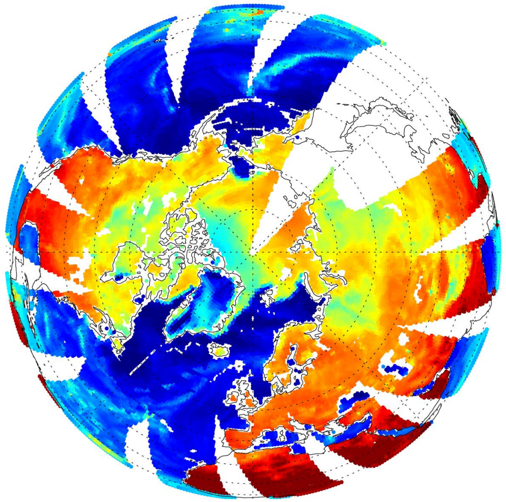
Vegetation
Soil

$$\mathbf{B}\mathbf{M}^T\mathbf{H}^T$$



$$\mathrm{x}_a = \mathrm{x}_b + \mathrm{B}\mathrm{H}^T(\mathrm{H}\mathrm{B}\mathrm{H}^T + \mathrm{R})^{-1}(\mathrm{y}^o - H(\mathrm{x}_b))$$

$$\mathrm{x}_a = \mathrm{x}_b + \mathrm{B}\mathrm{M}^T\mathrm{H}^T(\mathrm{H}\mathrm{M}\mathrm{B}\mathrm{M}^T\mathrm{H}^T + \mathrm{R})^{-1}(\mathrm{y}^o - H(M(\mathrm{x}_b)))$$

Radiance observation

$$y = H \begin{bmatrix} T_{\text{atmos}} \\ T_{\text{sfc}} \end{bmatrix}$$

Atmospheric temperature

Surface temperature

$$\begin{bmatrix} T^a_{\text{atmos}} \\ T^a_{\text{sfc}} \end{bmatrix} = \begin{bmatrix} T^b_{\text{atmos}} \\ T^b_{\text{sfc}} \end{bmatrix} + \begin{bmatrix} b_{\text{atmos}} & b_{atmos-\text{sfc}} \\ b_{atmos-\text{sfc}} & b_{\text{sfc}} \end{bmatrix} \mathrm{H}^T \left(\mathrm{H} \begin{bmatrix} b_{\text{atmos}} & b_{atmos-\text{sfc}} \\ b_{atmos-\text{sfc}} & b_{\text{sfc}} \end{bmatrix} \mathrm{H}^T + r \right)^{-1} \left(y^o - \mathrm{H} \begin{bmatrix} T^b_{\text{atmos}} \\ T^b_{\text{sfc}} \end{bmatrix} \right)$$

Coupling through the background errors

$$\begin{bmatrix} T^a_{\mathrm{atmos}} \\ T^a_{\mathrm{sfc}} \end{bmatrix} = \begin{bmatrix} T^b_{\mathrm{atmos}} \\ T^b_{\mathrm{sfc}} \end{bmatrix} + \begin{bmatrix} b_{\mathrm{atmos}} & 0 \\ 0 & b_{\mathrm{sfc}} \end{bmatrix} \mathrm{H}^T \left(\mathrm{H} \begin{bmatrix} b_{\mathrm{atmos}} & 0 \\ 0 & b_{\mathrm{sfc}} \end{bmatrix} \mathrm{H}^T + r \right)^{-1} \left(y^o - \mathrm{H} \begin{bmatrix} T^b_{\mathrm{atmos}} \\ T^b_{\mathrm{sfc}} \end{bmatrix} \right)$$

How to solve it for the atmosphere

- Pretend the problem is separable:
  - Retrieve surface first, using some simplified retrieval, then use it as a parameter for the atmosphere?
    - Examples: Assimilation of OSTIA, dynamic surface emissivity retrieval
- Augmented control vector
  - Treat the surface as a sink variable
    - Examples: assimilation of clear-sky IR and microwave radiances
- Treat the missing information as a parameter of the observation operator
  - Parameter error adds to the observation error
    - All the missing parameters that we forget about: e.g. Particle size distribution for all-sky assimilation
- Coupling
  - Outer loop coupling
  - Full coupling

Pretend the problem is separable – solve for surface and then atmosphere

$$\begin{bmatrix} T^a_{\text{atmos}} \\ T^a_{\text{sfc}} \end{bmatrix} = \begin{bmatrix} T^b_{\text{atmos}} \\ T^b_{\text{sfc}} \end{bmatrix} + \begin{bmatrix} b_{\text{atmos}} & 0 \\ 0 & b_{\text{sfc}} \end{bmatrix} \mathrm{H}^T \left(\mathrm{H} \begin{bmatrix} b_{\text{atmos}} & 0 \\ 0 & b_{\text{sfc}} \end{bmatrix} \mathrm{H}^T + r \right)^{-1} \left(y^o - \mathrm{H} \begin{bmatrix} T^b_{\text{atmos}} \\ T^b_{\text{sfc}} \end{bmatrix} \right)$$

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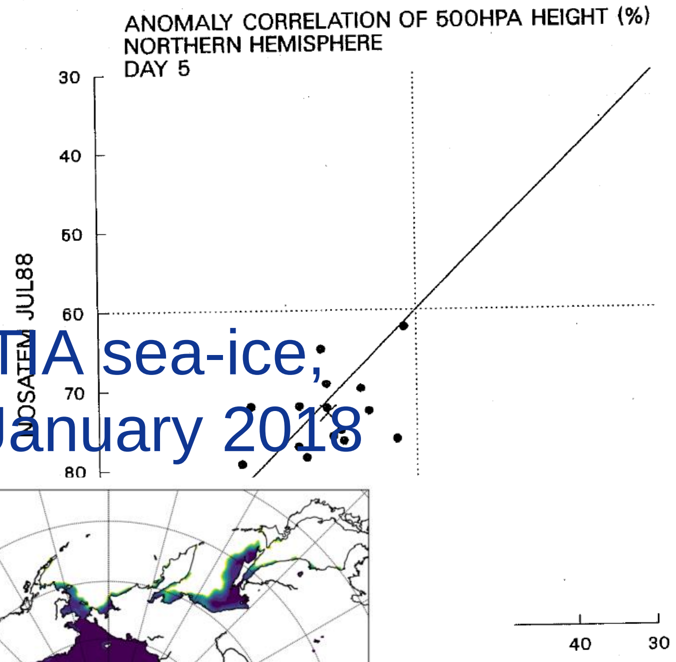
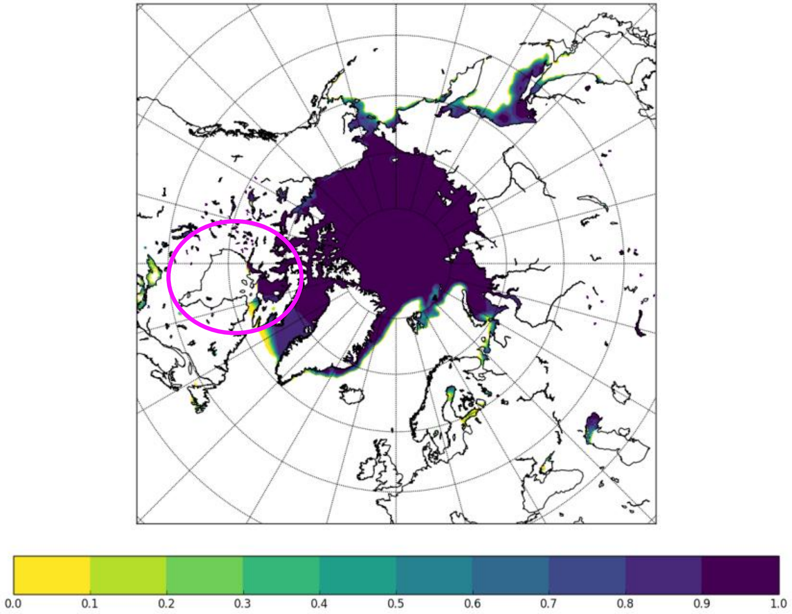
Problems with using external retrievals -

- Suboptimal
- Gross errors are hard to characterise

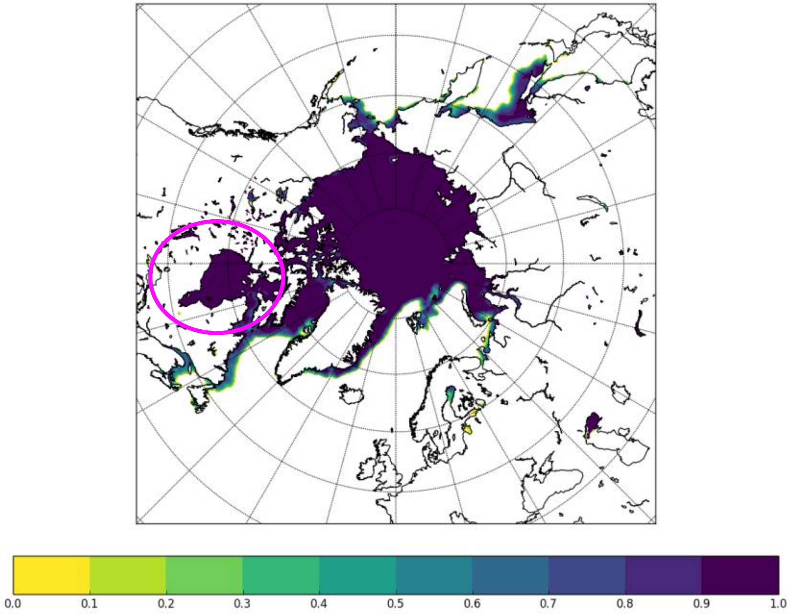


ıtion of operational forecasts
rtical axis), for 15 cases in
of July 87. Bottom : with the

OSTIA sea-ice, 20th January 2018



OSTIA sea-ice, 21st January 2018

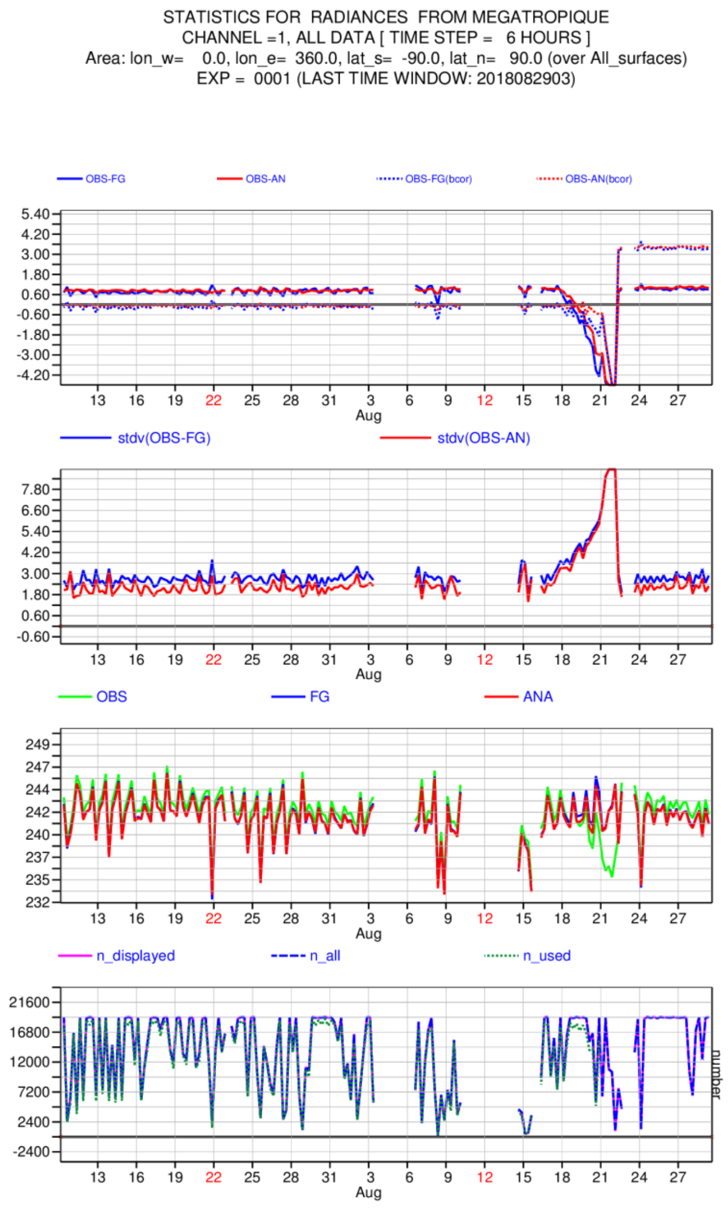


Courtesy daily report and Phil Browne

When something goes wrong

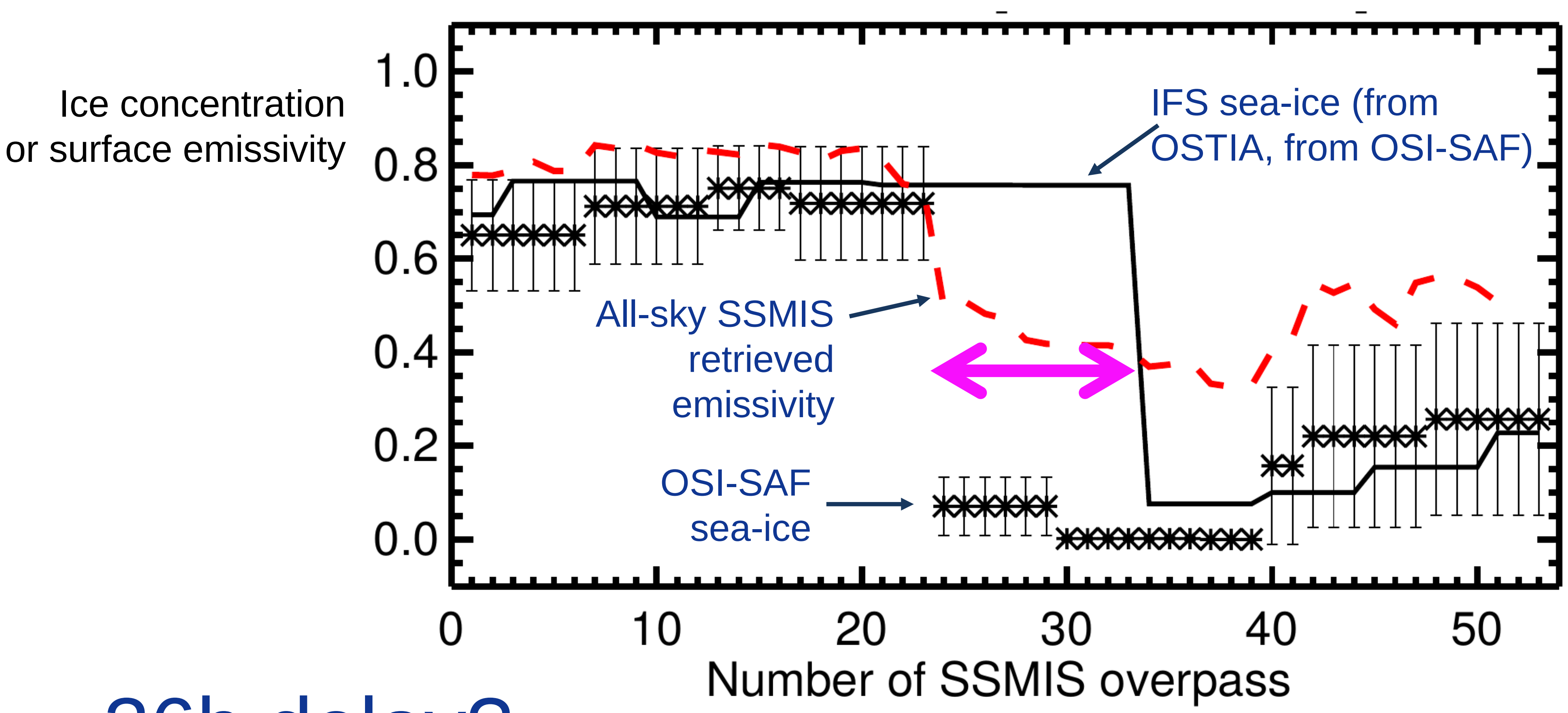
- We assimilate OSTIA which assimilates OSI-SAF retrievals from SSMIS radiances….
  - How is the bias correction done?
  - How are data anomalies handled?
  - How is cloud / precipitation detected and "removed"?
  - How is wind roughening of ocean surface treated?

All-sky, all-surface data assimilation



Sea ice and 19 GHz retrieved emissivity – Baordo+Geer 2015

at a point over the arctic sea-ice, Feb 2015



36h delay?

Issues with assimilating retrievals of surface properties

- Even if other parts of the system are modelled, their background values have errors
  - Modelling of e.g. the atmospheric component may not be as sophisticated as used for atmospheric DA
- They are done externally and independently
  - There can be significant processing delays
  - Long and vulnerable processing chains: We assimilate OSTIA which assimilates OSI-SAF retrievals from SSMIS radiances…
  - External centres may not have available the wide range of satellite monitoring, QC, bias correction

The most up-to-date and accurate state of the rest of the system comes from the analysis: direct coupled radiance assimilation is optimal

Benefit from existing sophisticated modelling for atmospheric radiance assimilation

Ingest the L1 data in-house

The treatment of satellite radiances for the atmosphere includes all this (bias correction, keeping up with new satellites)

Augmented control vector

$$\begin{bmatrix} T^a_{\text{atmos}} \\ T^a_{\text{sfc}} \end{bmatrix} = \begin{bmatrix} T^b_{\text{atmos}} \\ T^b_{\text{sfc}} \end{bmatrix} + \begin{bmatrix} b_{\text{atmos}} & 0 \\ 0 & b_{\text{sfc}} \end{bmatrix} \mathrm{H}^T \left(\mathrm{H} \begin{bmatrix} b_{\text{atmos}} & 0 \\ 0 & b_{\text{sfc}} \end{bmatrix} \mathrm{H}^T + r \right)^{-1} \left(y^o - \mathrm{H} \begin{bmatrix} T^b_{\text{atmos}} \\ T^b_{\text{sfc}} \end{bmatrix} \right)$$

And in a more realistic system:

- We are missing M^T to help constrain the surface solution
- Wouldn't it be great to improve T_{sfc} with observations from the surface assimilation?

Augmented observation error

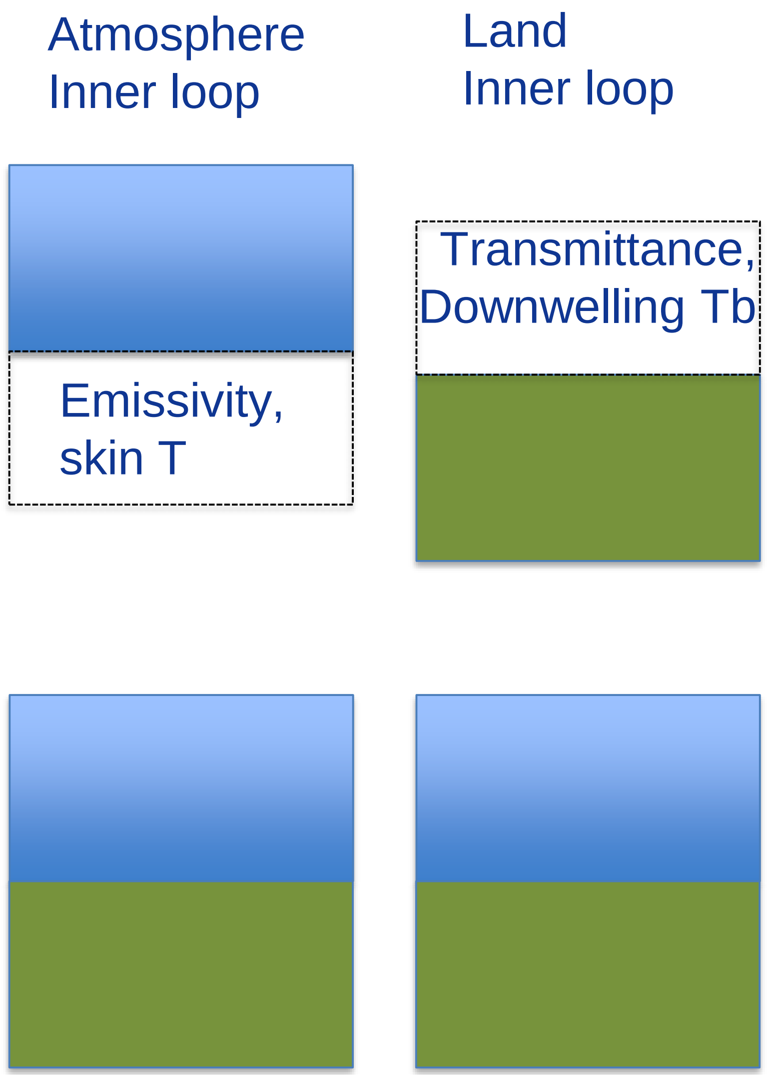
$$\begin{bmatrix} T^{a}_{\mathrm{atmos}} \\ T^{b}_{\mathrm{sfc}} \end{bmatrix} = \begin{bmatrix} T^{b}_{\mathrm{atmos}} \\ T^{b}_{\mathrm{sfc}} \end{bmatrix} + \begin{bmatrix} b_{\mathrm{atmos}} & 0 \\ 0 & 0 \end{bmatrix} \mathrm{H}^{T} \left(\mathrm{H} \begin{bmatrix} b_{\mathrm{atmos}} & 0 \\ 0 & 0 \end{bmatrix} \mathrm{H}^{T} + r' \right)^{-1} \left(y^{o} - \mathrm{H} \begin{bmatrix} T^{b}_{\mathrm{atmos}} \\ T^{b}_{\mathrm{sfc}} \end{bmatrix} \right)$$

$$r' = r + \mathrm{H} \begin{bmatrix} 0 & 0 \\ 0 & b_{\mathrm{sfc}} \end{bmatrix} \mathrm{H}^{T}$$

Outer loop coupling

- Separable observation operator?
  - From the atmosphere, can the surface be described as e.g. a skin temperature, emissivity, and bidirectional reflection distribution function?
  - From the surface, can the atmosphere be described as e.g. a single transmittance, an emitting temperature?

- Inseparable observation operator?
  - Need to run both surface and atmospheric operators coupled together
  - All relevant atmospheric and surface state needs to be available in both the atmospheric and surface analysis



Any more catches?

We need better forward modelling

Models need to represent the relevant physical properties

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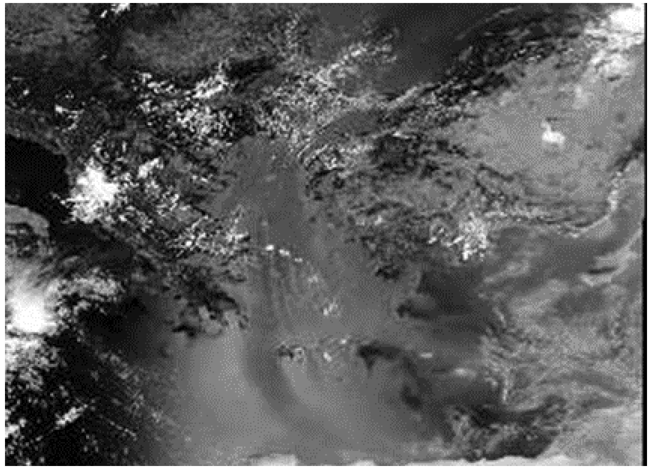
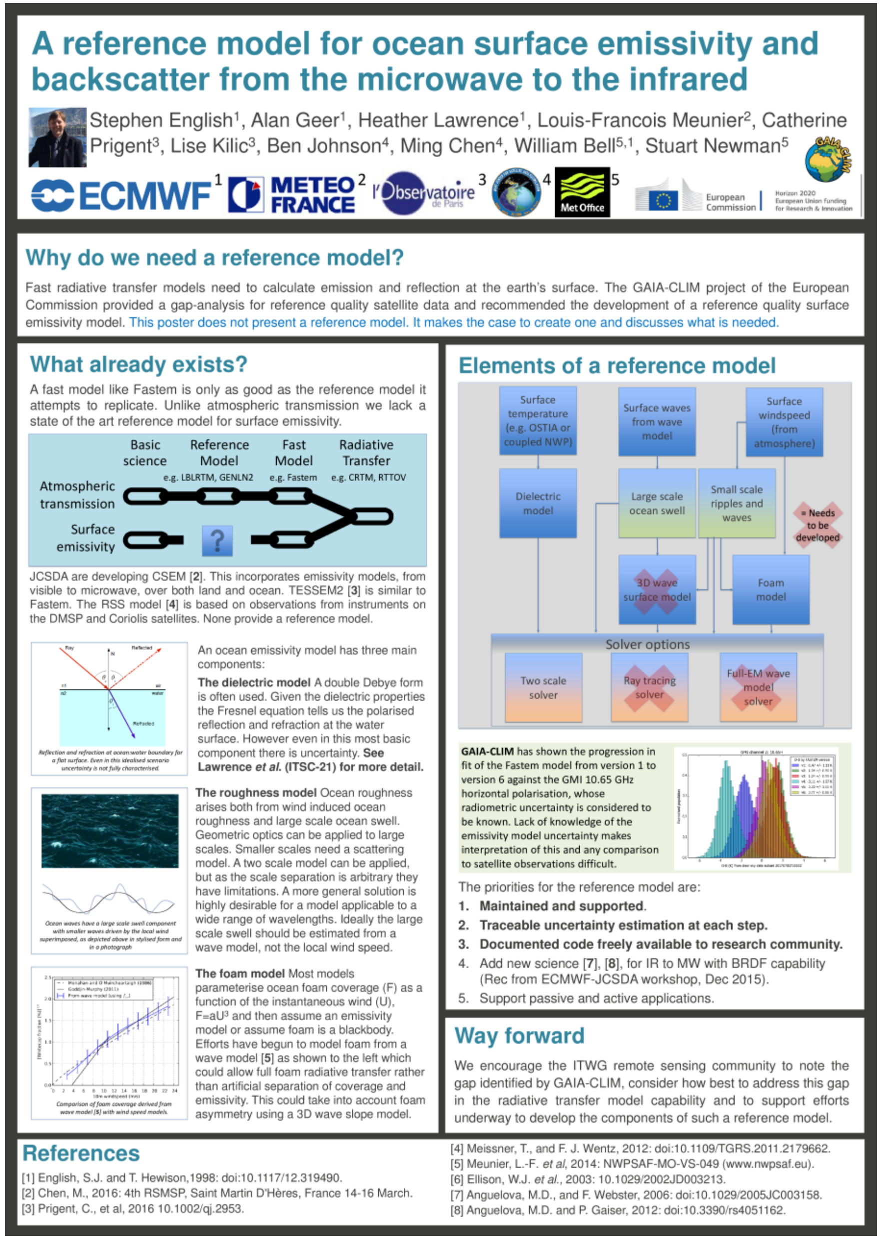
We need better forward modelling

Models need to represent the relevant physical properties

Forward modelling of ocean surface radiative transfer



- Wave and capilliary structure at all scales
- Foam and whitecapping
- Rain ripples
- Active (e.g. scatterometer) and passive (all spectrum)
- Skin layer (temperature profile)



Snow Microwave Radiative Transfer – Picard et al. (2018)

G. Picard et al.: Snow Microwave Radiative Transfer model

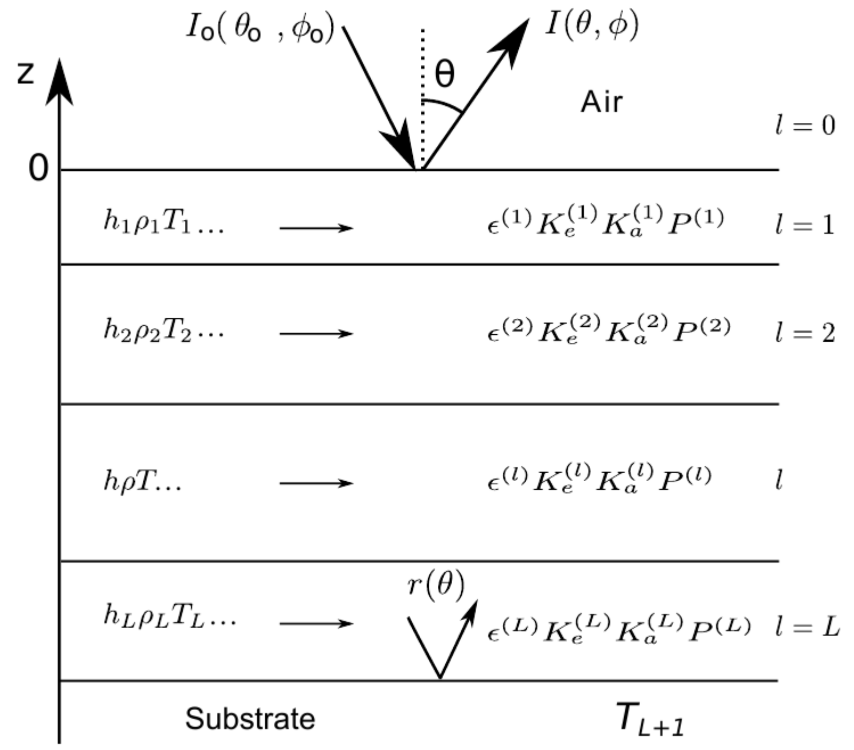


Figure 1. Multilayered medium modeled by SMRT. The incident radiation I_o comes either from a radar beam (active mode) or from the sky (passive mode with atmospheric contribution).

Any more catches?

We need better forward modelling

Models need to represent the relevant physical properties

Example of all-sky data assimilation

- Model does not have a sufficient representation of microphysical and macrophysical parameters to which the all-sky radiances are sensitive, but we can still get great impact from this data

Parameter error = Observation error

$$\mathrm{BM}^T\mathrm{H}^T$$