

Coupling through the observation operator

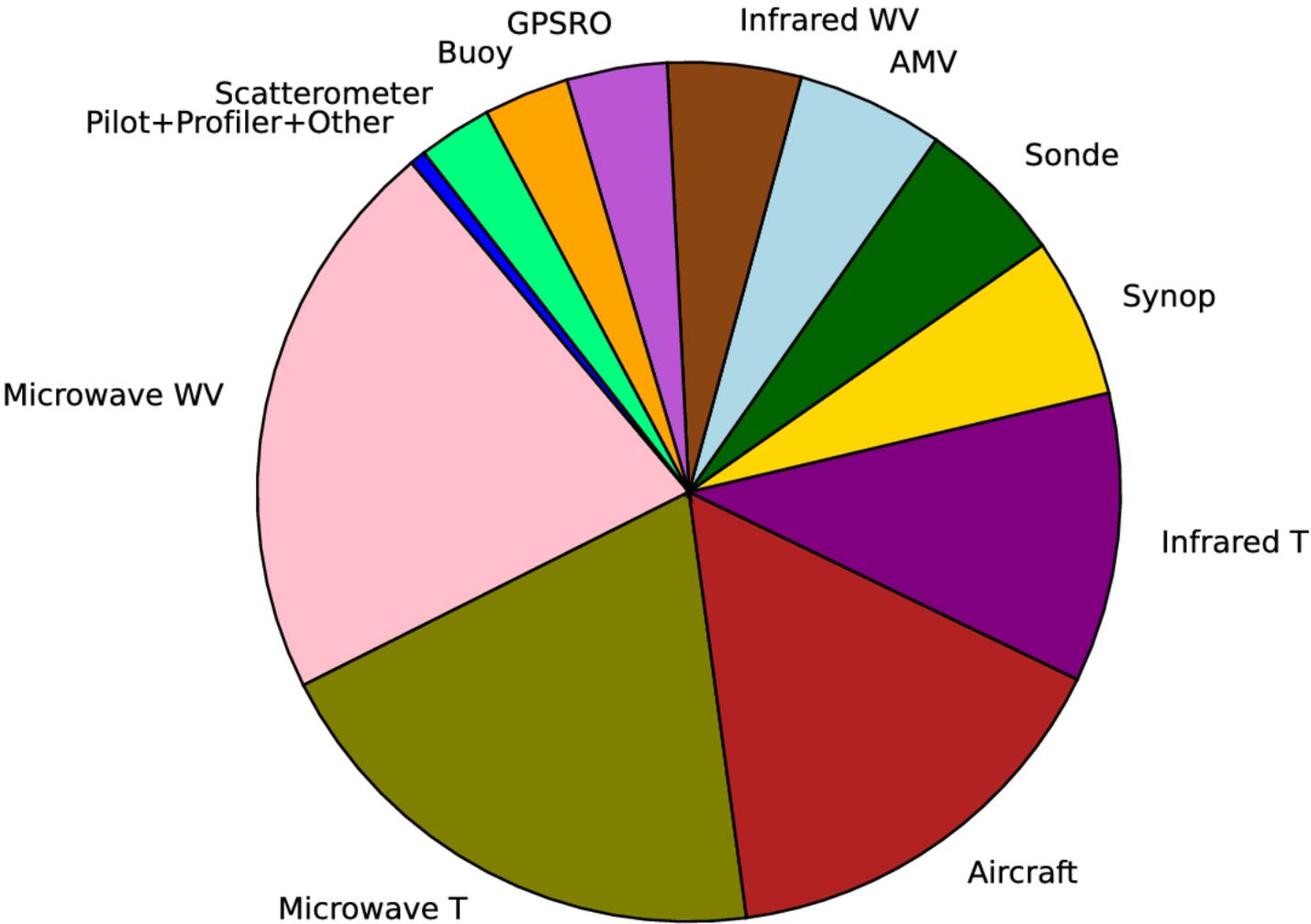
Alan Geer

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

NERC Satellite Receiving Station, Dundee University, Scotland,
<http://www.sat.dundee.ac.uk/> are thanked for providing GOES and AVHRR imagery



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



Ancient ECMWF history

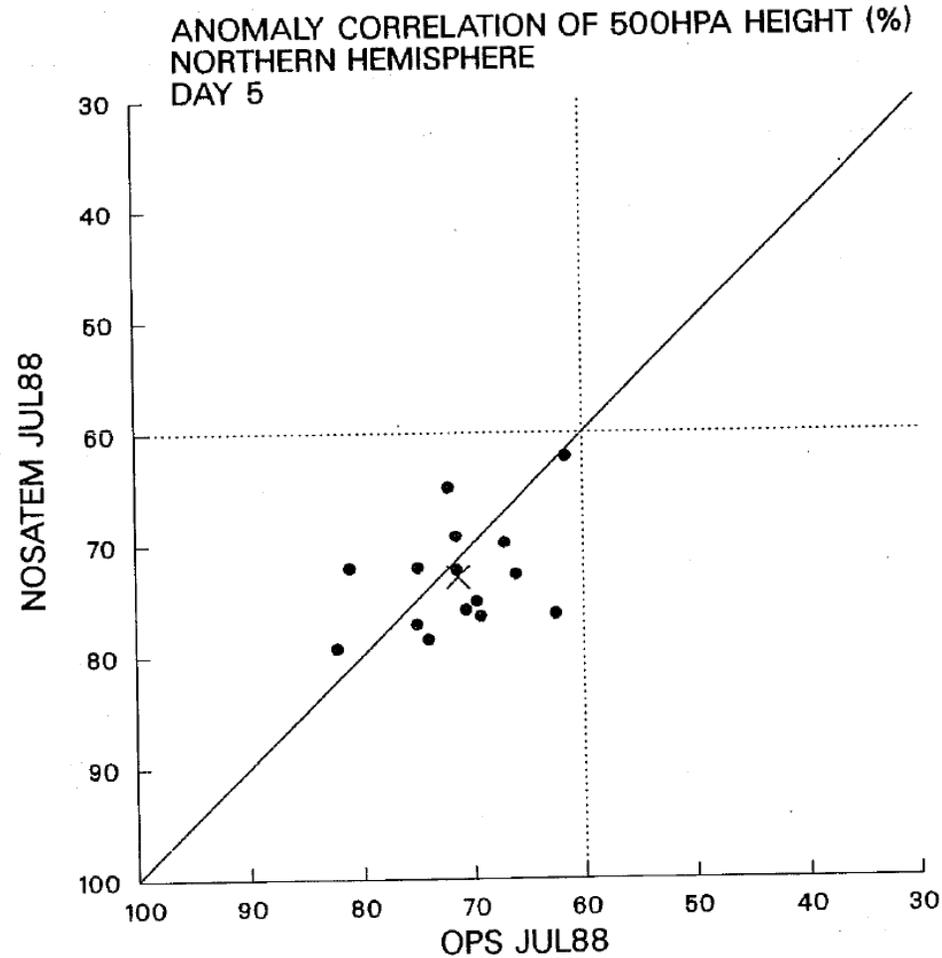
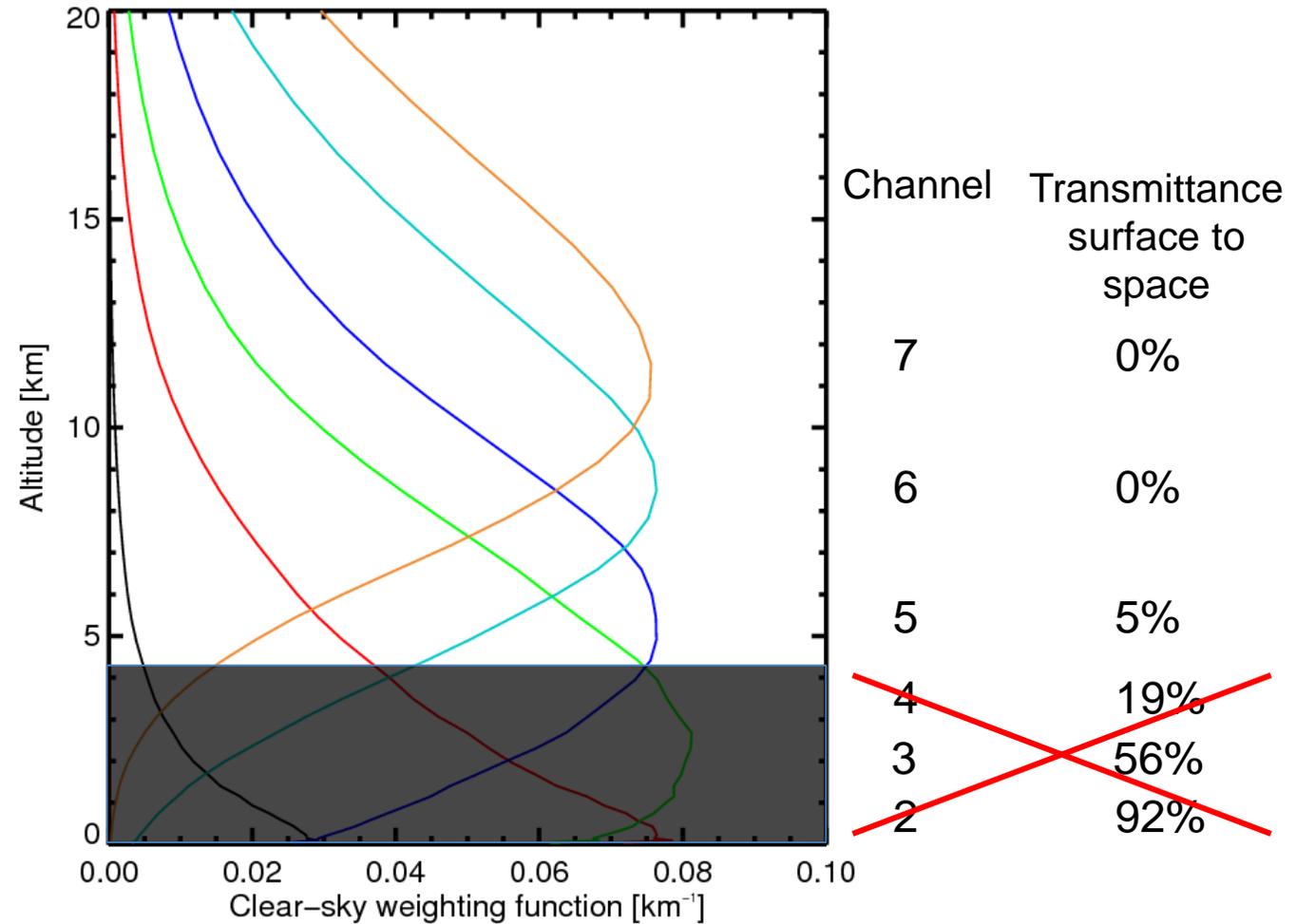


Fig. 3 Scatter diagrams comparing the anomaly correlation of operational forecasts (horizontal axis) and "NO-SATEM" forecasts (vertical axis), for 15 cases in February 1987.

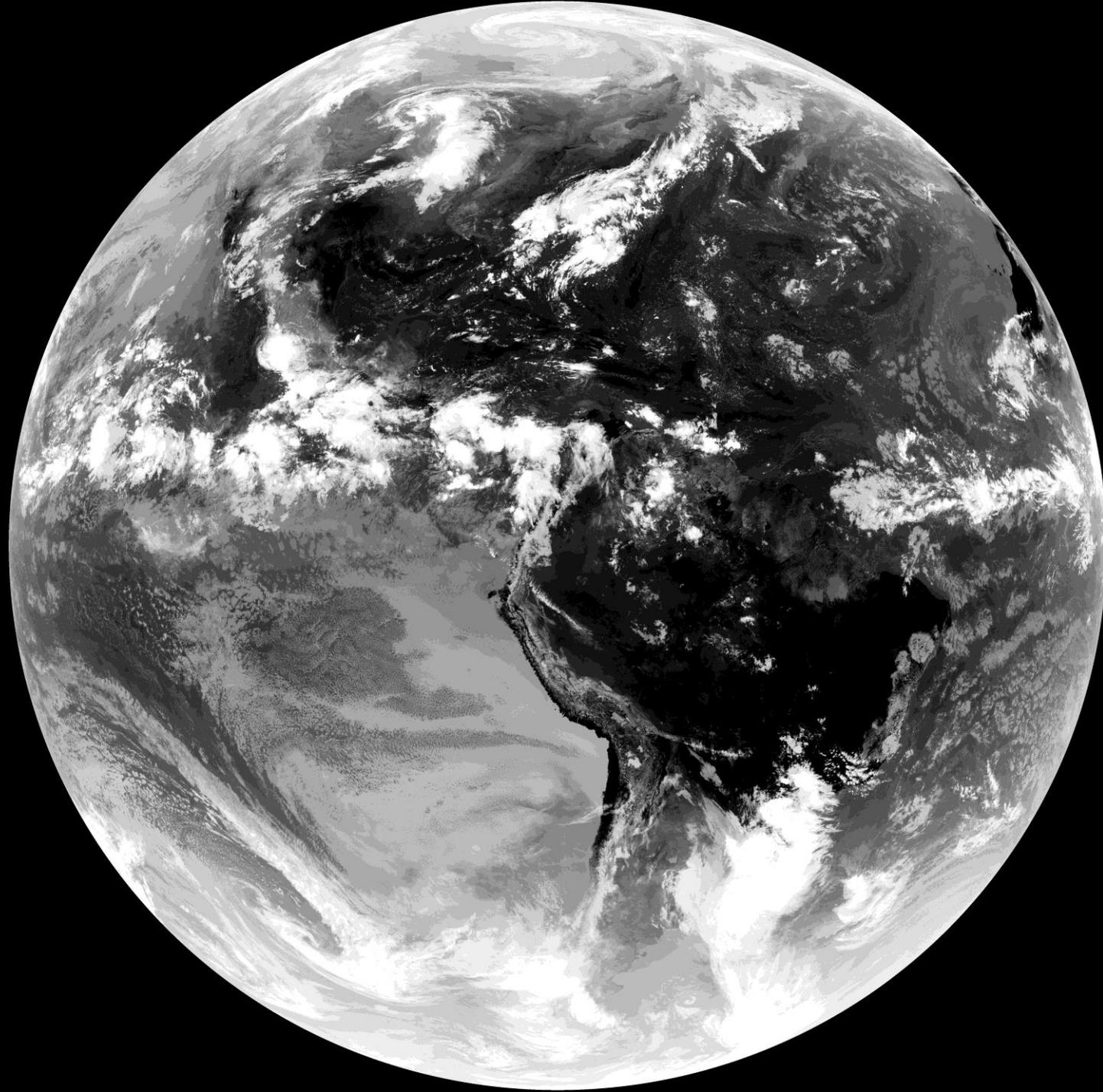
Pailleux et al. (1989, TM159)

AMSU-A clear-sky weighting functions

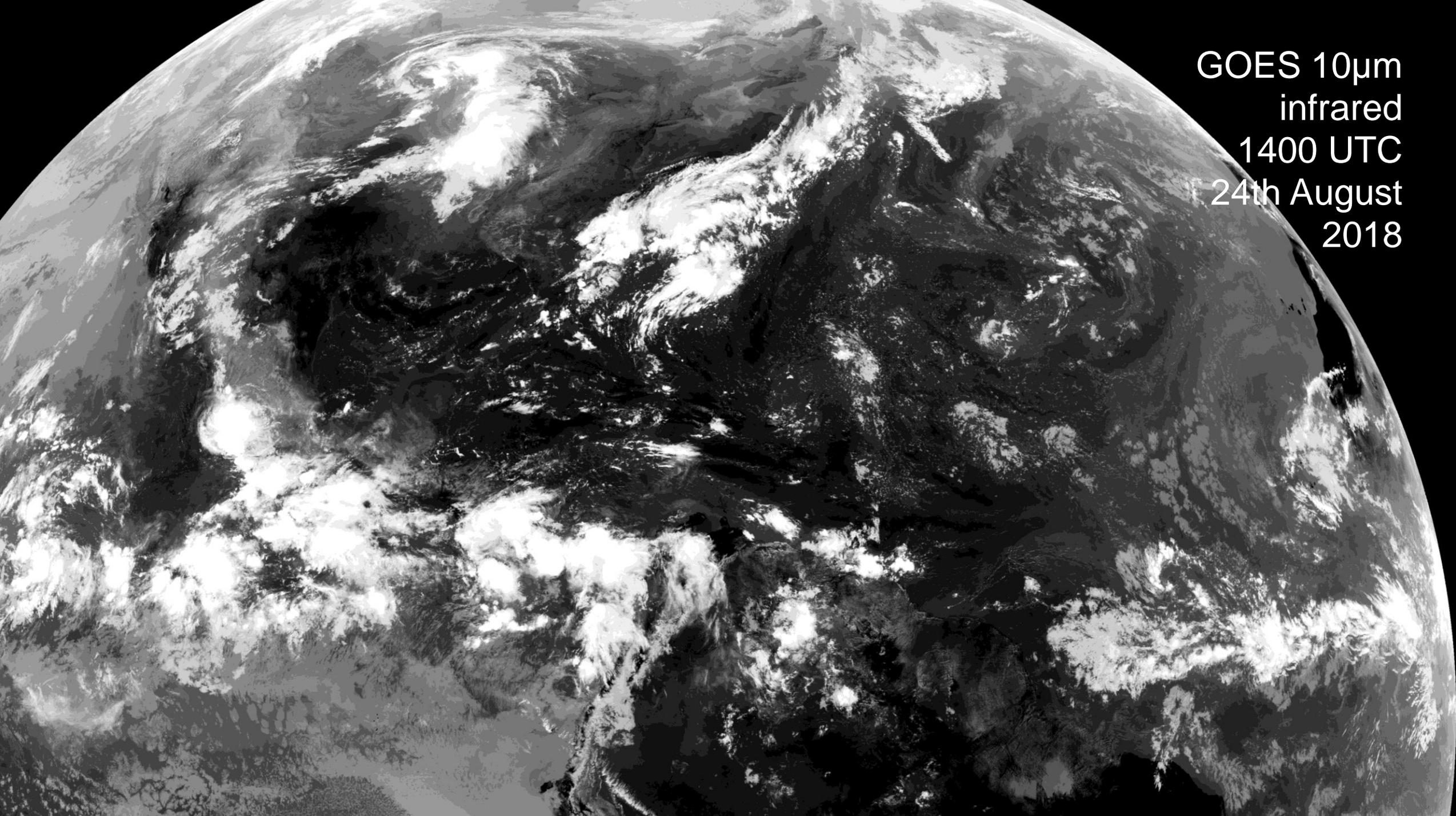
(Channels 8-14 don't see surface – not shown)



What is a satellite observation?



GOES 10 μ m
infrared
1400 UTC
24th August
2018

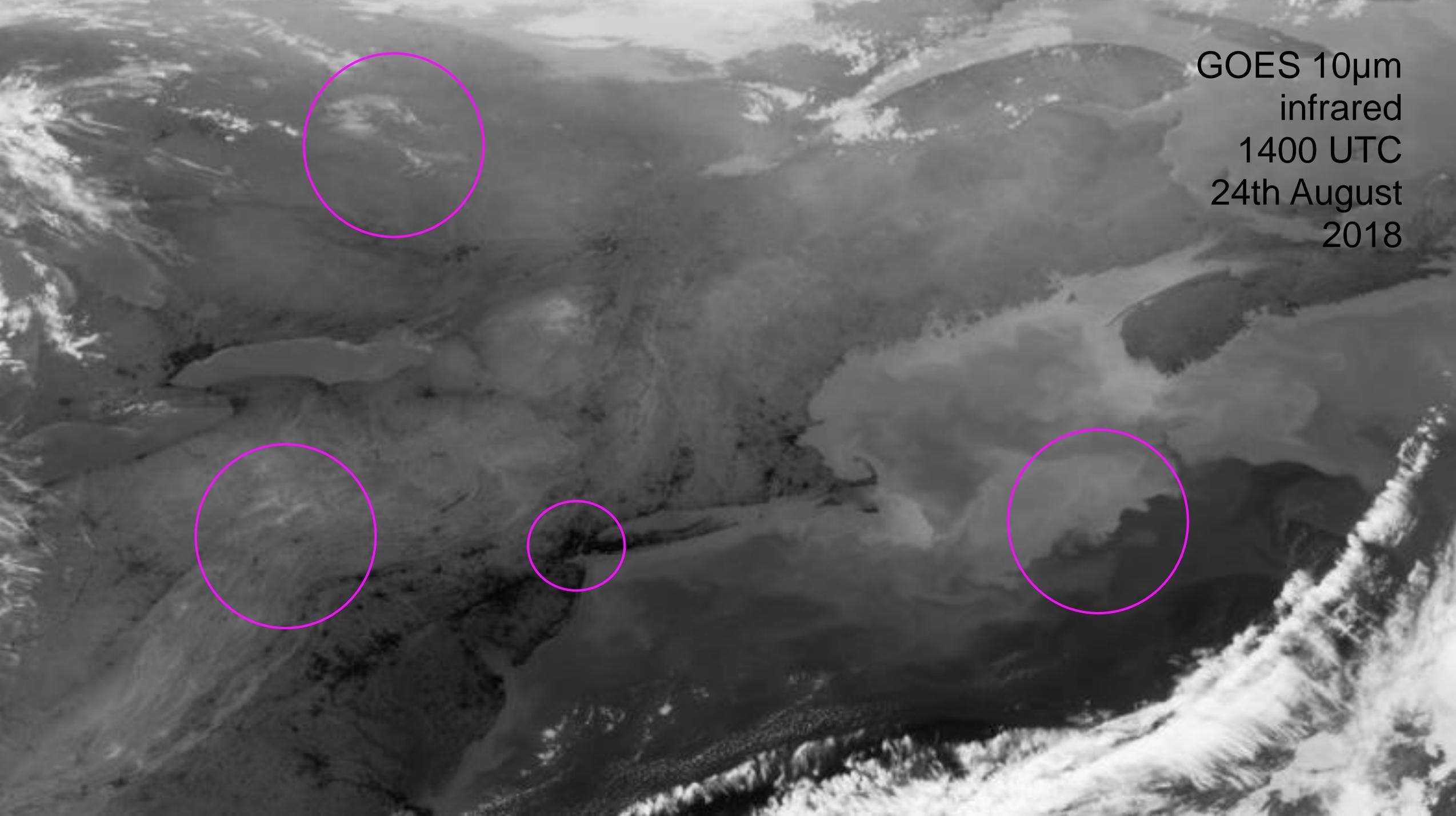


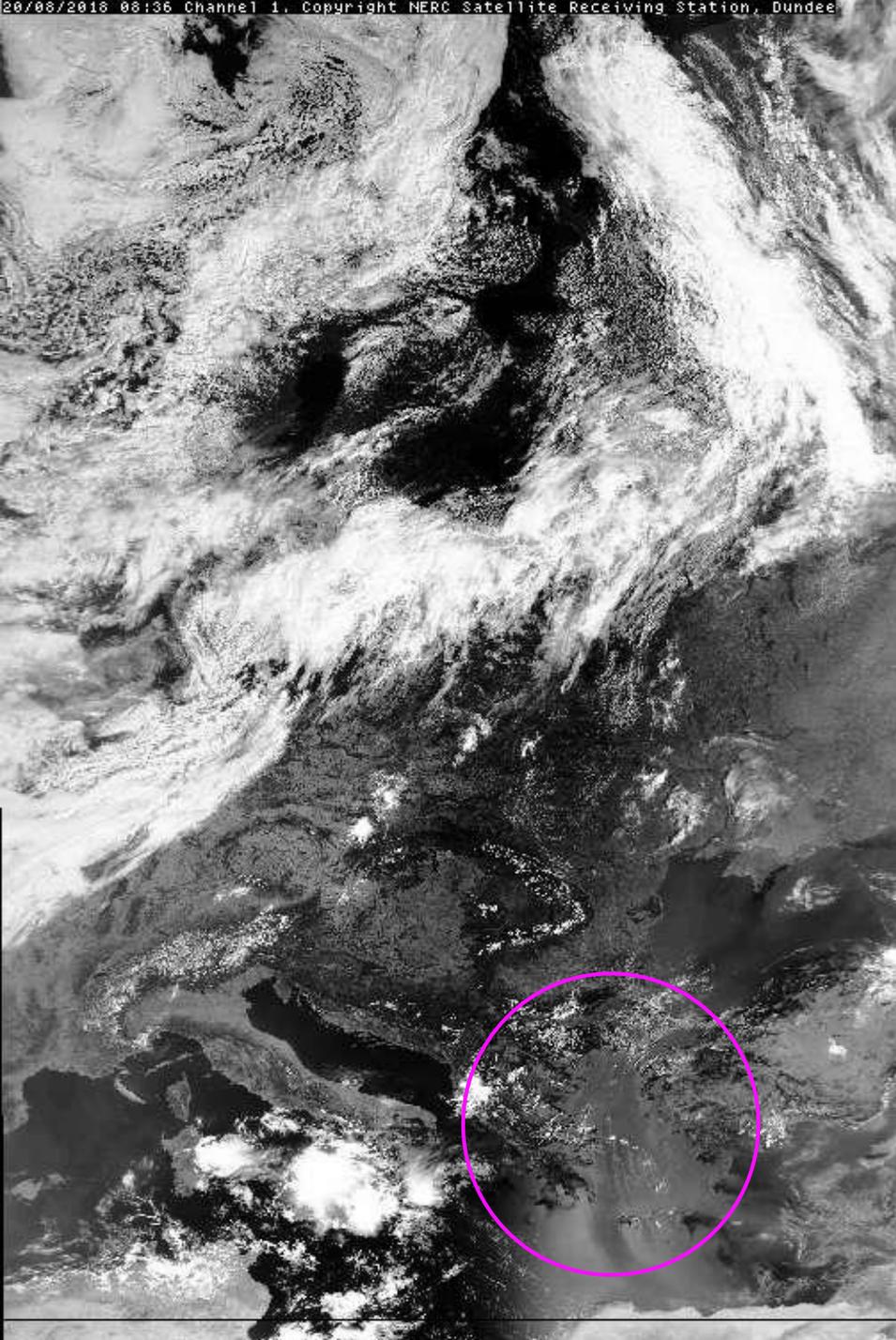
GOES 10 μ m
infrared
1400 UTC
24th August
2018

A grayscale satellite image showing a large, well-defined tropical storm system over the ocean. The storm features a prominent eye and a dense, swirling cloud structure. The surrounding ocean surface shows some cloud patterns and a dark, possibly landmass, area in the lower right. The image is captured in the 10-micrometer infrared band, highlighting cloud tops and surface temperatures.

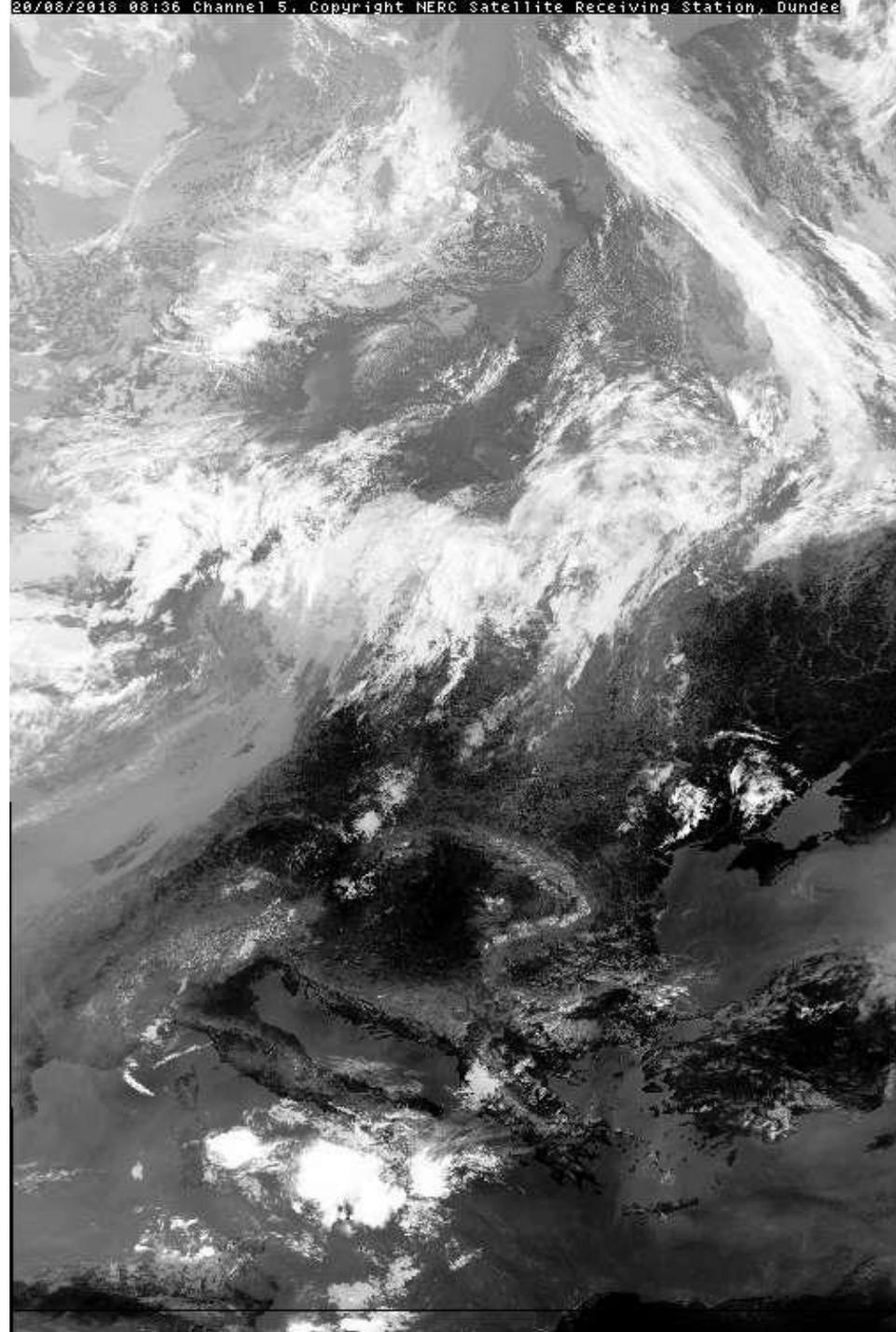
GOES 10 μ m
infrared
1400 UTC
24th August
2018

GOES 10 μ m
infrared
1400 UTC
24th August
2018





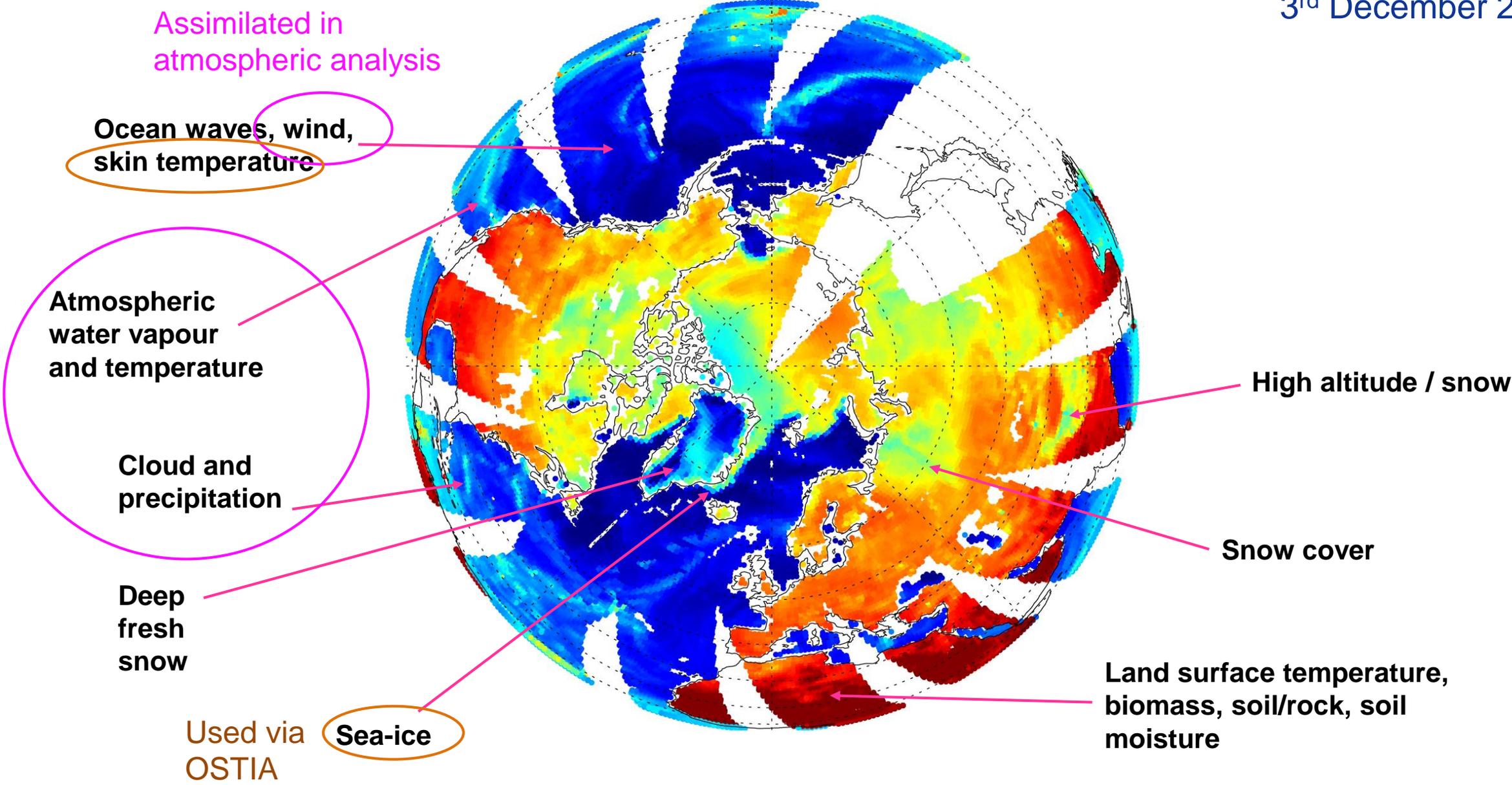
0.6µm
VIS



12µm
IR

AVHRR
20th
August
2018

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



Assimilated in atmospheric analysis

Ocean waves, wind, skin temperature

Atmospheric water vapour and temperature

Cloud and precipitation

Deep fresh snow

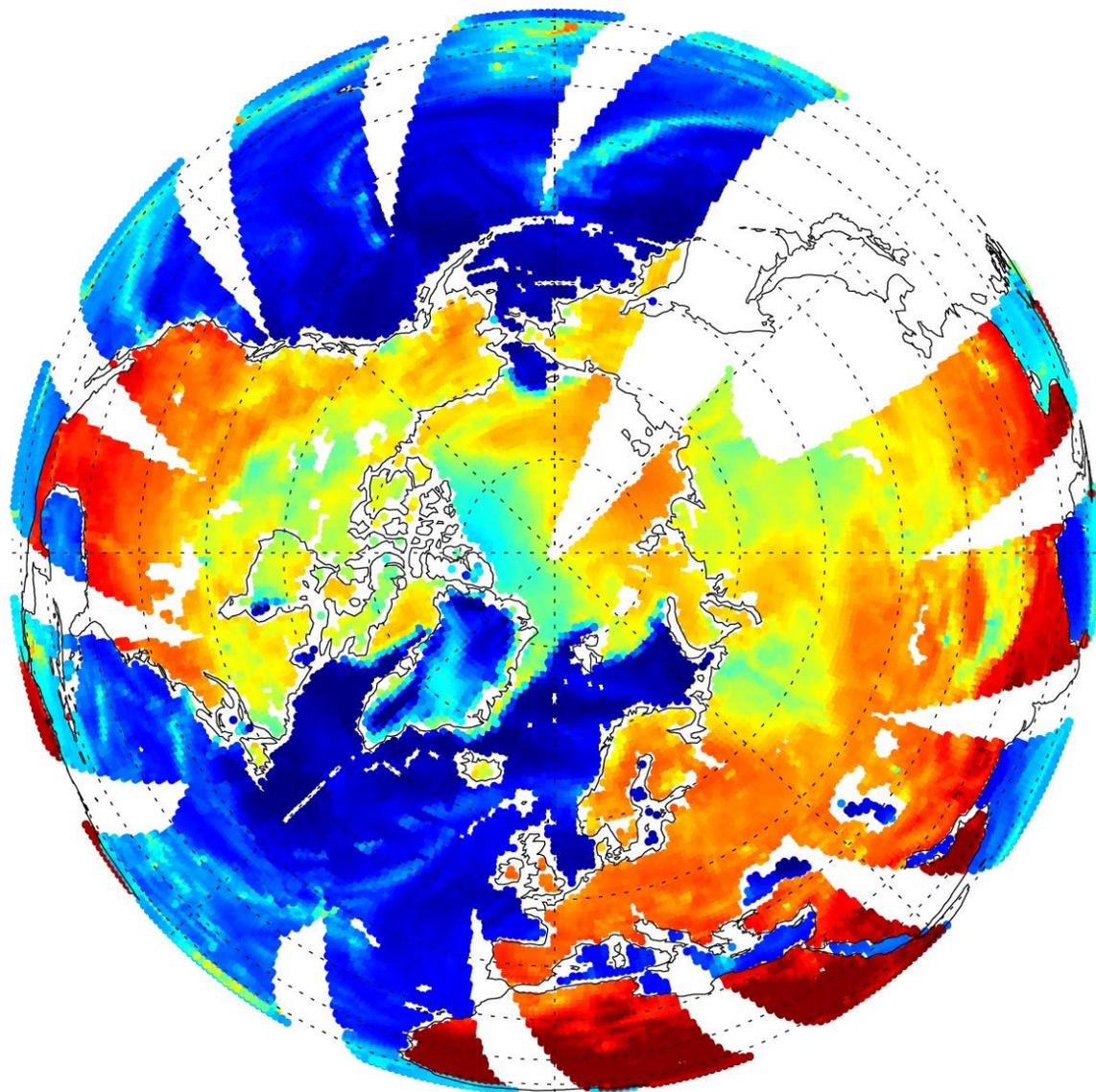
Used via OSTIA

Sea-ice

High altitude / snow

Snow cover

Land surface temperature, biomass, soil/rock, soil moisture



Brightness temperature (T_b) [K]

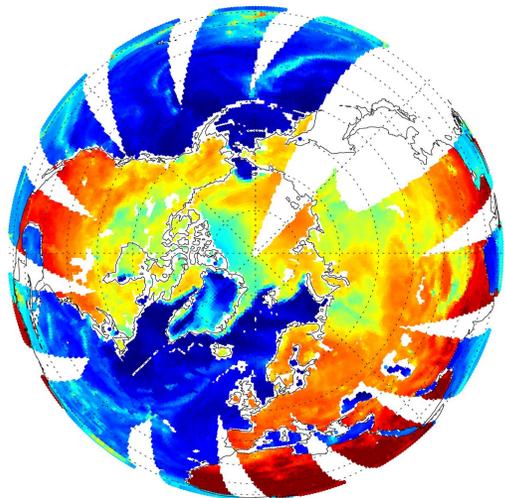


280 K



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

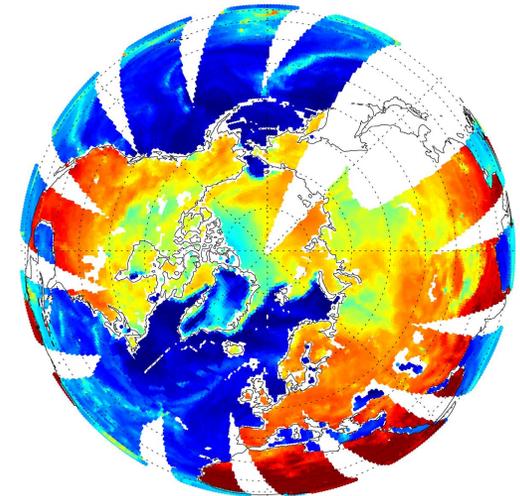
Ice

Vegetation

Soil

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

All-sky, all-surface
microwave radiance
observations



Approximations:

- Local linearity of observation operator and model
- Gaussian errors

$$x_a = x_b + \underbrace{B M^T H^T}_{\text{Background errors}} \underbrace{(H M B M^T H^T + R)^{-1}}_{\text{Linearised and adjoint models}} \underbrace{(y^o - H(M(x_b)))}_{\text{Background departure}}$$

Analysis Background

Background errors

Linearised and adjoint models

Observation errors

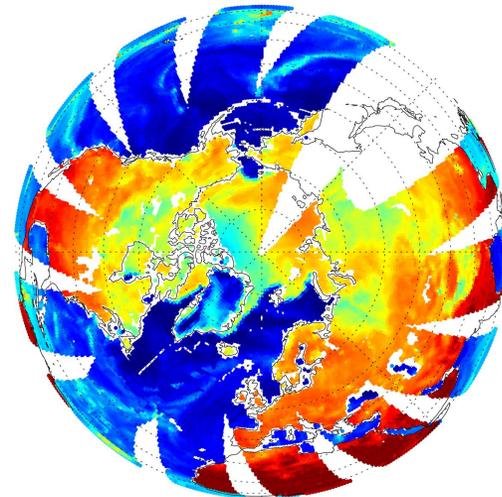
Observation

Forecast model

Weighting of background
departures in observation space

$$X_a = X_b + \underbrace{BM^T H^T}_{\text{Mapping and weighting into analysis space}} \left(\underbrace{HMBM^T H^T + R}_{\text{Weighting of background departures in observation space}} \right)^{-1} (y^o - H(M(x_b)))$$

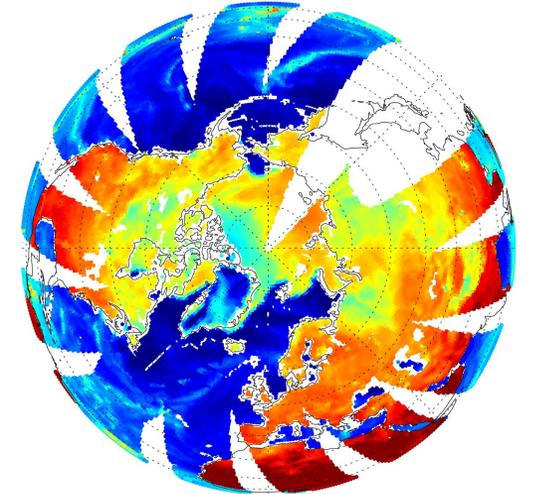
Mapping and
weighting into
analysis space



Atmospheric temperature,
water vapour, wind, cloud,
precipitation

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

$BM^T H^T$



$$x_a = x_{ab} = M^T H^T (H M B B^T H^T + R)^{-1} (y - H M(x_b))$$

Radiance
observation

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

Atmospheric temperature

Surface temperature

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

↑
Coupling through the
background errors

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

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

$$\begin{bmatrix} T_{\text{atmos}}^a \\ T_{\text{sfc}}^a \end{bmatrix} = \begin{bmatrix} T_{\text{atmos}}^b \\ T_{\text{sfc}}^b \end{bmatrix} + \begin{bmatrix} 0 \\ b_{\text{sfc}} \end{bmatrix} + \begin{bmatrix} 0 \\ b_{\text{sfc}} \end{bmatrix} \left(\begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \right)^{-1} \left(\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \right)^{-1} \begin{bmatrix} T_{\text{atmos}}^b \\ T_{\text{sfc}}^b \end{bmatrix}$$

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

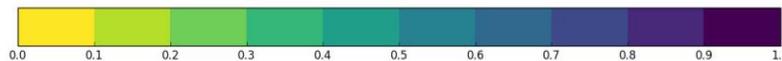
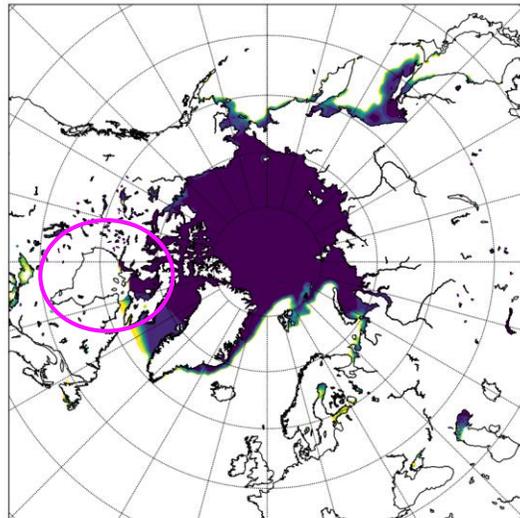
$$\begin{bmatrix} T_{\text{atmos}}^b \\ T_{\text{sfc}}^a \end{bmatrix} = \begin{bmatrix} T_{\text{atmos}}^b \\ T_{\text{sfc}}^b \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & b_{\text{sfc}} \end{bmatrix} H^T \left(H \begin{bmatrix} 0 & 0 \\ 0 & b_{\text{sfc}} \end{bmatrix} H^T + r \right)^{-1} \left(y^o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

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

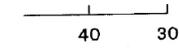
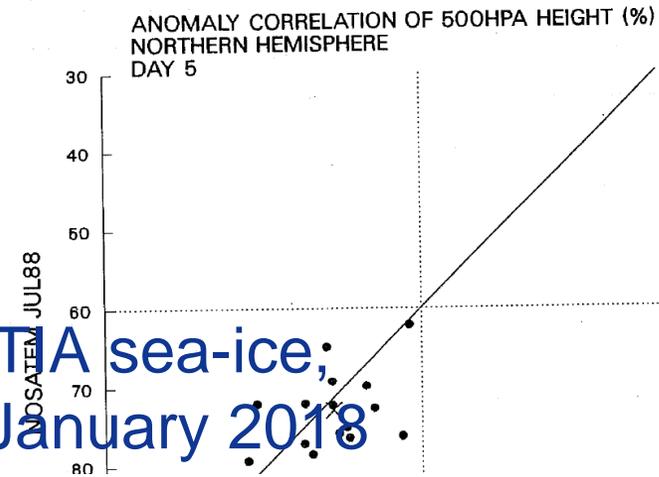
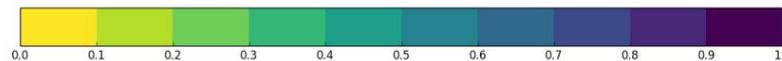
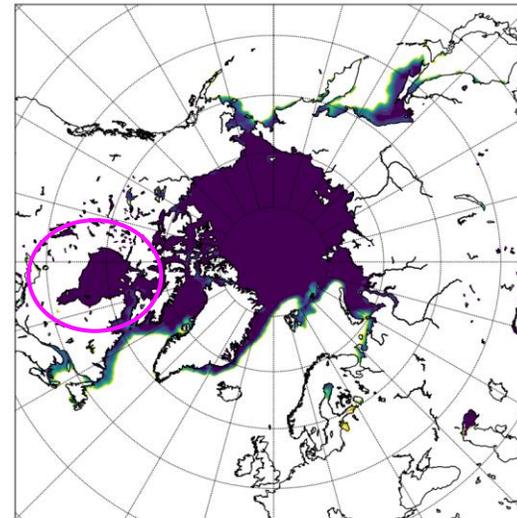
Problems with using external retrievals -

- Suboptimal
- Gross errors are hard to characterise

OSTIA sea-ice,
20th January 2018



OSTIA sea-ice,
21st January 2018



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

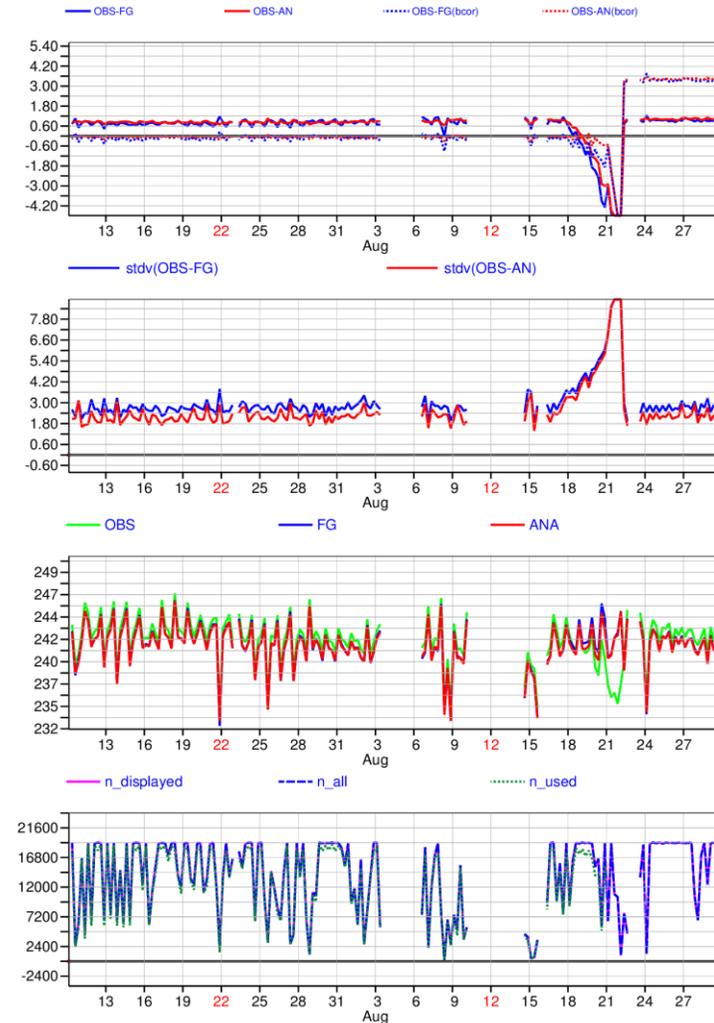
Courtesy daily report and Phil Browne

When something goes wrong

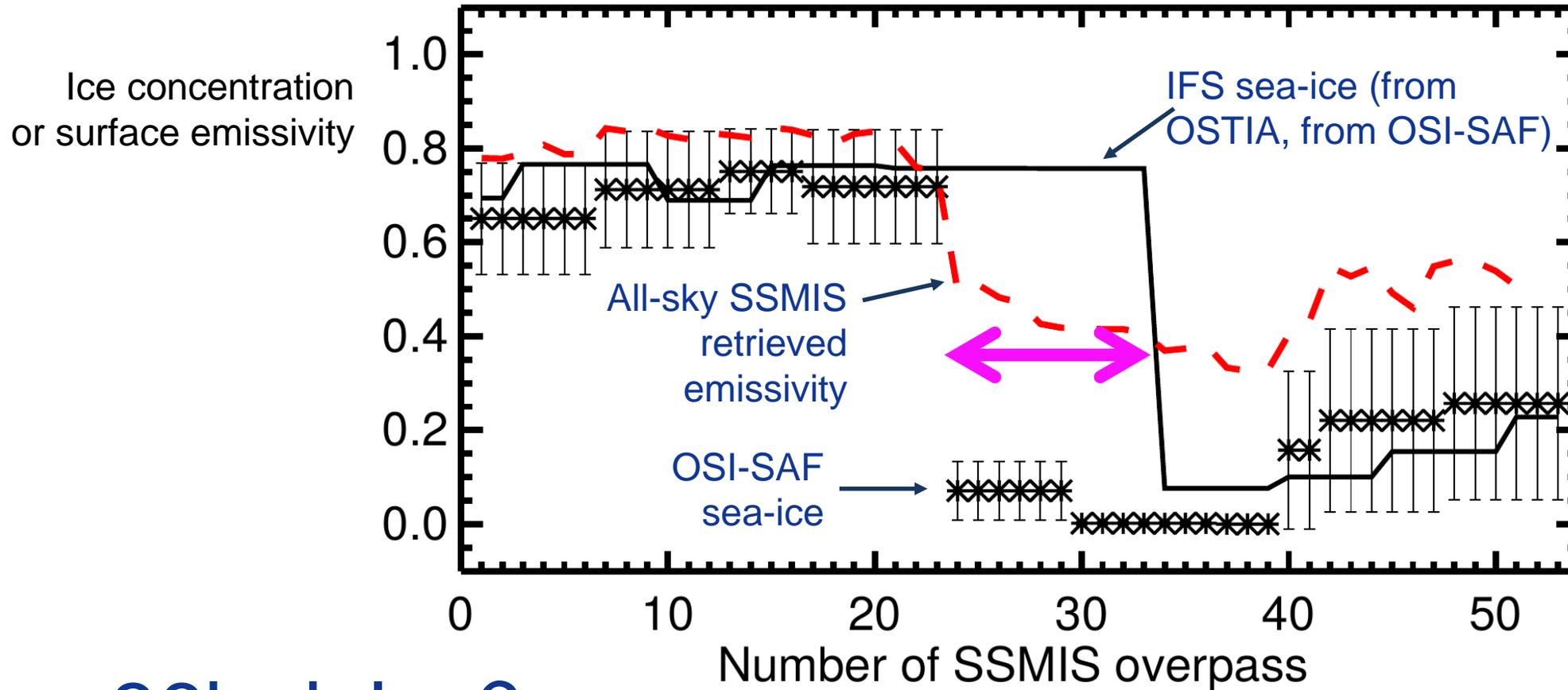
- We assimilate OSTIA which assimilates OSI-SAF retrievals from SSMIS radiances....
 - How is the bias correction done? →
 - How are data anomalies handled? →
 - How is cloud / precipitation detected and “removed”?
 - How is wind roughening of ocean surface treated?

All-sky, all-surface data assimilation

STATISTICS FOR RADIANCES FROM MEGATROPIQUE
CHANNEL =1, ALL DATA [TIME STEP = 6 HOURS]
Area: lon_w= 0.0, lon_e= 360.0, lat_s= -90.0, lat_n= 90.0 (over All_surfaces)
EXP = 0001 (LAST TIME WINDOW: 2018082903)



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

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

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

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

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

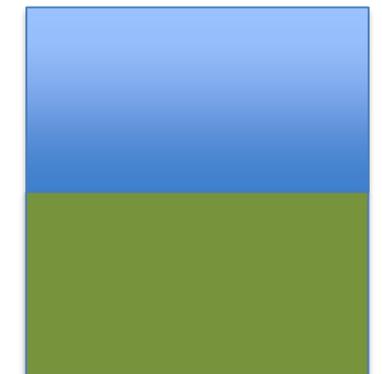
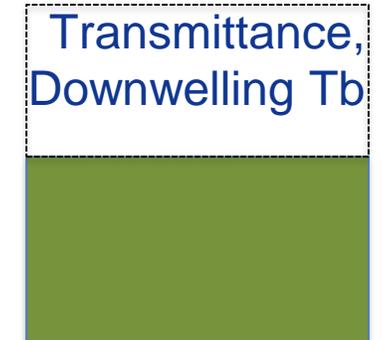
Outer loop coupling

- 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

Atmosphere
Inner loop



Land
Inner loop



Any more catches?

We need better forward modelling

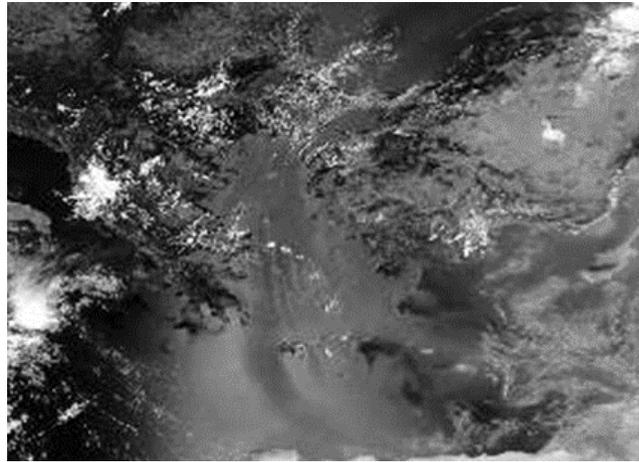
Models need to represent the relevant physical properties

Any more catches?

We need better forward modelling

Models need to represent the relevant physical properties

Forward modelling of ocean surface radiative transfer



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

A reference model for ocean surface emissivity and backscatter from the microwave to the infrared

Stephen English¹, Alan Geer¹, Heather Lawrence¹, Louis-Francois Meunier², Catherine Prigent³, Lise Kilić³, Ben Johnson⁴, Ming Chen⁴, William Bell^{5,1}, Stuart Newman⁵

ECMWF¹ METEO FRANCE² Observatoire de Paris³ Met Office⁴ European Commission⁵

Why do we need a reference model?

Fast radiative transfer models need to calculate emission and reflection at the earth's surface. The GAIA-CLIM project of the European Commission provided a gap-analysis for reference quality satellite data and recommended the development of a reference quality surface emissivity model. This poster does not present a reference model. It makes the case to create one and discusses what is needed.

What already exists?

A fast model like Fastem is only as good as the reference model it attempts to replicate. Unlike atmospheric transmission we lack a state of the art reference model for surface emissivity.

JCSDA are developing CSEM [2]. This incorporates emissivity models, from visible to microwave, over both land and ocean. TESSEM2 [3] is similar to Fastem. The RSS model [4] is based on observations from instruments on the DMSP and Coriolis satellites. None provide a reference model.

Elements of a reference model

GAIA-CLIM has shown the progression in fit of the Fastem model from version 1 to version 6 against the GM1 10.65 GHz horizontal polarisation, whose radiometric uncertainty is considered to be known. Lack of knowledge of the emissivity model uncertainty makes interpretation of this and any comparison to satellite observations difficult.

The priorities for the reference model are:

1. Maintained and supported.
2. Traceable uncertainty estimation at each step.
3. Documented code freely available to research community.
4. Add new science [7], [8], for IR to MW with BRDF capability (Rec from ECMWF-JCSDA workshop, Dec 2015).
5. Support passive and active applications.

Way forward

We encourage the ITWG remote sensing community to note the gap identified by GAIA-CLIM, consider how best to address this gap in the radiative transfer model capability and to support efforts underway to develop the components of such a reference model.

References

[1] English, S.J. and T. Hewison, 1998. doi:10.1117/12.319490.
 [2] Chen, M., 2016: 4th RMSMP, Saint Martin D'Heres, France 14-16 March.
 [3] Prigent, C., et al, 2016 10.1002/cj.2953.
 [4] Meissner, T., and F. J. Wentz, 2012: doi:10.1109/TGRS.2011.2179662.
 [5] Meunier, L.-F., et al, 2014: NWPSAF-MO-VS-049 (www.nwpsaf.eu).
 [6] Ellison, W.J., et al., 2003: 10.1029/2002JD003213.
 [7] Anguelova, M.D., and F. Webster, 2006: doi:10.1029/2005JC003158.
 [8] Anguelova, M.D. and P. Gaiser, 2012: doi:10.3390/rs4051162.

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

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

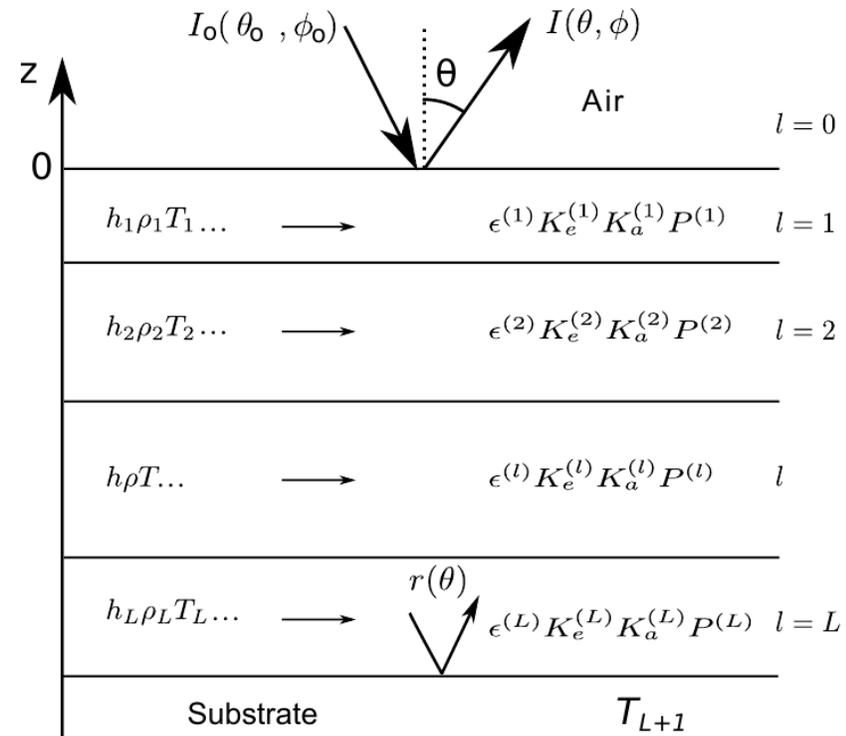


Figure 1. Multilayered medium modeled by SMRT. The incident radiation I_0 comes either from a radar beam (active mode) or from the sky (passive mode with atmospheric contribution).

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

An aerial, black and white photograph of a rugged coastline. The image shows dark, rocky land meeting the sea. White, frothy waves are crashing against the shore, creating a stark contrast with the dark rocks. The perspective is from a high angle, looking down at the coastline. The text 'BM^TH^T' is overlaid in the upper center of the image.

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