# Bayesian Cloud Detection for AVHRR instruments

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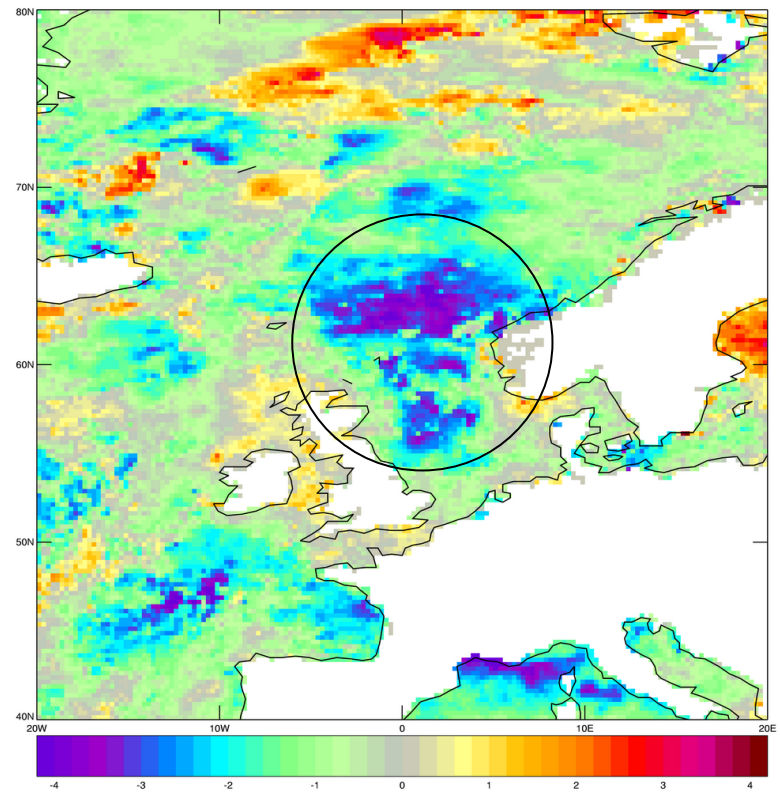
# Cloud Detection

- Is essential for many areas of remote sensing
- Relies on contrasts between clear and cloudy radiances
  - Temperature
  - Emissivity
  - Reflectance
  - Spatial texture / coherence
  - Temporal texture / coherence
- 99% of clouds are easy
- 1% of cases are difficult (but important)

# Cloud Detection




-4 K OSTIA +4 K

OSTIA anomaly 26/07/2011

- Large cold bias affected weather prediction for the UK
- Bias due to undetected cloud in operational AATSR scheme
- If AATSR had used Bayesian scheme this cloud would have been detected

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# Bayesian structure

- Fundamentally, cloud detection is estimation of the probability a pixel is free of cloud
- Given:
  - the radiances for the pixel
  - the radiances for other pixels
  - background knowledge of the state (NWP)
  - the uncertainties in all the above
- $Pc\boldsymbol{y}\uparrow o\ ,\boldsymbol{x}\uparrow b$

  c = clear

  $\mathbf{y}^o$ = observations

  $\mathbf{x}^b$ = background state

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# Bayesian Clear-Sky Probability

- Apply Bayes' theorem:

$$P(c|\boldsymbol{y}^{o}, \boldsymbol{x}^{b}) = P(c)P(\boldsymbol{y}^{o}|\boldsymbol{x}^{b}, c) / P(c)P(\boldsymbol{y}^{o}|\boldsymbol{x}^{b}, c) + P(\bar{c})P(\boldsymbol{y}^{o}|\boldsymbol{x}^{b}, \bar{c})$$

- P(y|x) terms are probability density function (PDF)s
  - Physical calculation (from radiative transfer model)
  - Empirical calculation or Look Up Table (LUT)
- Split into independent spectral and texture probabilities:

$$P(\boldsymbol{y}^{o}|\boldsymbol{x}^{b}, c) = P(\boldsymbol{y}^{s,o}|\boldsymbol{x}^{b}, c)\, P(\boldsymbol{y}^{t,o}|\boldsymbol{x}^{b}, c)$$

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# Clear-sky spectral PDF

- Can calculate from output of radiative transfer model

$$P\boldsymbol{y}_{s}^{o}\,\boldsymbol{x}_{b},c=\exp\{-0.5(\boldsymbol{y}_{o}-\boldsymbol{y}_{b})^{T}(\mathbf{KS}_{a}\mathbf{K}^{T}+\mathbf{S}_{e})^{-1}(\boldsymbol{y}_{o}-\boldsymbol{y}_{b})\}/($$

- Uses prior information (NWP) and uncertainties
- Same calculations as physical SST retrieval
- PDF is (hyper) ellipsoid in BT/reflectance space
- Can calculate for any instrument supported by RTM

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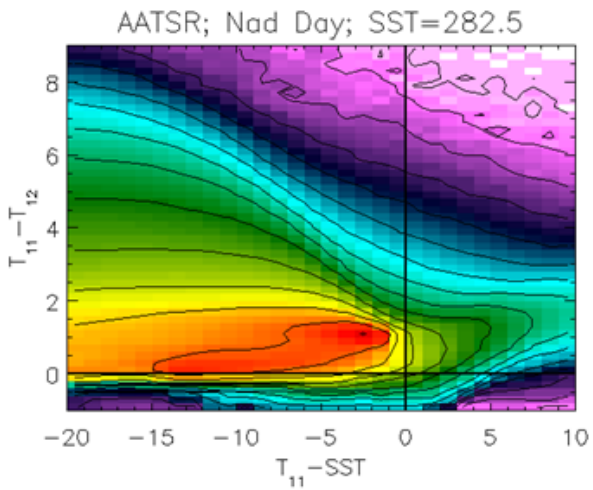
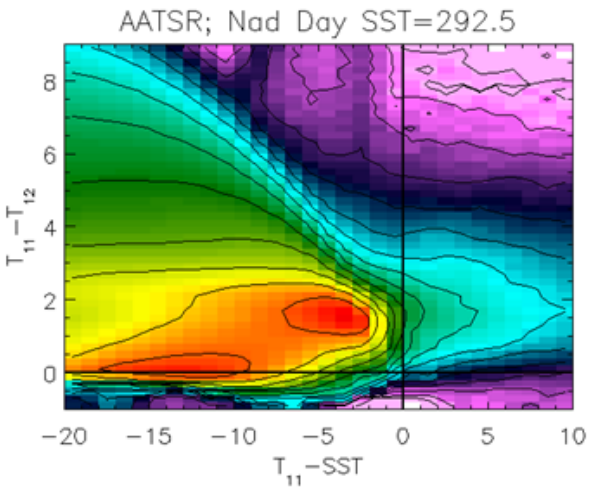
# Cloudy-sky spectral PDF

- Forward modelling of cloudy BTs is much harder
- Use lookup tables based on histograms of cloudy observations
  - Need a large sample of pre-screened observations
  - Or run a large number of cloudy RT simulations
- For ARC project we build histogram from all ATSR cloudy observations
  - Bootstrapped using SADIST threshold mask
  - Then iterated based on Bayesian mask

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# Textural PDF

- Currently use 3x3 standard deviation of 11 µm BT
- Both clear and cloudy use LUT
- Improves screening of cloud edges
- But can flags ocean fronts

# Adaption to Metop AVHRR

- Clear-sky PDFs
  - Calculated as required from RT model
  - Can do for any instrument supported by RTM
- Look up tables
  - Pre-calculated
  - Instrument specific
  - We have ATSR LUTs from ARC project
- Want to adapt ATSR LUTs for use with AVHRR
  - Zenith angle
  - Spectral response

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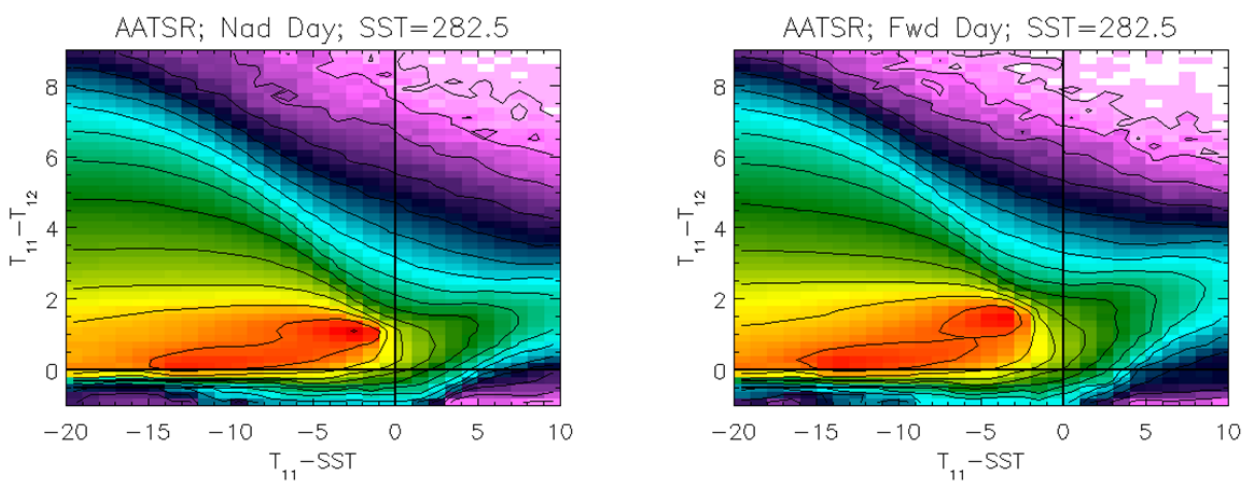
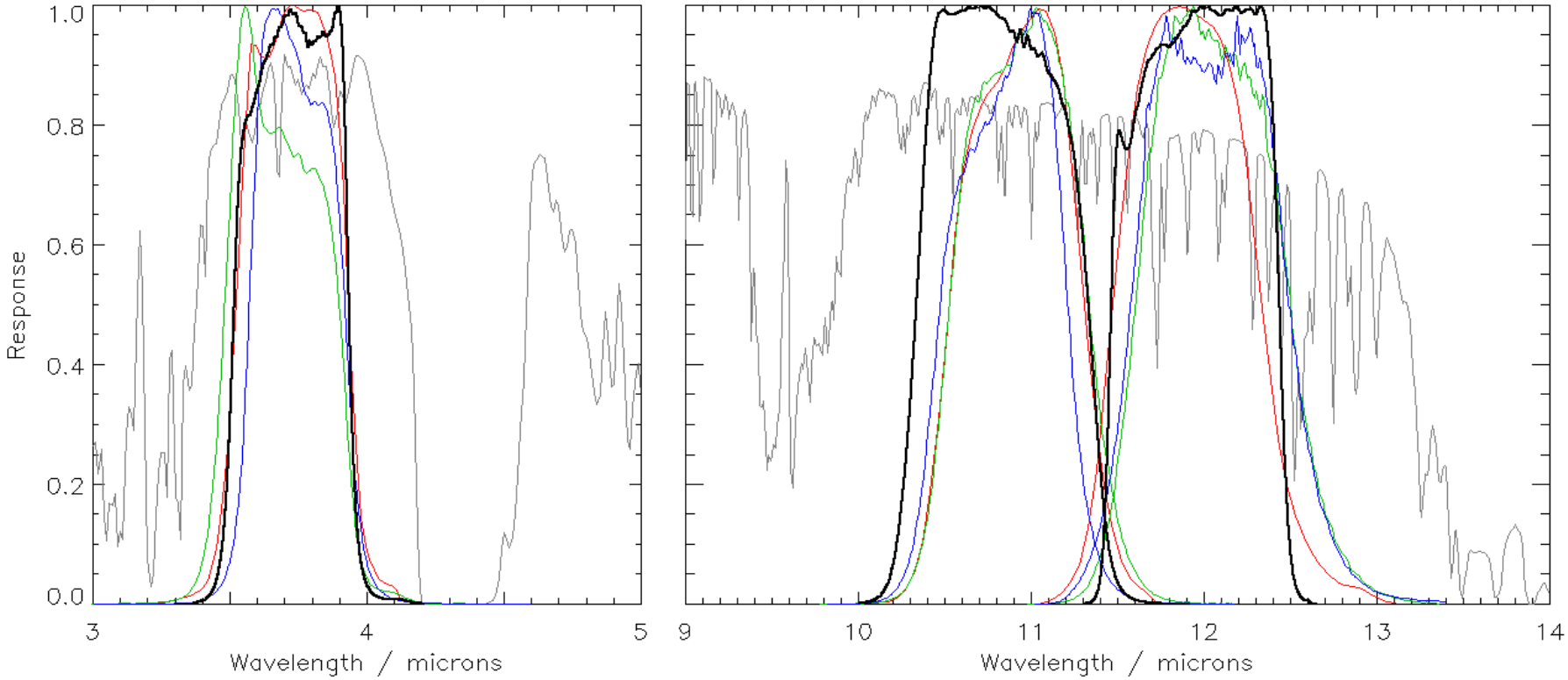
# Adapting AATSR LUTs for AVHRR

- Zenith angle range
  - AATSR LUTs for nadir (0-22°) and forward (~55°)
- Interpolate between two LUTs:
  - Linear in path length
  - $f=(1/\cos\theta\ -1)/0.75$ subject to $f<1$
  - $PDF(\theta)=PDF(0°)(1-f)+PDF(55°)f$



# Adapting AATSR LUTs for AVHRR

- Spectral Response Function (SRF)




AVHRR-A ATSR1 ATSR2 AATSR

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# Adapting AATSR LUTs for AVHRR

- Spectral Response Function (SRF)
- Common channels for all instruments
  - 3.7 µm, 11 µm, 12 µm
- Differences in SRF and channel centre
- Simulate typical BTs using RTTOV11
- Simulating clear-sky conditions
  - But PDF LUTs are for cloudy-sky
  - Critical area of LUT is where cloudy-BTs are similar to clear-BTs
  - AATSR 12 µm includes adjustment for 12 µm anomaly

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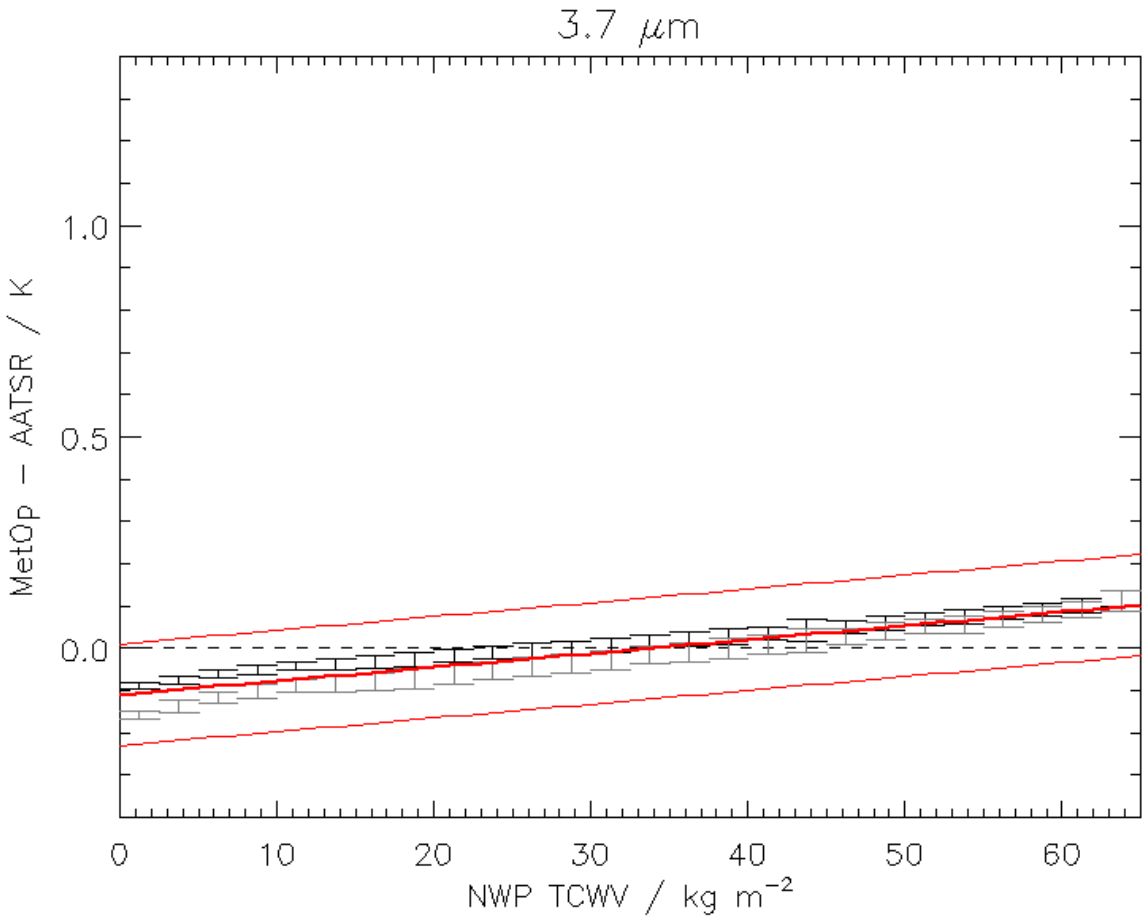
# AVHRR-A – AATSR (3.7 µm)

– θ=0°
– θ=55°

– quadratic fit
± NEDT

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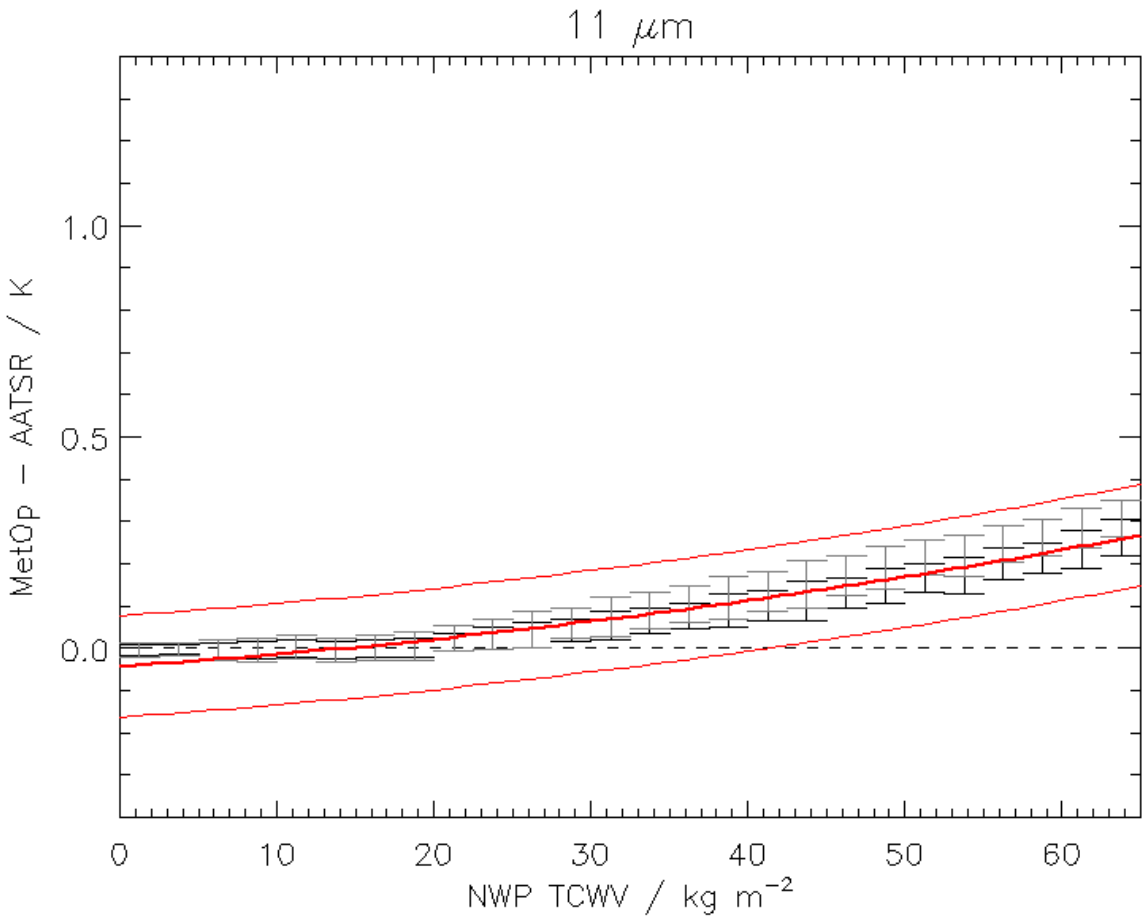
# AVHRR-A – AATSR (11 µm)

– θ=0°
– θ=55°

– quadratic fit
± NEDT

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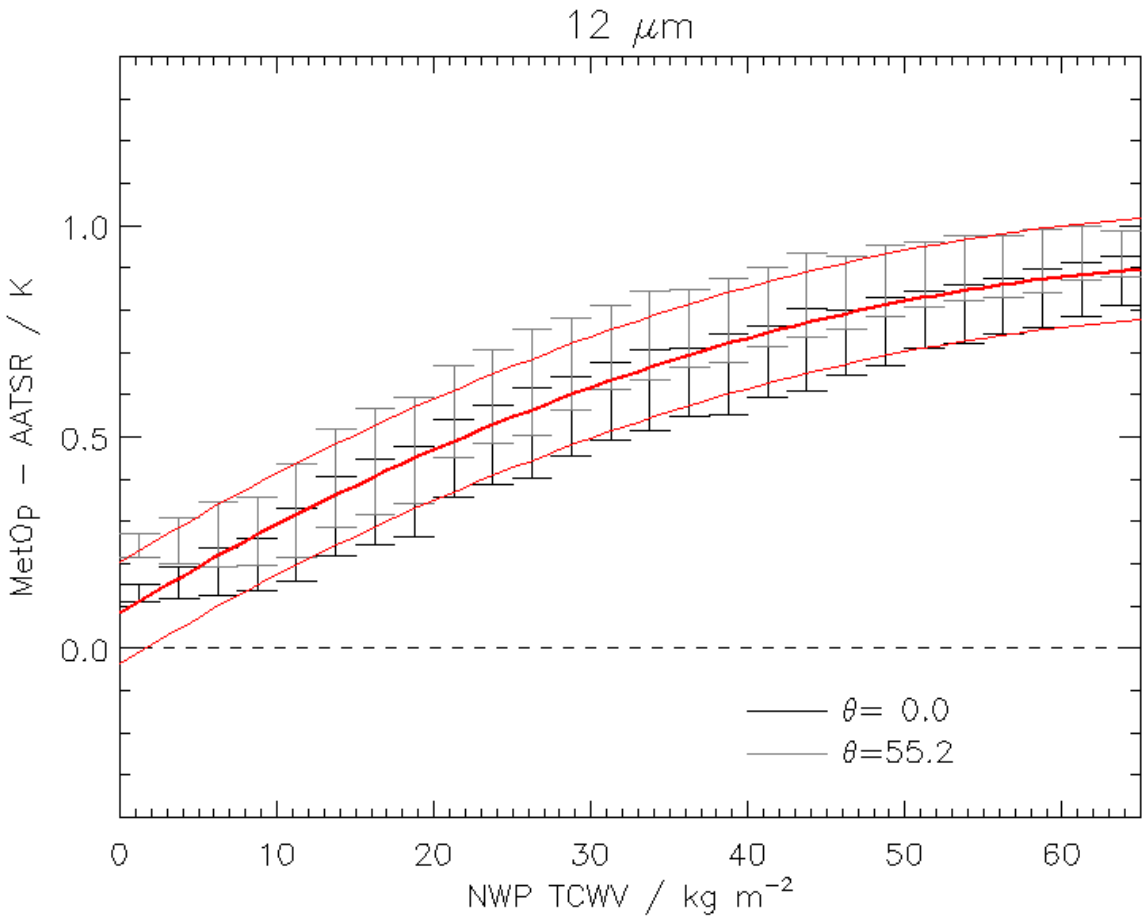
# AVHRR-A – AATSR (12 µm)

– θ=0°
– θ=55°

– quadratic fit
± NEDT

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# Adapting AATSR LUTs for AVHRR

- BT differences
  - Vary with total column water vapour (TCWV)
  - Largest (up to ~1 K) for 12 µm channel
- Difference between 0° and 55° simulations
  - Close to NEDT (0.12 K)
  - AVHRR observations quantised close to NEDT
  - Can neglect zenith angle effect on BT shift
- Use AATSR LUTs for AVHRR by modifying BTs before doing lookup

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# Adapting AATSR LUTs for AVHRR

- From RTTOV simulations:
  - $BT_{AVHRR} - BT_{AATSR} = a_n + b_n w + c_n w^2$
- Coefficients *a*, *b*, *c* defined for each channel
- Convert BTs to AATSR-like BTs prior to accessing LUT
- Can reuse same LUTs for multiple instruments
  - Shift-coefficients read from ASCII file

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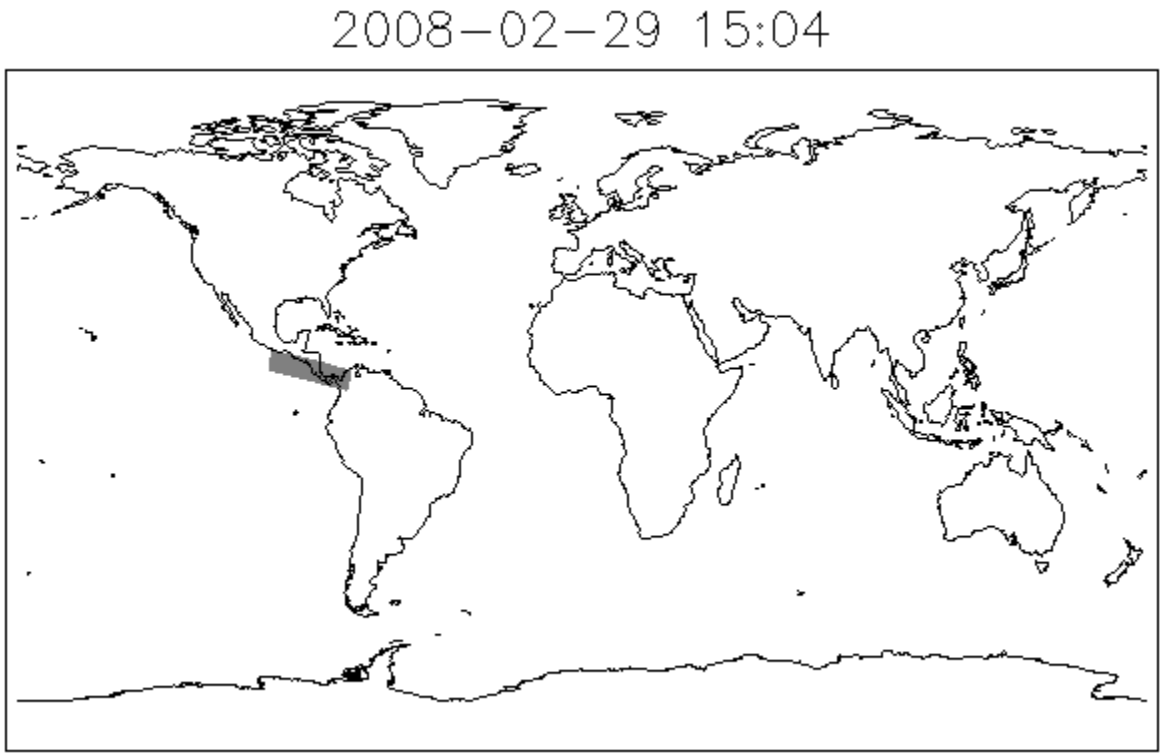
# Results

# 2008-02-29 15:04:03

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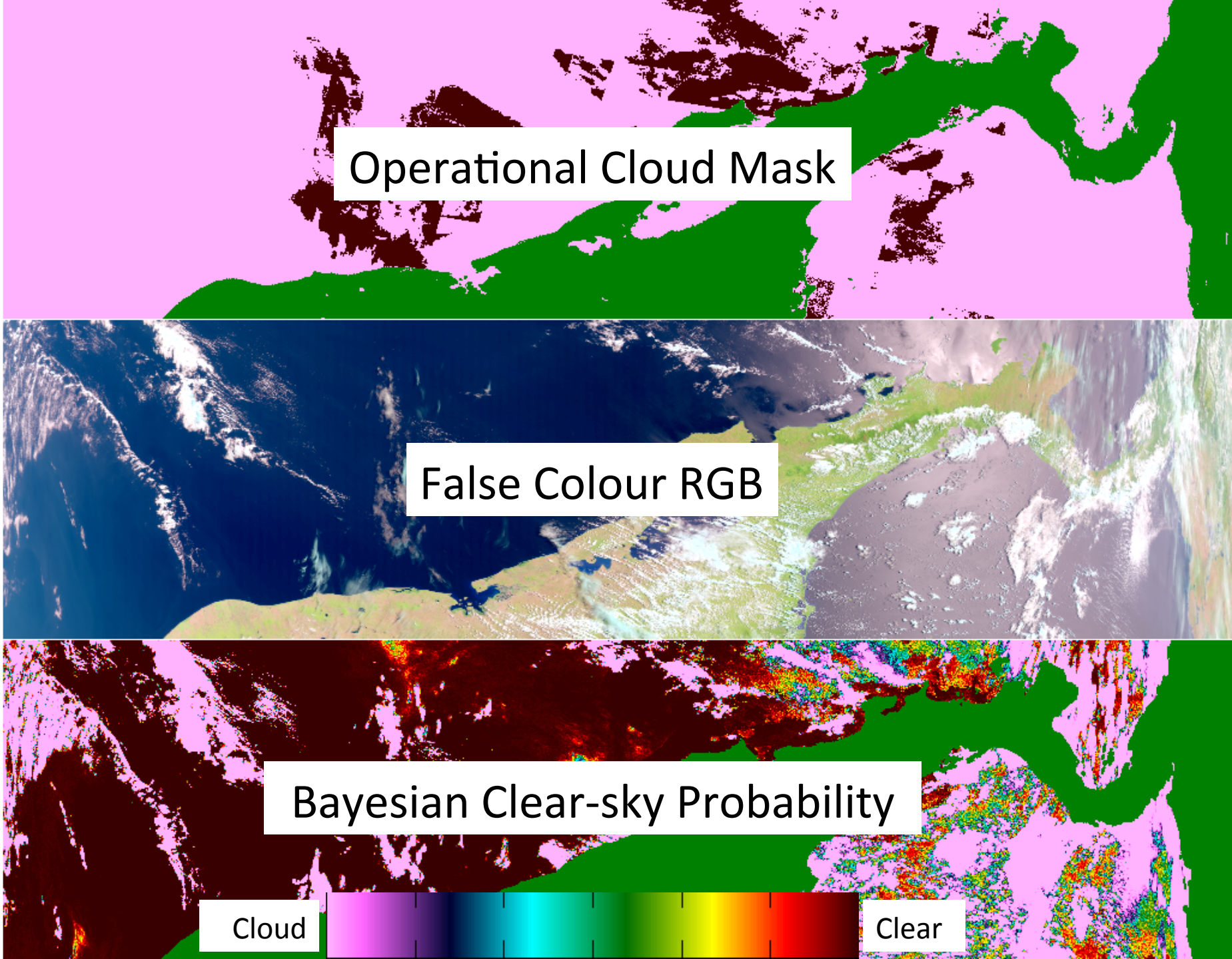
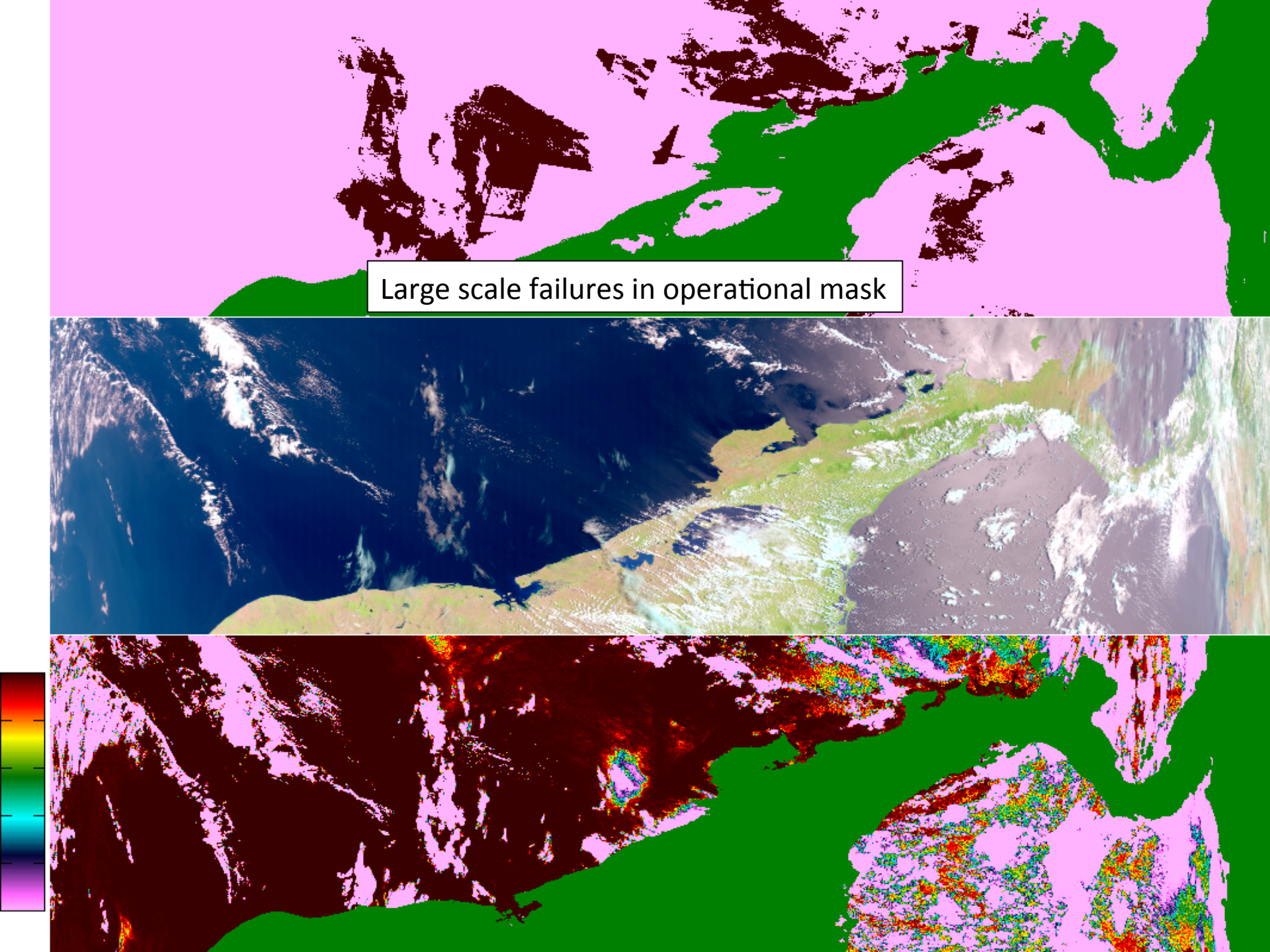

Operational Cloud Mask
False Colour RGB
Bayesian Clear-sky Probability
Cloud
Clear


Large scale failures in operational mask

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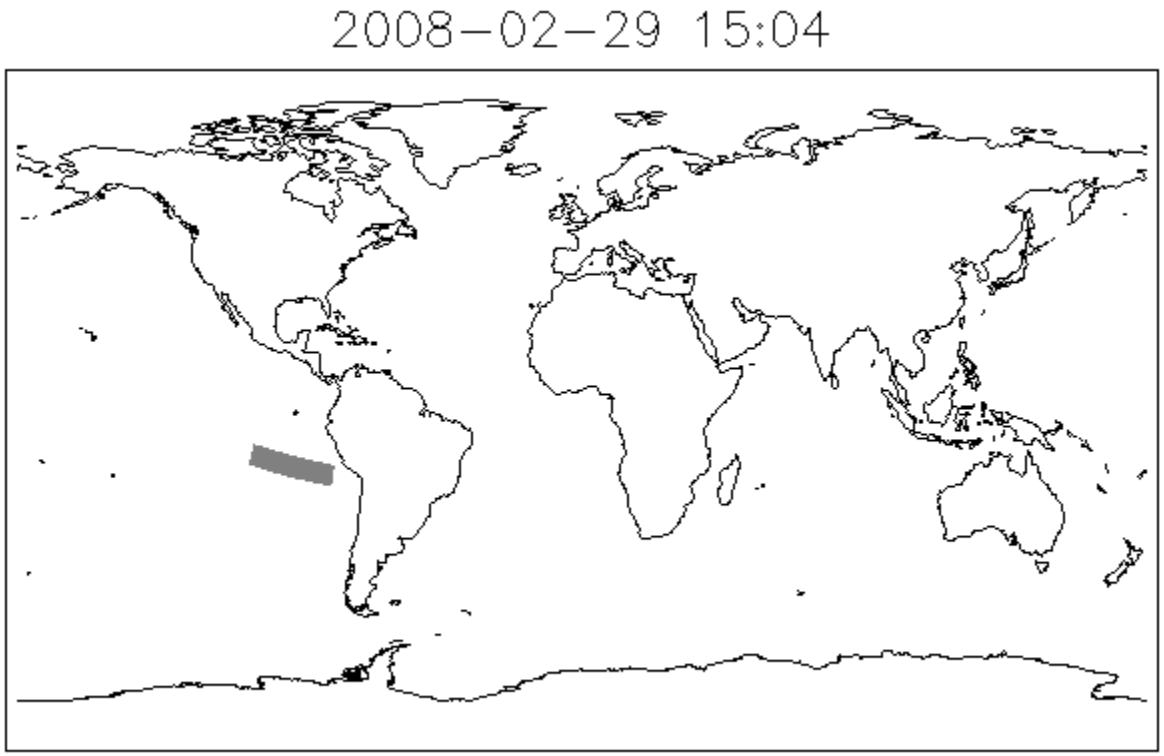


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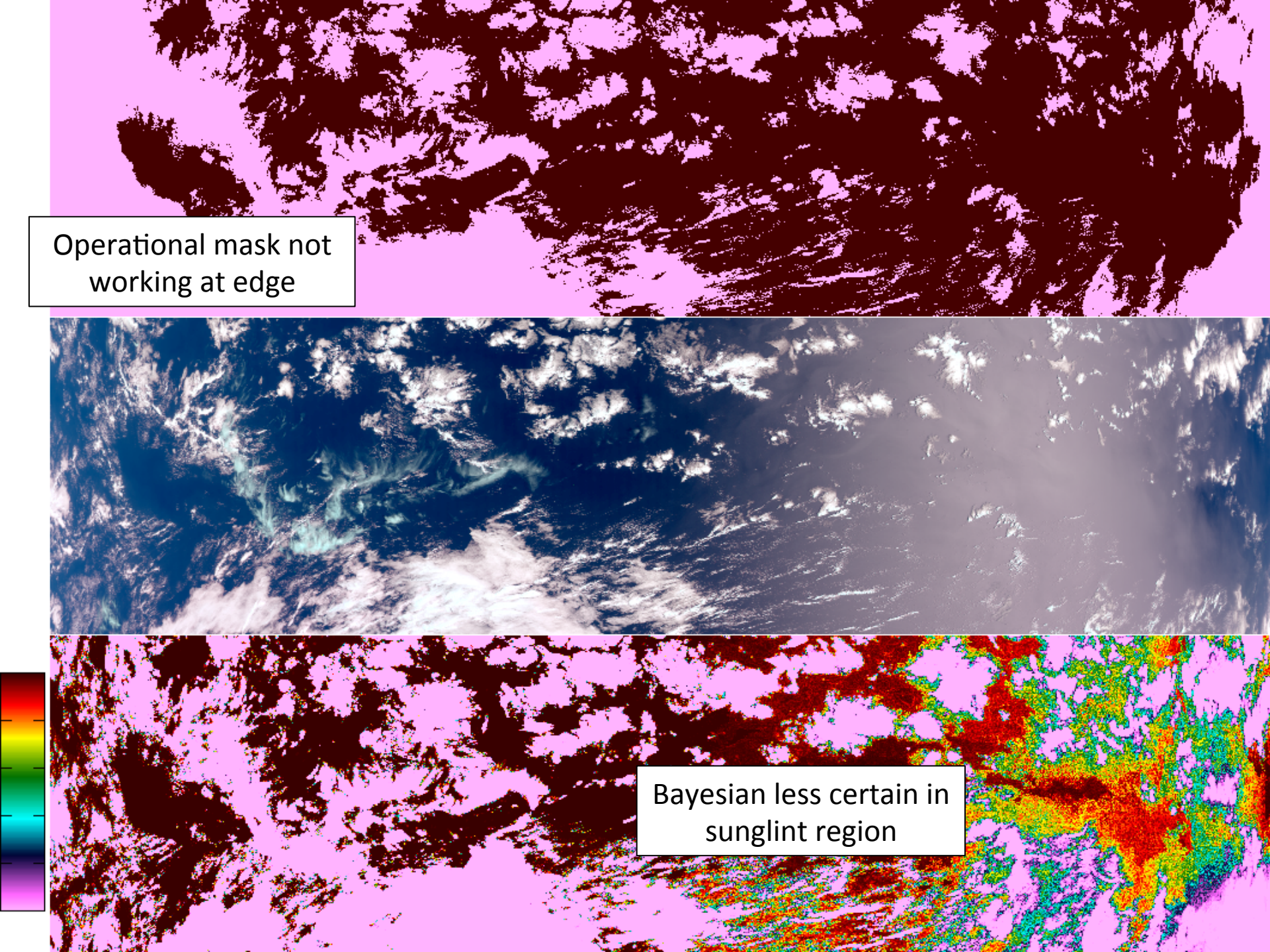
Operational mask not working at edge
Bayesian less certain in sunglint region

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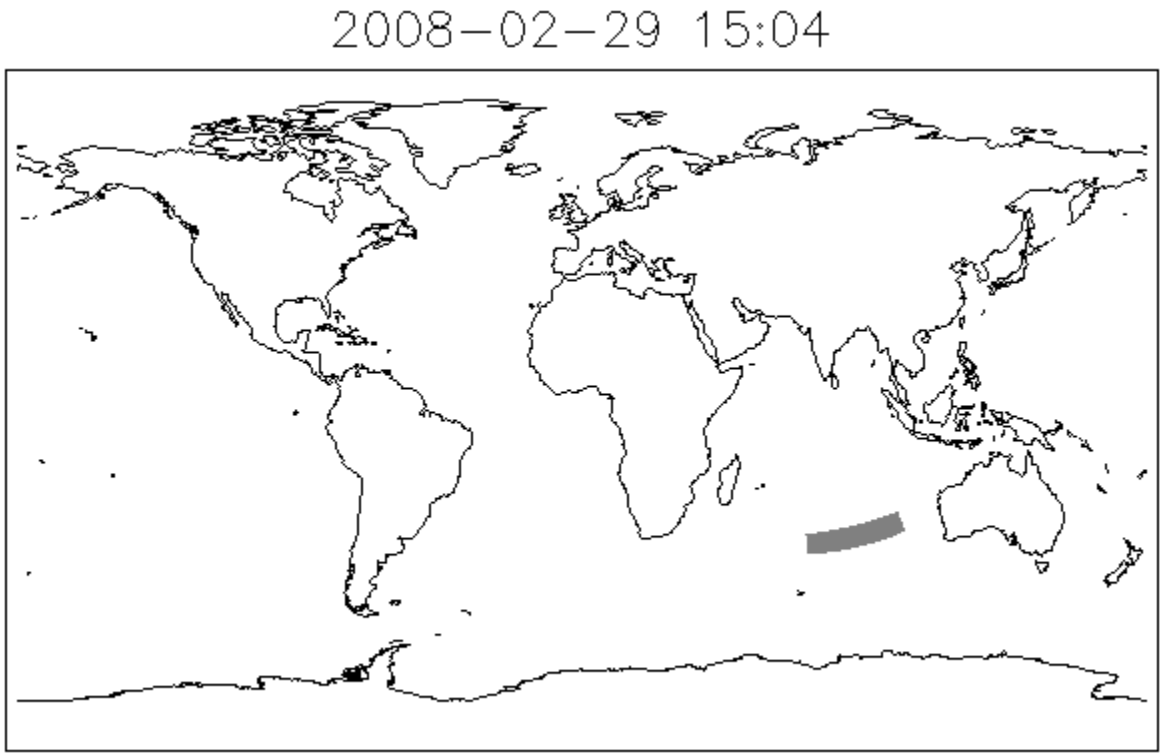


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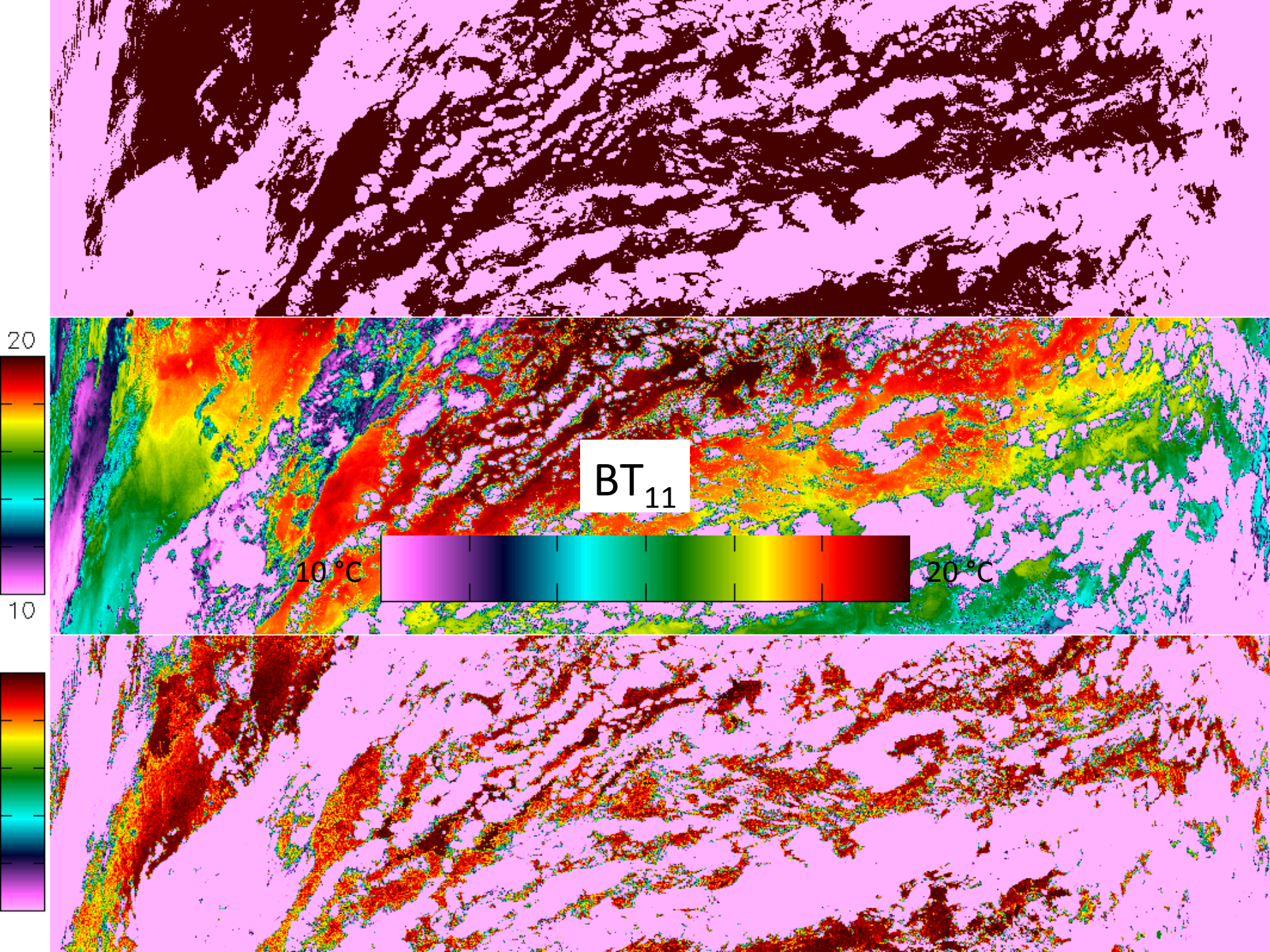
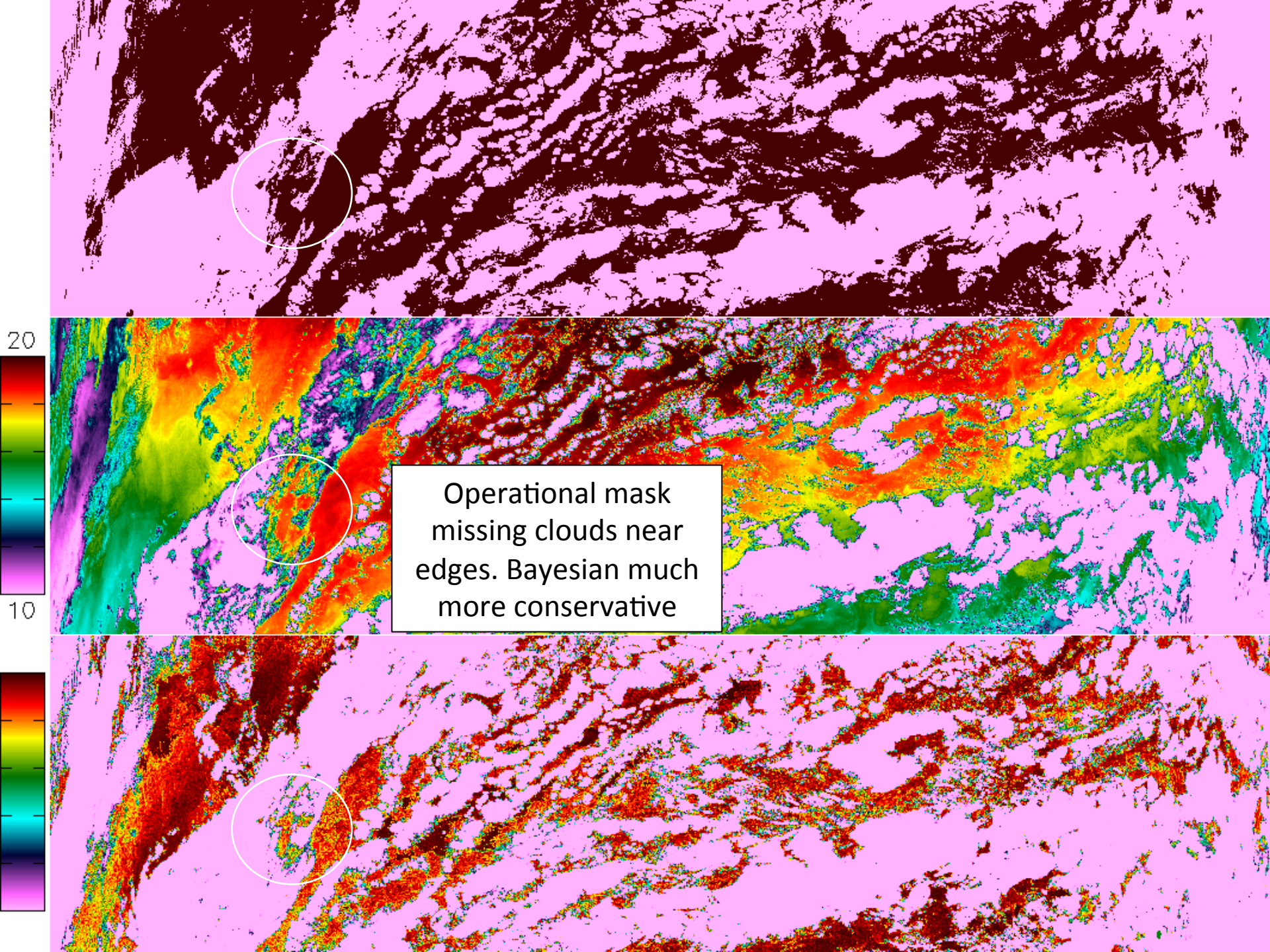
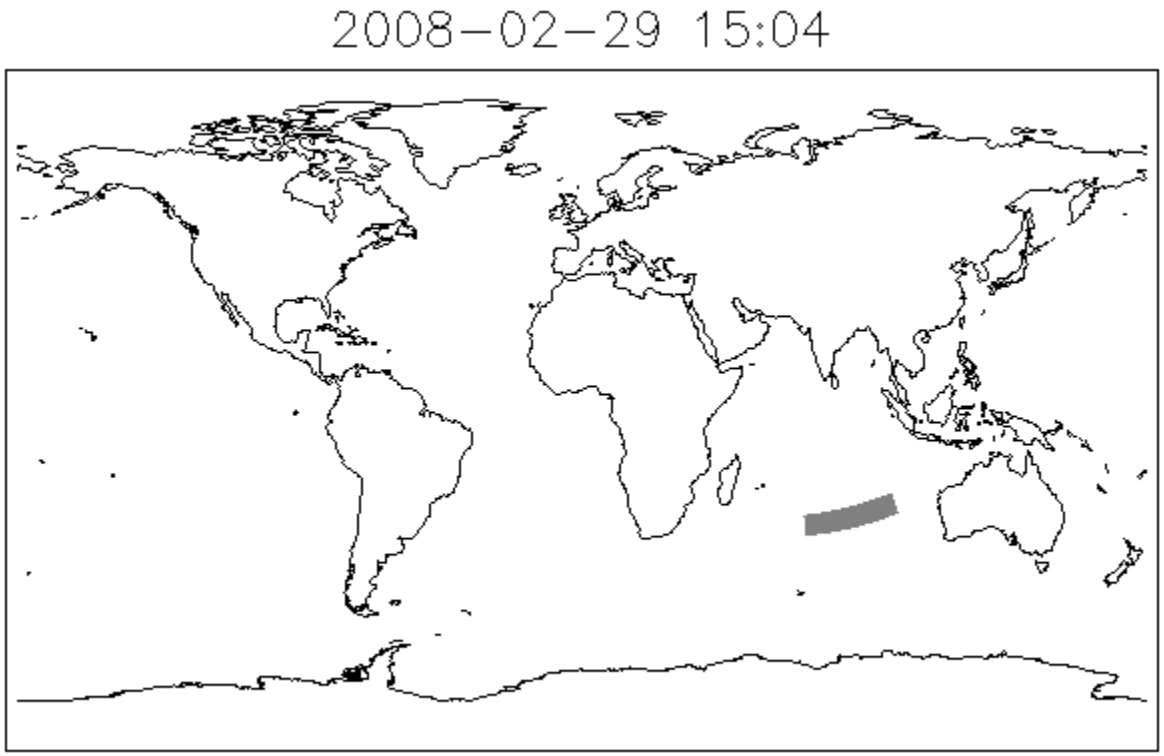

20
10
BT11
10 °C
20 °C


20
10
Operational mask missing clouds near edges. Bayesian much more conservative

# 2008-02-29 15:04:03

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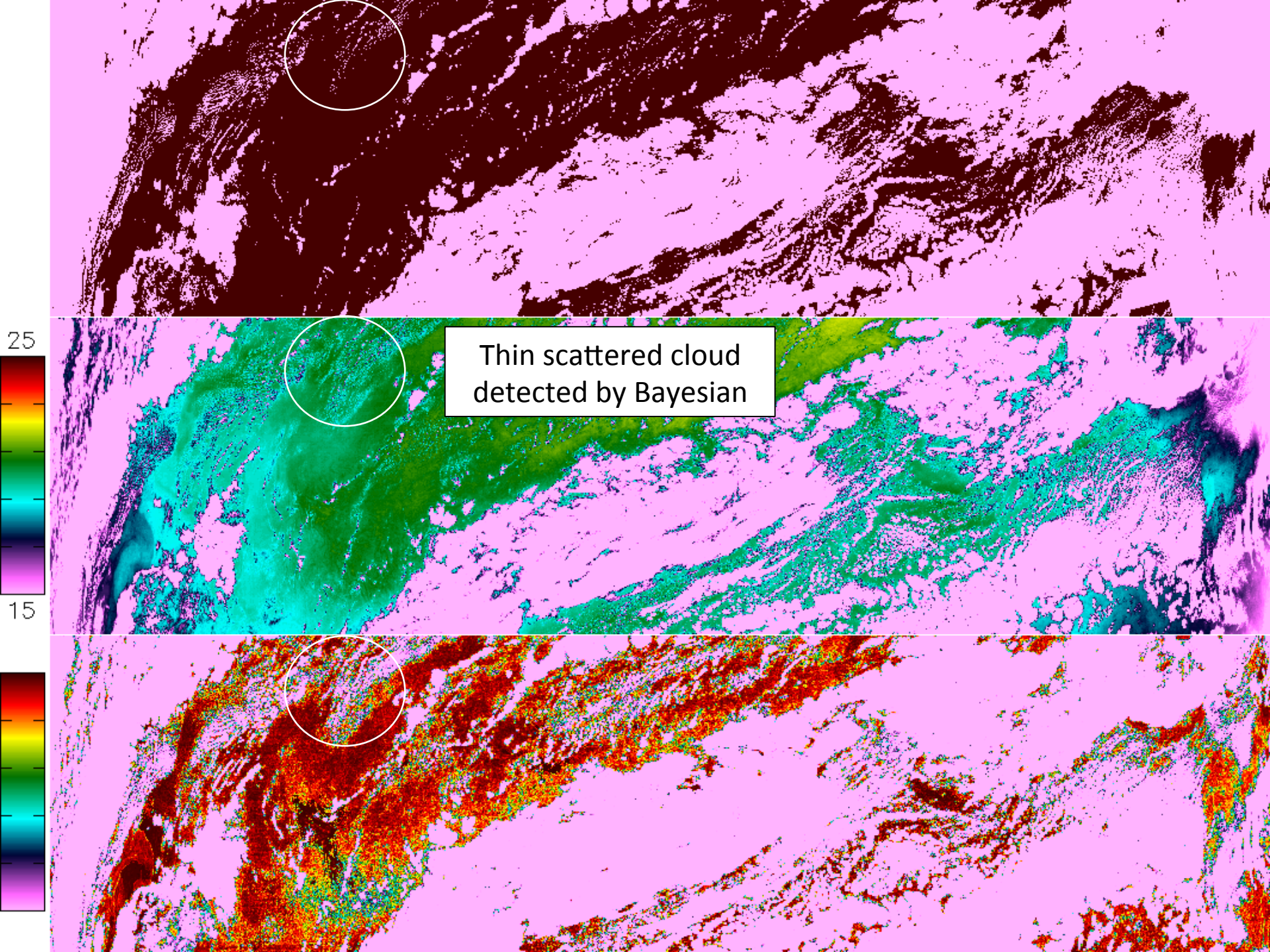
25
15
Thin scattered cloud detected by Bayesian

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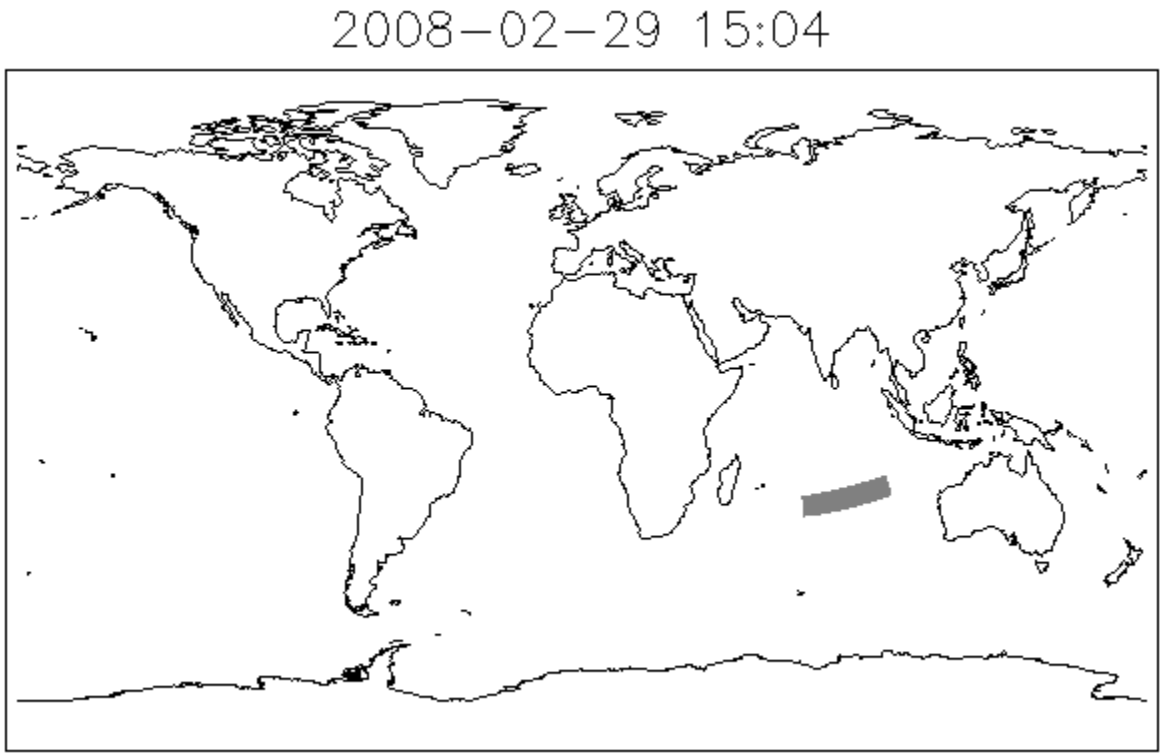


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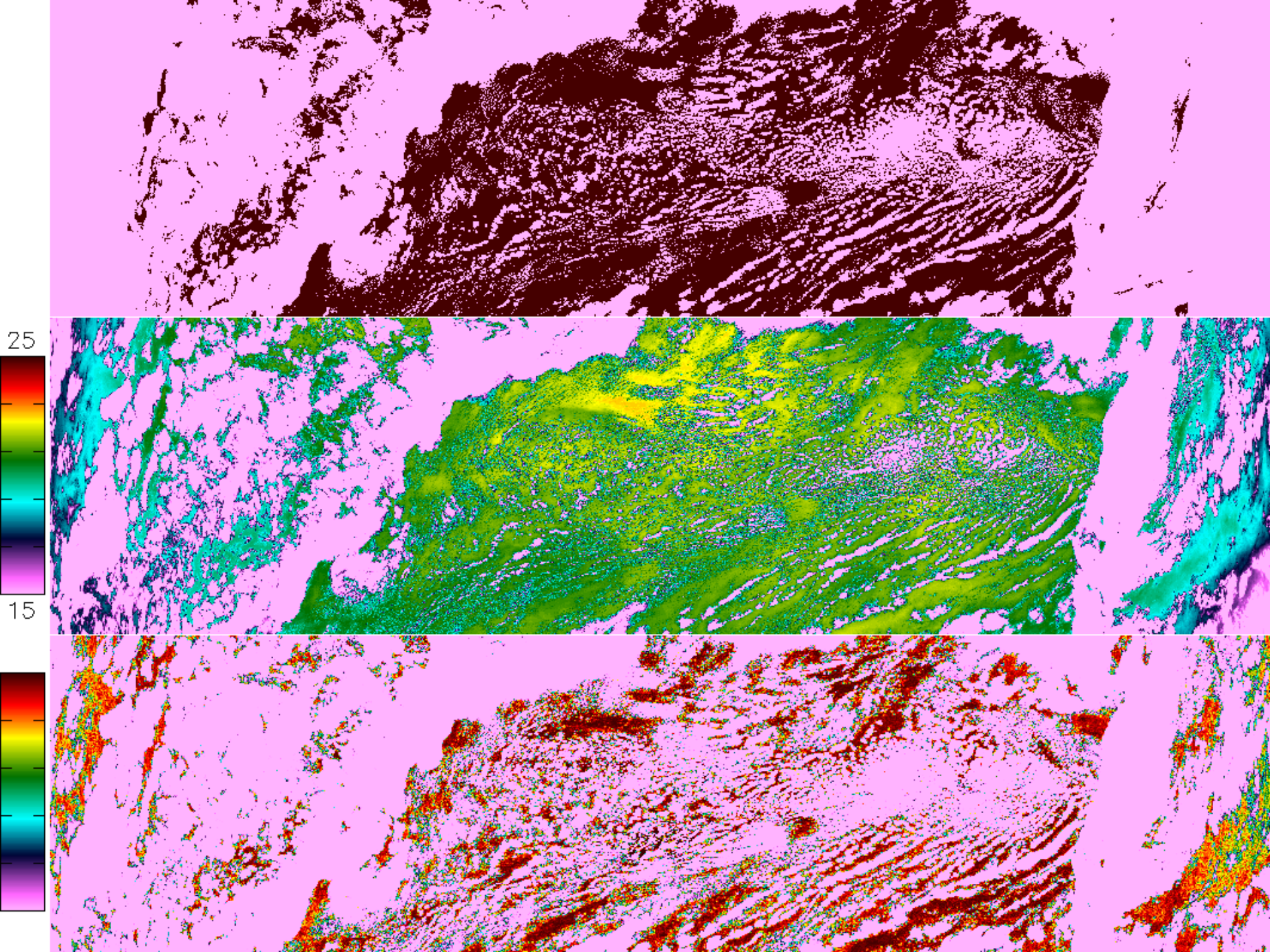
25
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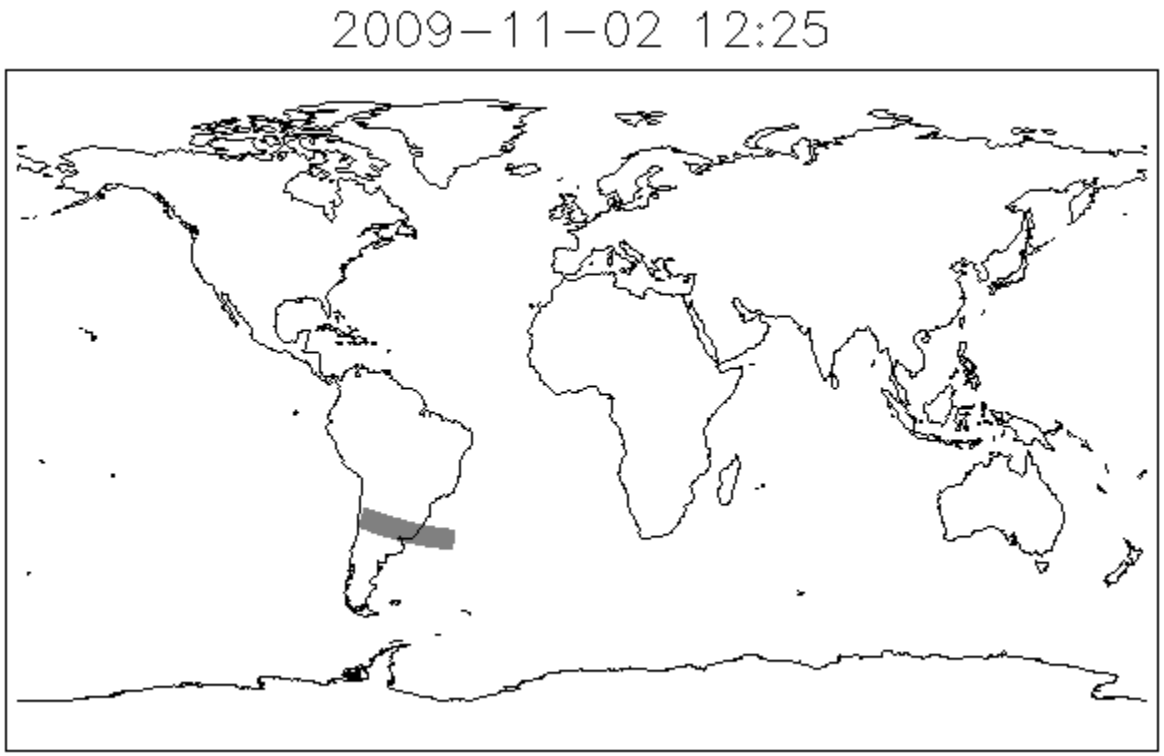
# 2009-11-02 12:25:03

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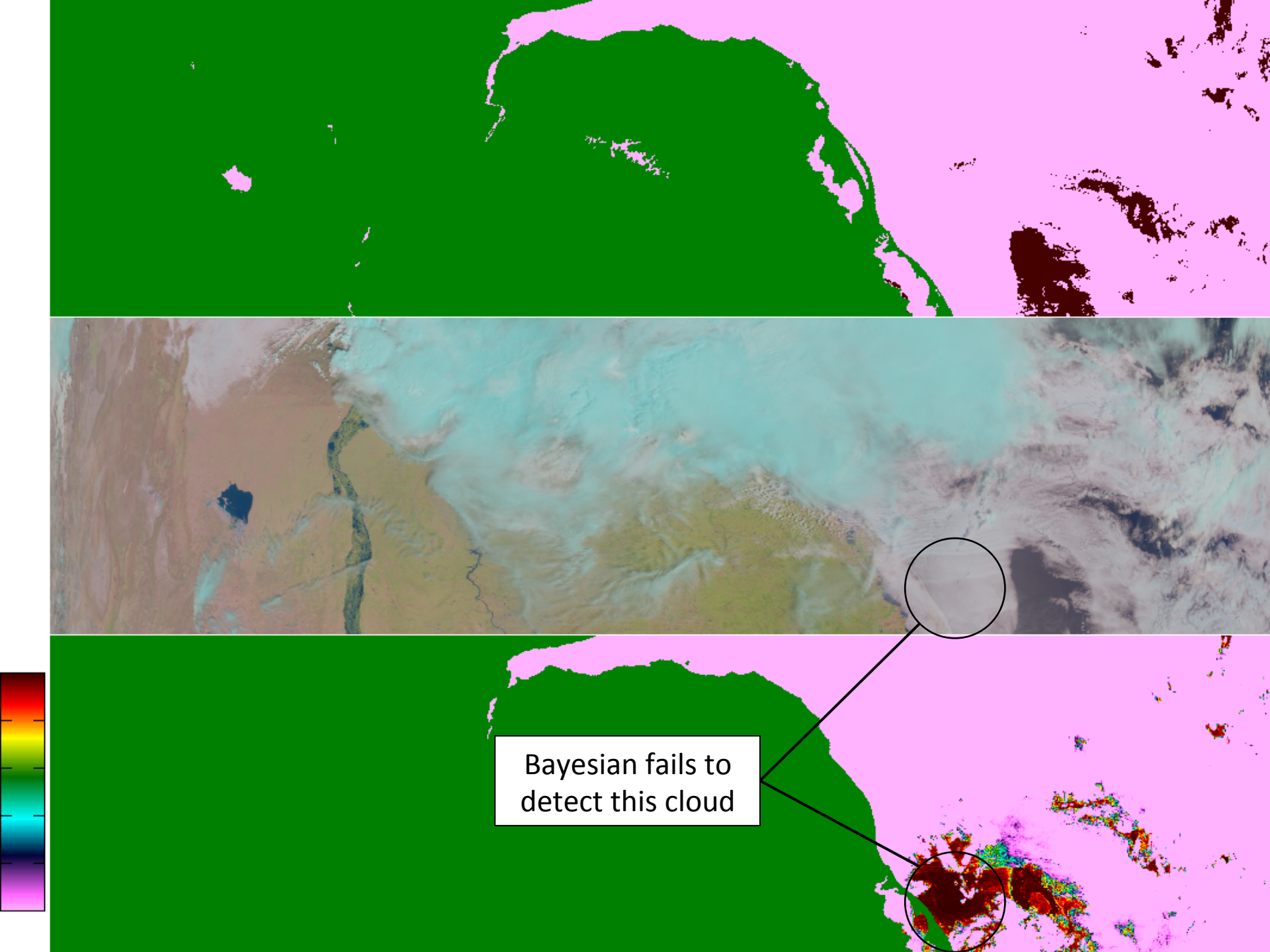
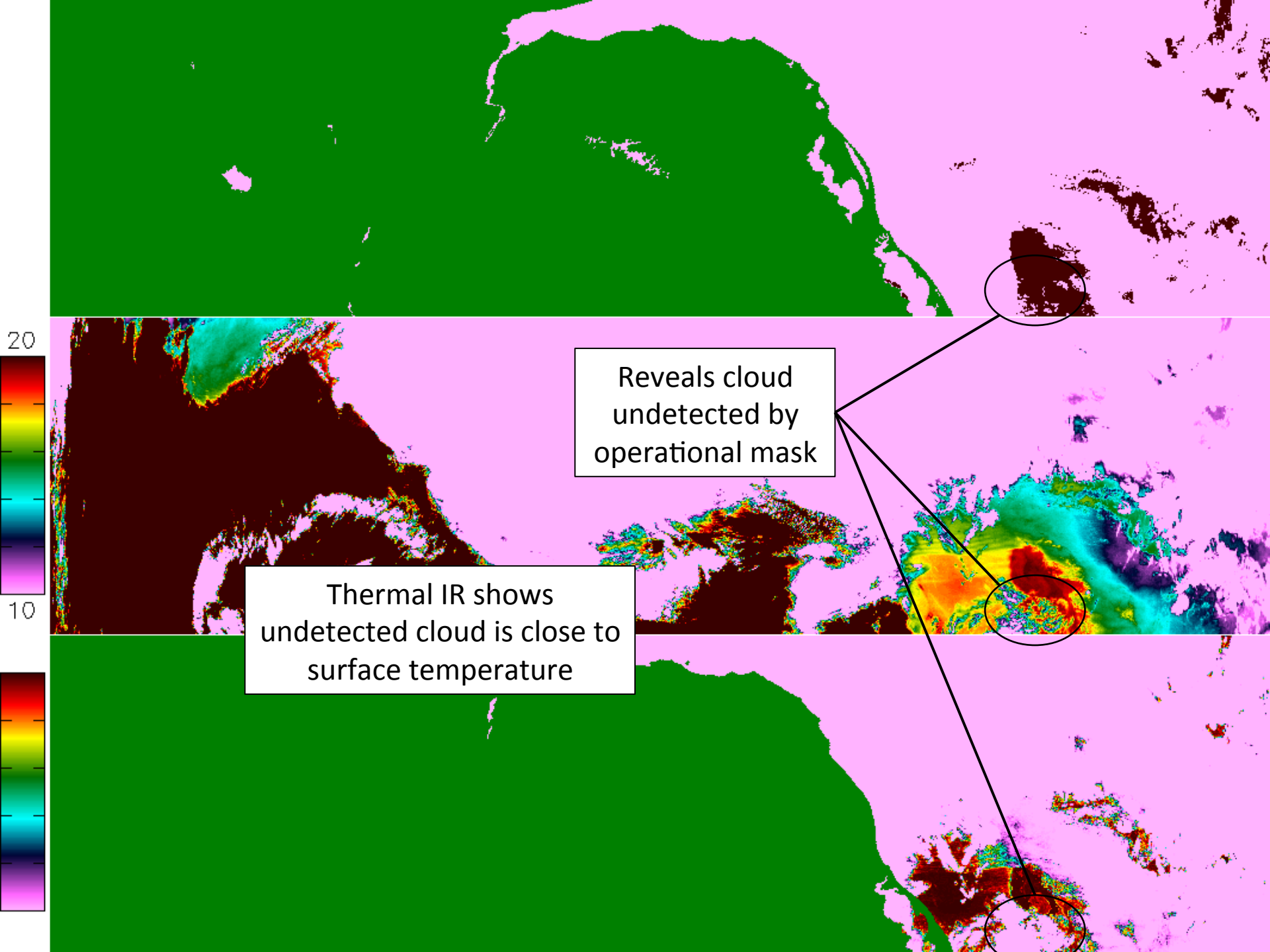
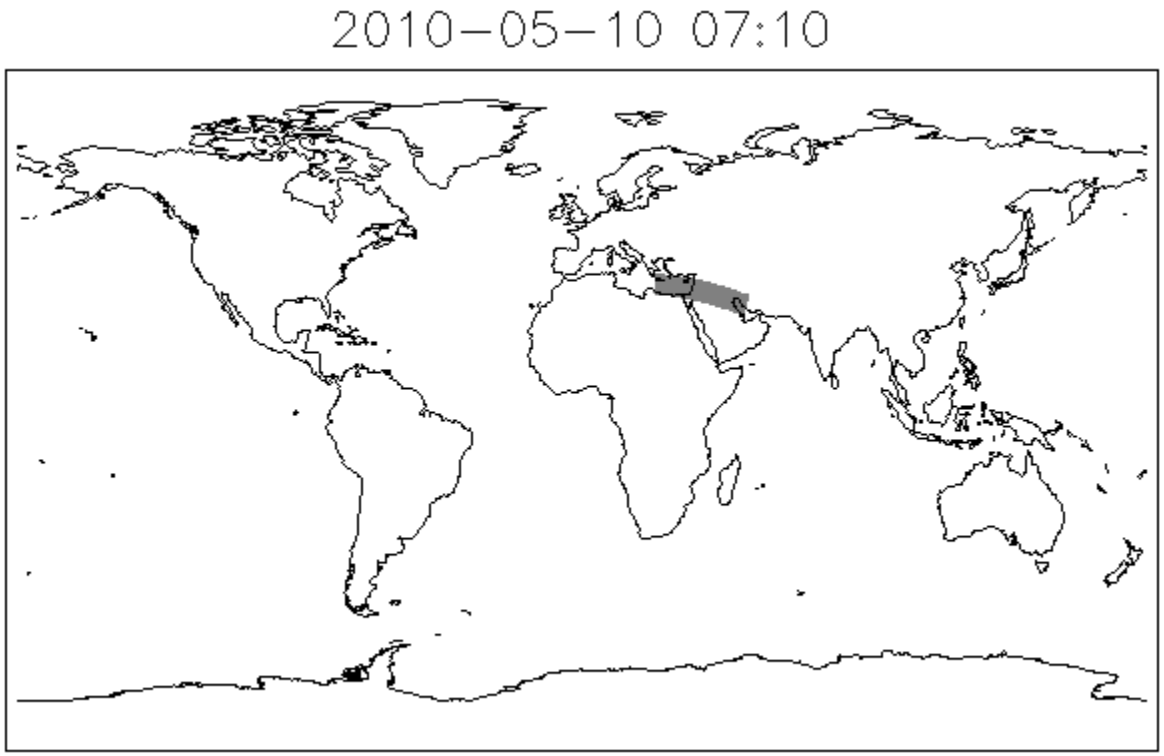

Bayesian fails to
detect this cloud


20
10
Reveals cloud undetected by operational mask
Thermal IR shows undetected cloud is close to surface temperature

# 2010-05-10 07:10:03

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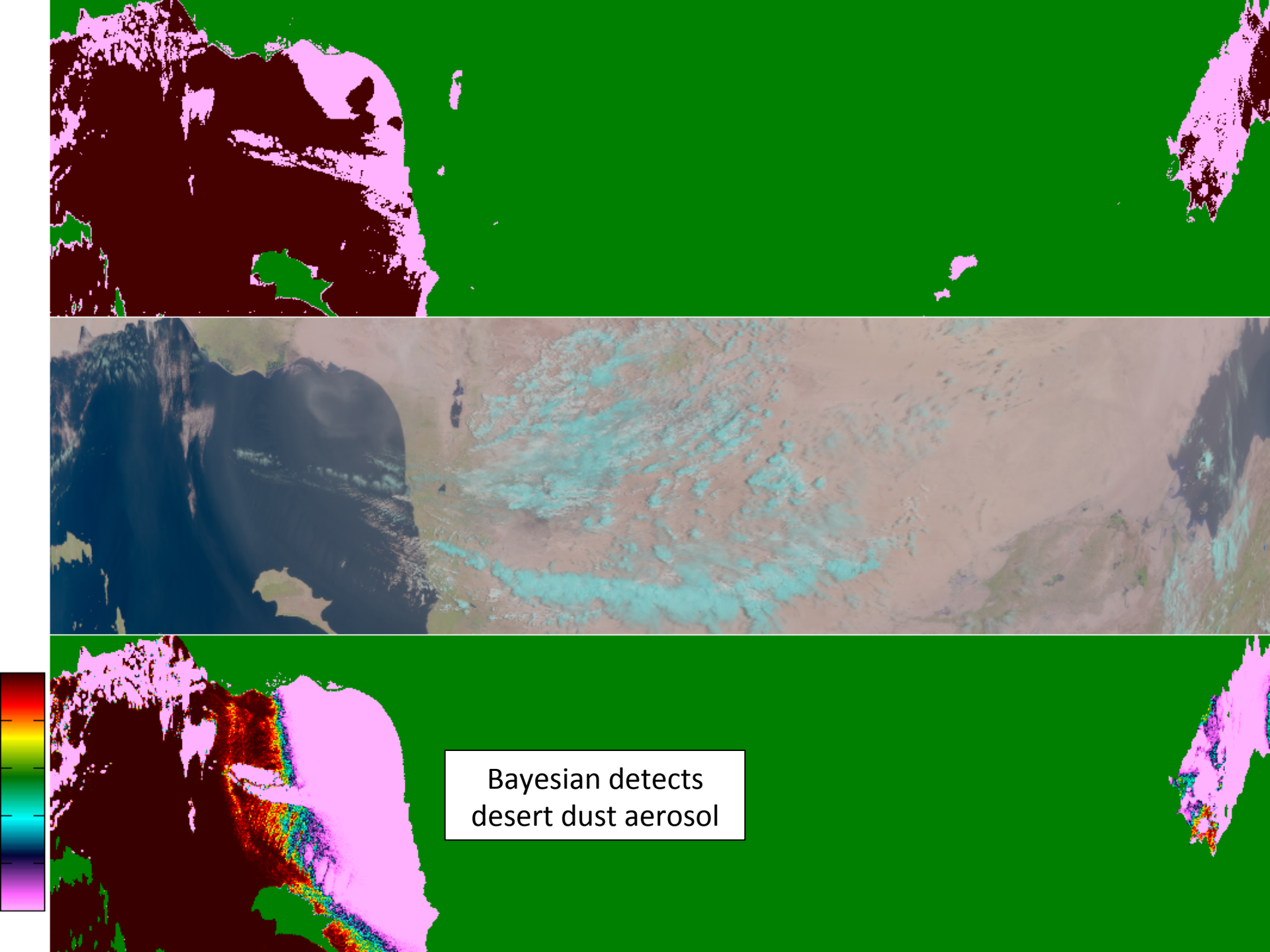
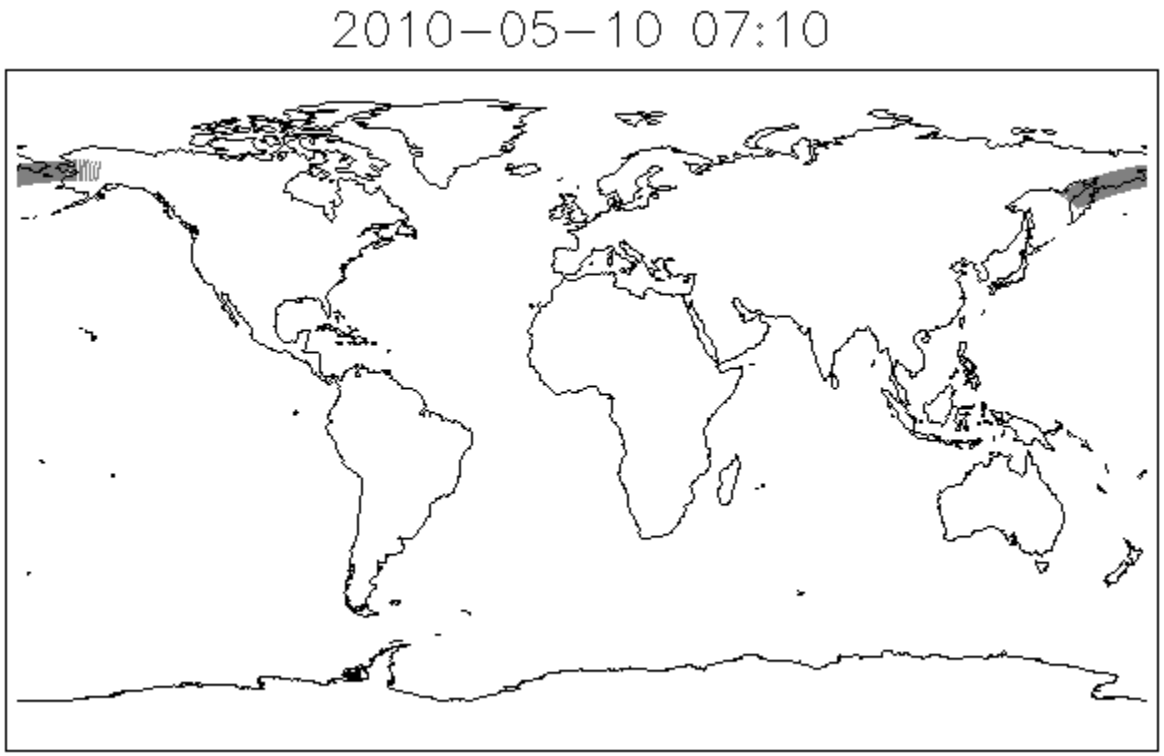
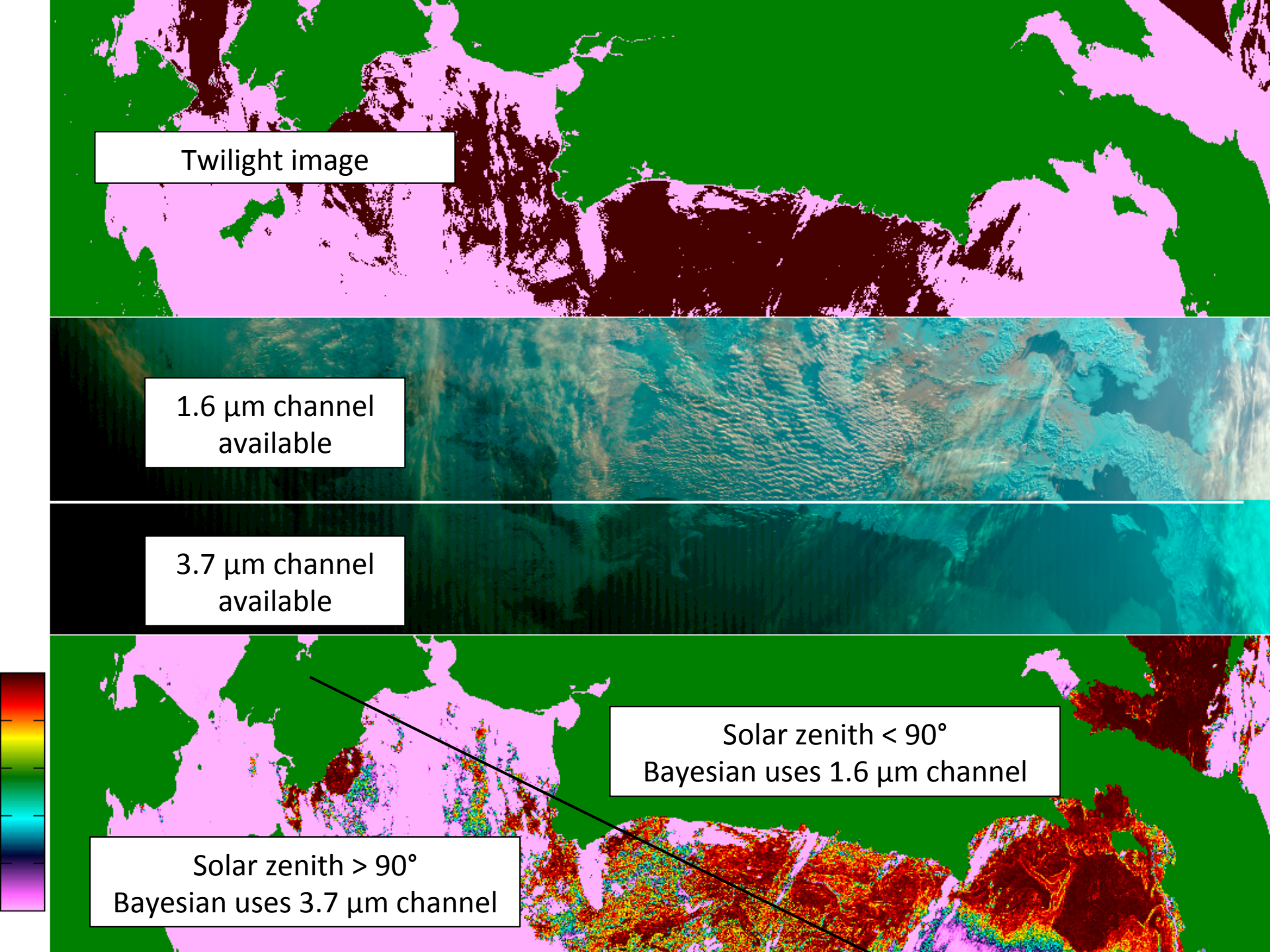
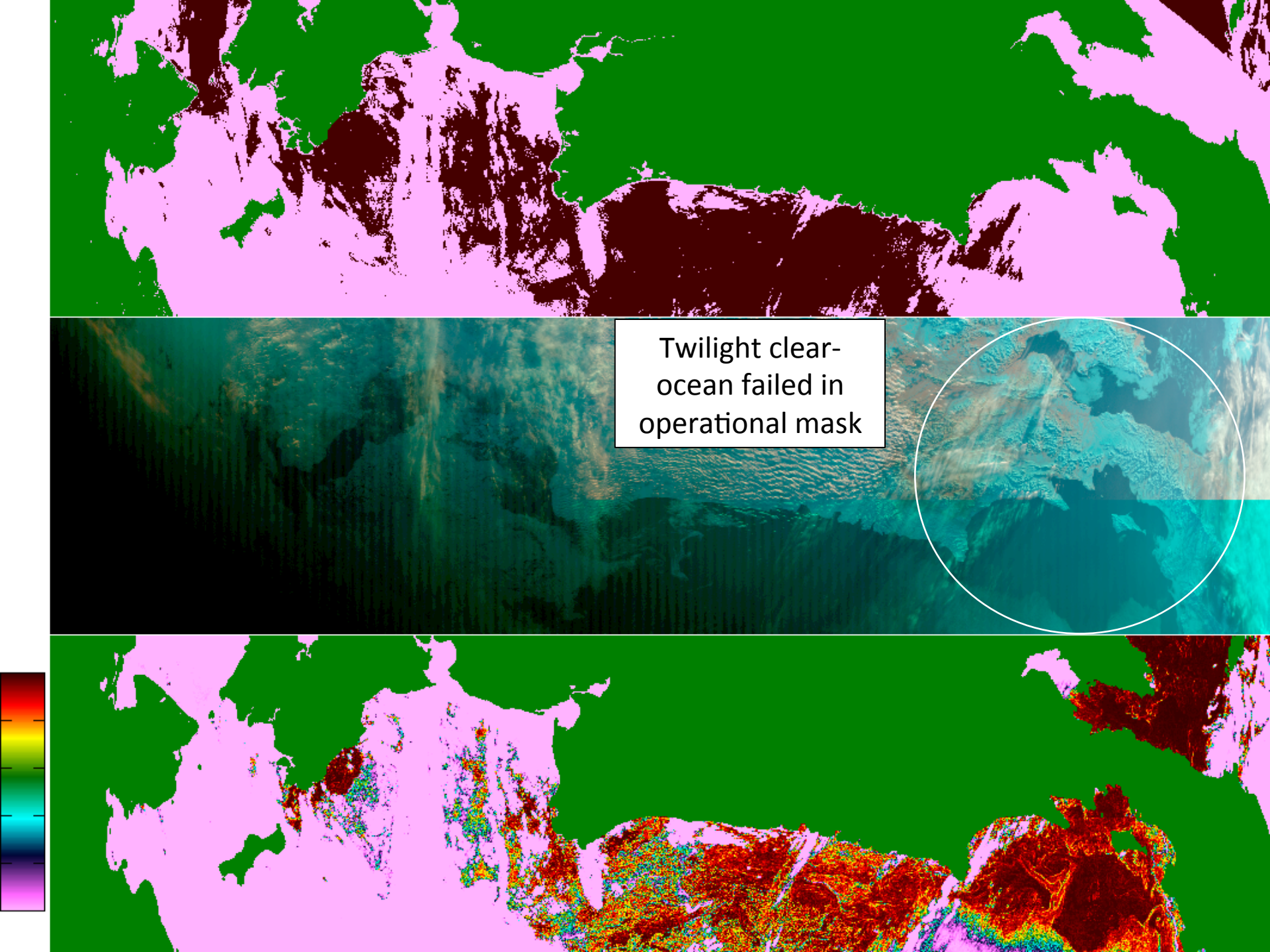
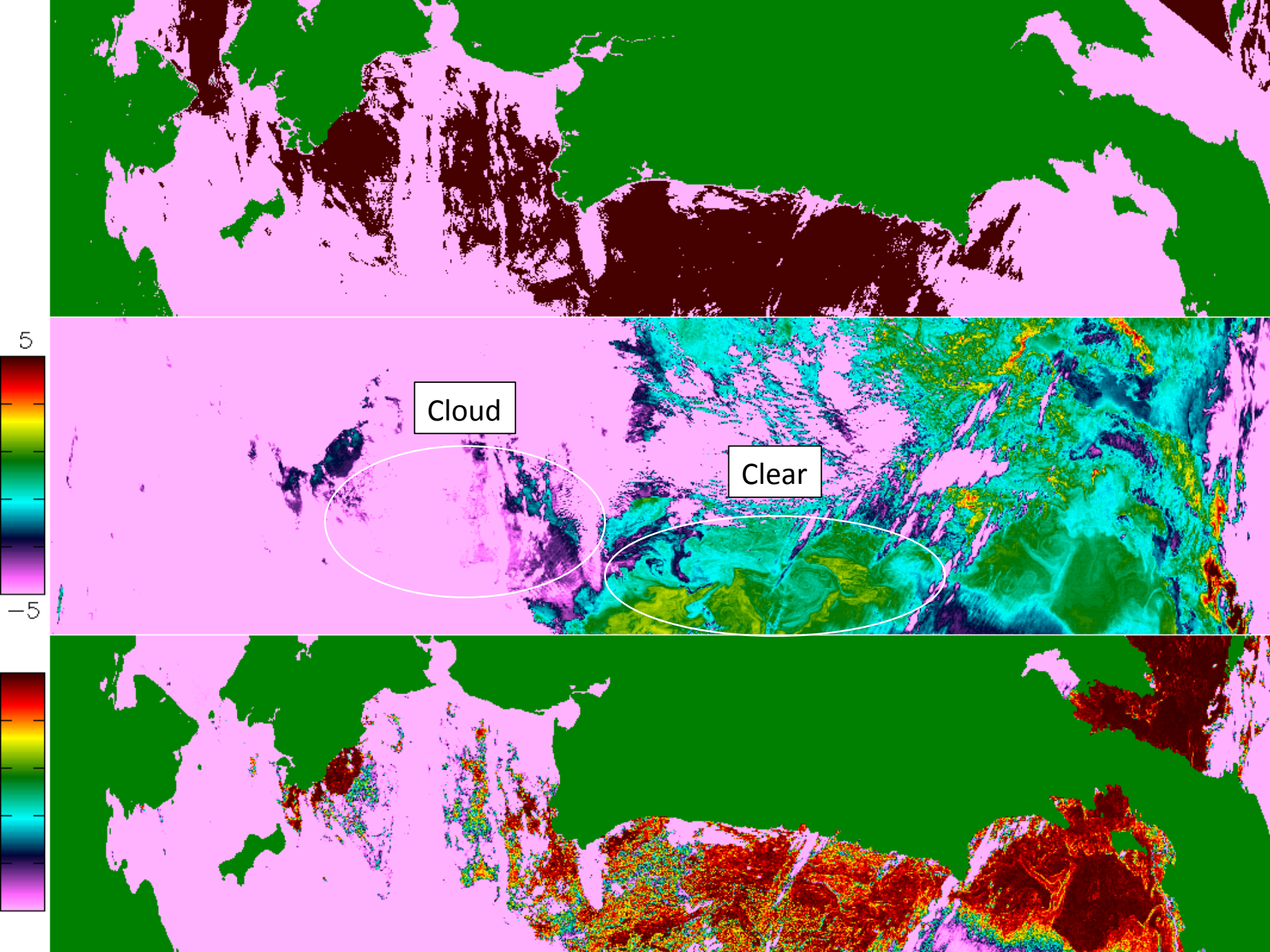

Bayesian detects
desert dust aerosol

# 2010-05-10 07:10:03

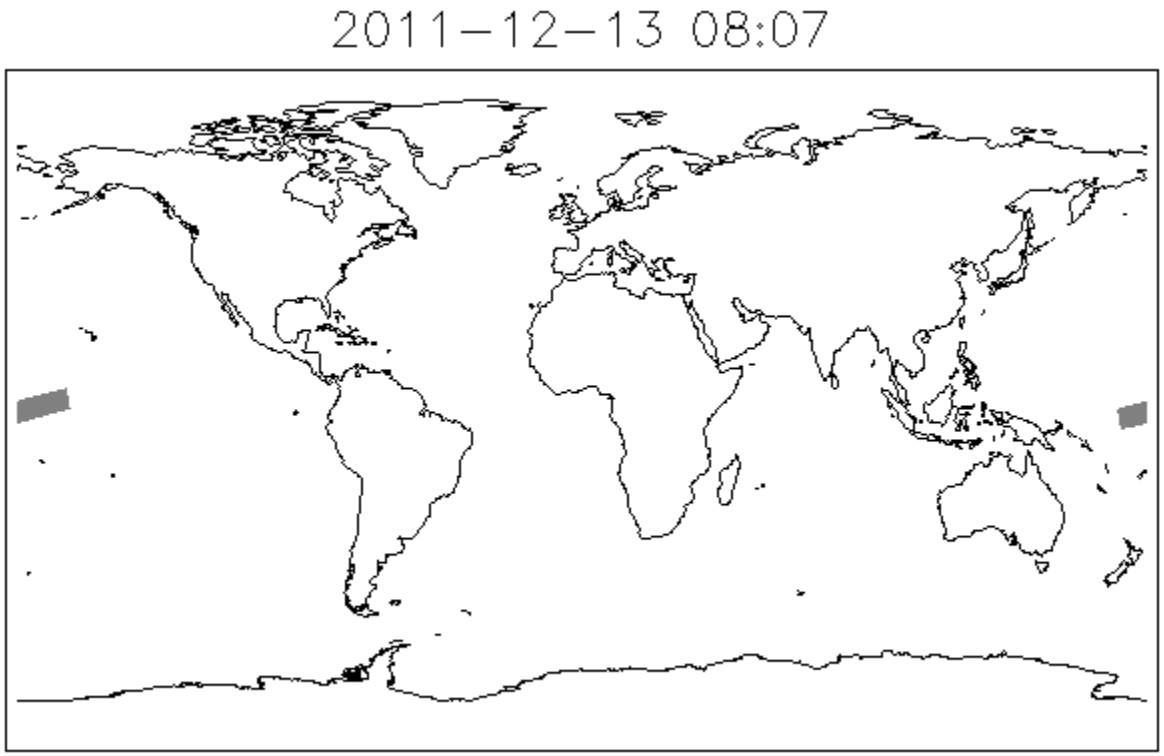


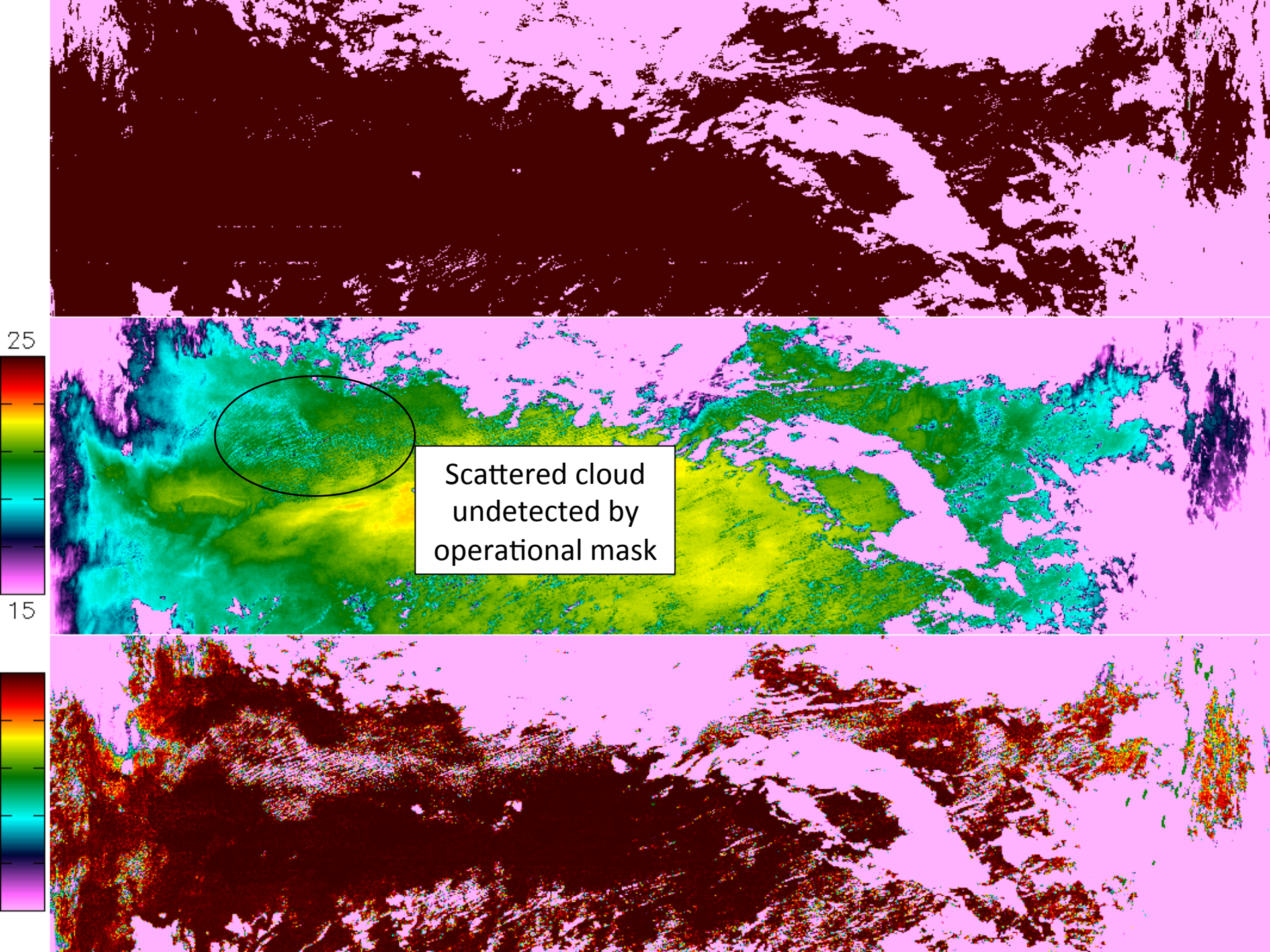

Twilight image
1.6 µm channel available
3.7 µm channel available
Solar zenith < 90°
Bayesian uses 1.6 µm channel
Solar zenith > 90°
Bayesian uses 3.7 µm channel


Twilight clear-ocean failed in operational mask


5
−5
Cloud
Clear

# 2011-12-13 08:07:03

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15
Scattered cloud undetected by operational mask

# Summary

- In most areas of disagreement, Bayesian mask appears more effective than operational mask
- Bayesian detects more:
  - Cloud edges
  - Thin / scattered cloud
  - Desert dust aerosol
- Bayesian can fail to detect:
  - Low-lying cloud
  - Current implementation does not use visible channels
    - Due to ARC heritage – needed consistency with ATSR-1
    - Tests with visible channels show a big improvement in day time cloud detection

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# Other Work (CCI Phase 2)

- Need Bayesian cloud screening for all AVHRRs
- Approach
  - Two reference look up tables
    - Dual-view based on AATSR
    - Single-view based on Metop AVHRR
    - (Geostationary based on SEVIRI)
  - Include visible channels
  - BT shifts for:
    - ATSR1/2 -> AATSR
    - AVHRRx -> Metop AVHRR
  - Investigate impact of GAC resolution
    - New / modified texture LUTs

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# Other Work (other)

- Cloud screening over lakes
  - ARC Lake and GloboLakes
- Cloud screening over land
  - GlobTemperature
- n-way classification (e.g. Clear, Cloud, Dust, Sea-ice..)
  - Conceptually easy – just add more PDF terms
  - Some small scale proof-of-concept tests:
    - Clear/Cloud/Dust – Mackie 2009 (PhD thesis)
    - Clear/Cloud/Sea Ice – Bulgin et al. 2014 (CCI Phase 1)
  - Requires quite a lot of code refactoring for practical use
- Forward modelling of cloudy PDF
  - Reduce use of LUTs
  - Difficult to get right
- Other texture measures

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# Questions?

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