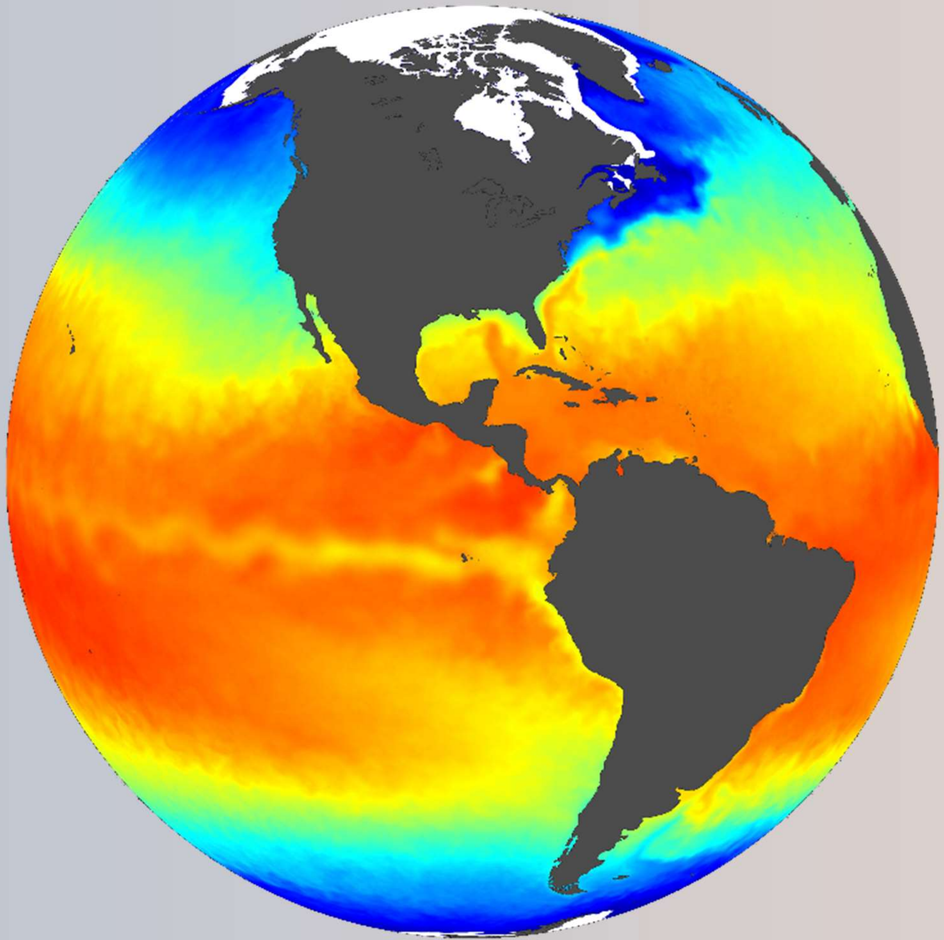


To provide operational users and the science community with the SST measured by the satellite constellation

Key SST retrieval concepts

Peter Minnett and

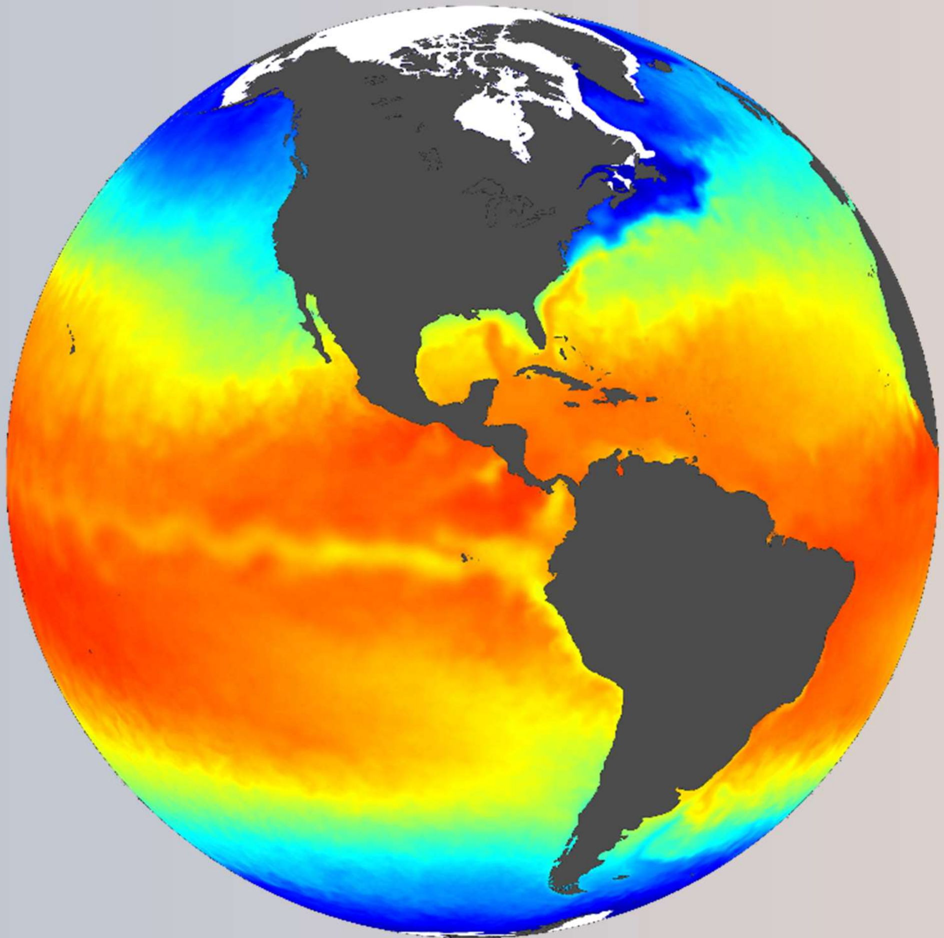
Chris Merchant

GHRSST

Group for High Resolution Sea Surface Temperature

CEOS

Committee on Earth Observation Satellites
Sea Surface Temperature Virtual Constellation



To provide operational users and the science community with the SST measured by the satellite constellation

Cloud screening (in brief)

Peter Minnett

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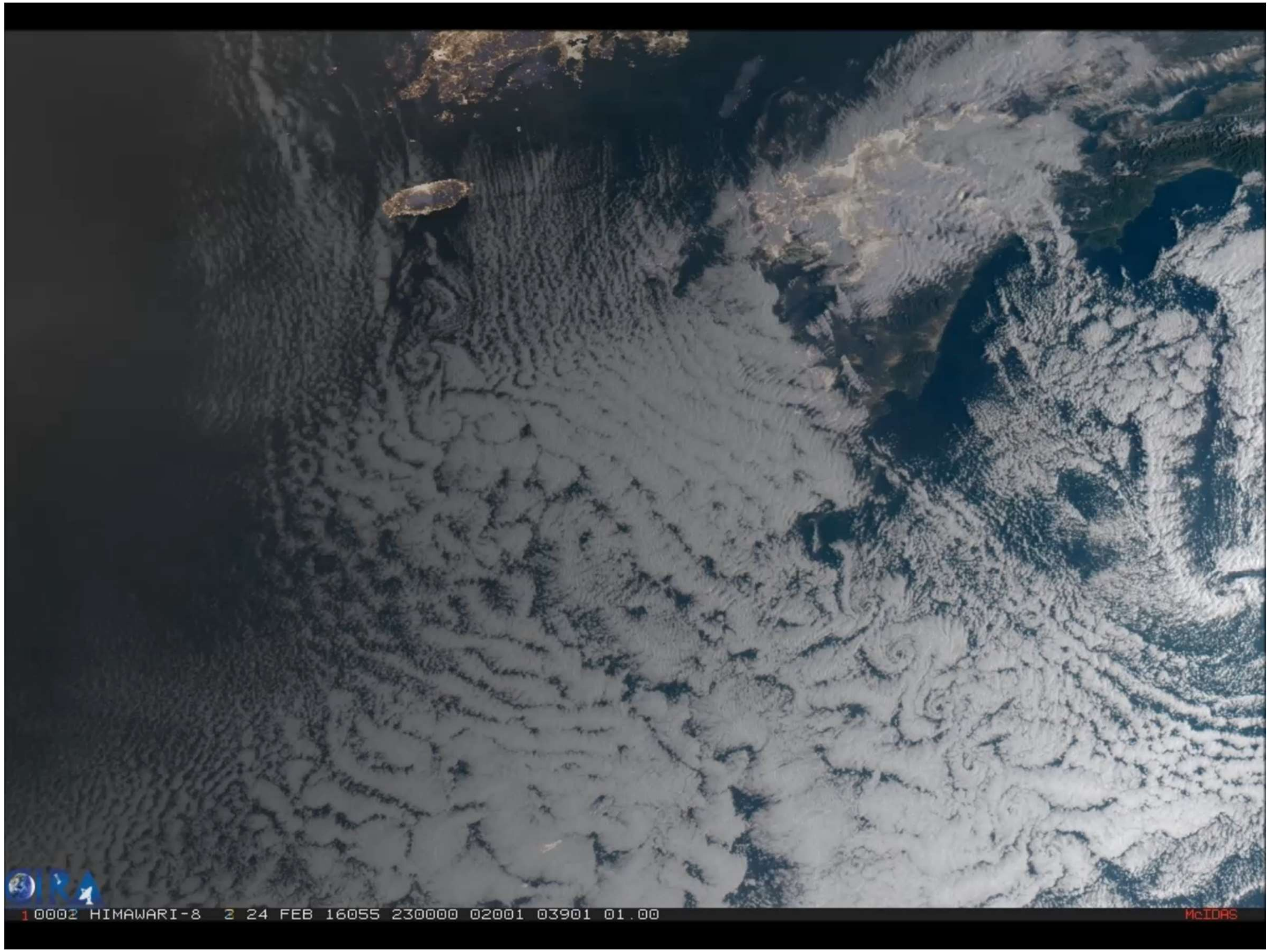
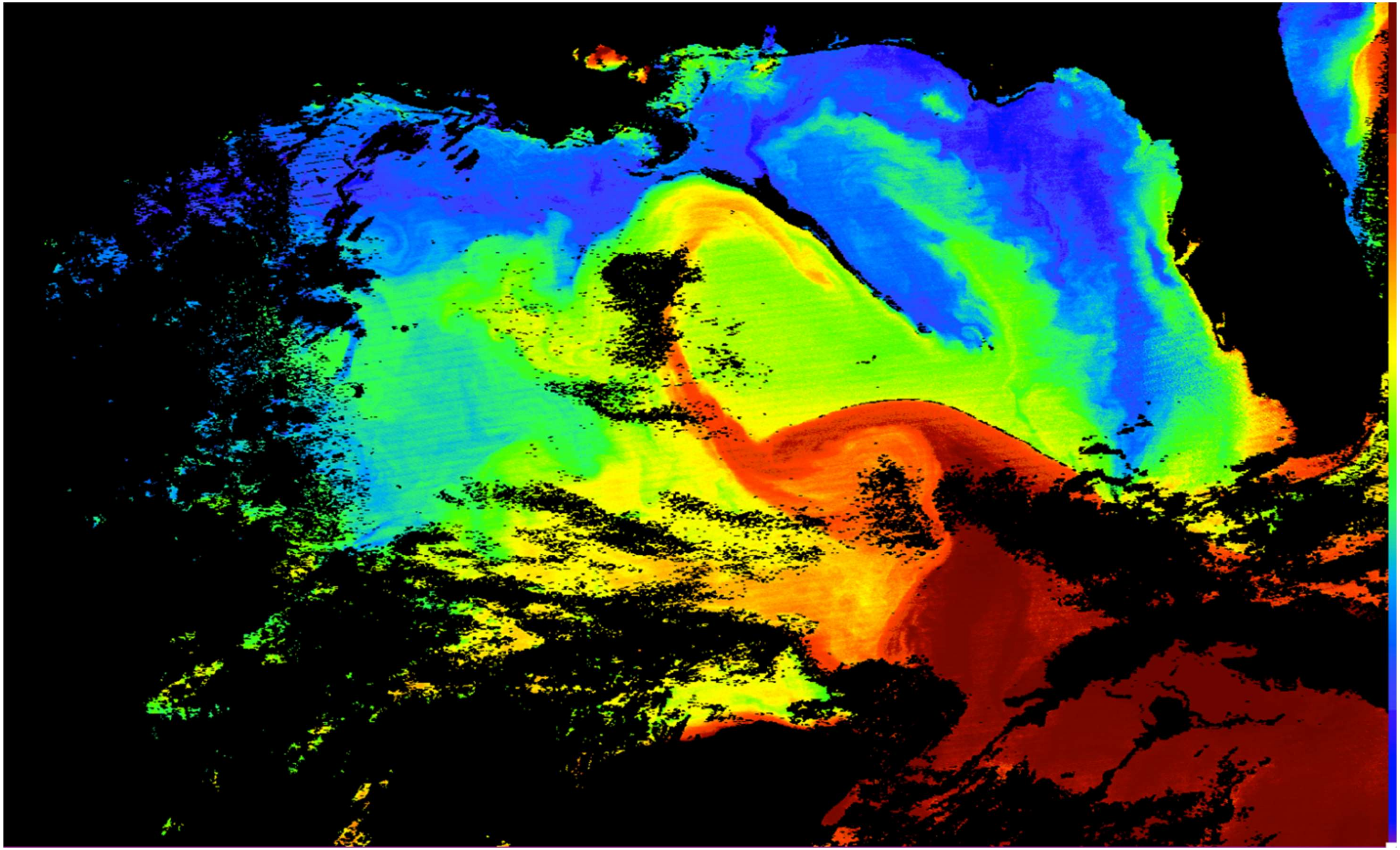
CEOS Committee on Earth Observation Satellites Sea Surface Temperature Virtual Constellation

Clouds from space

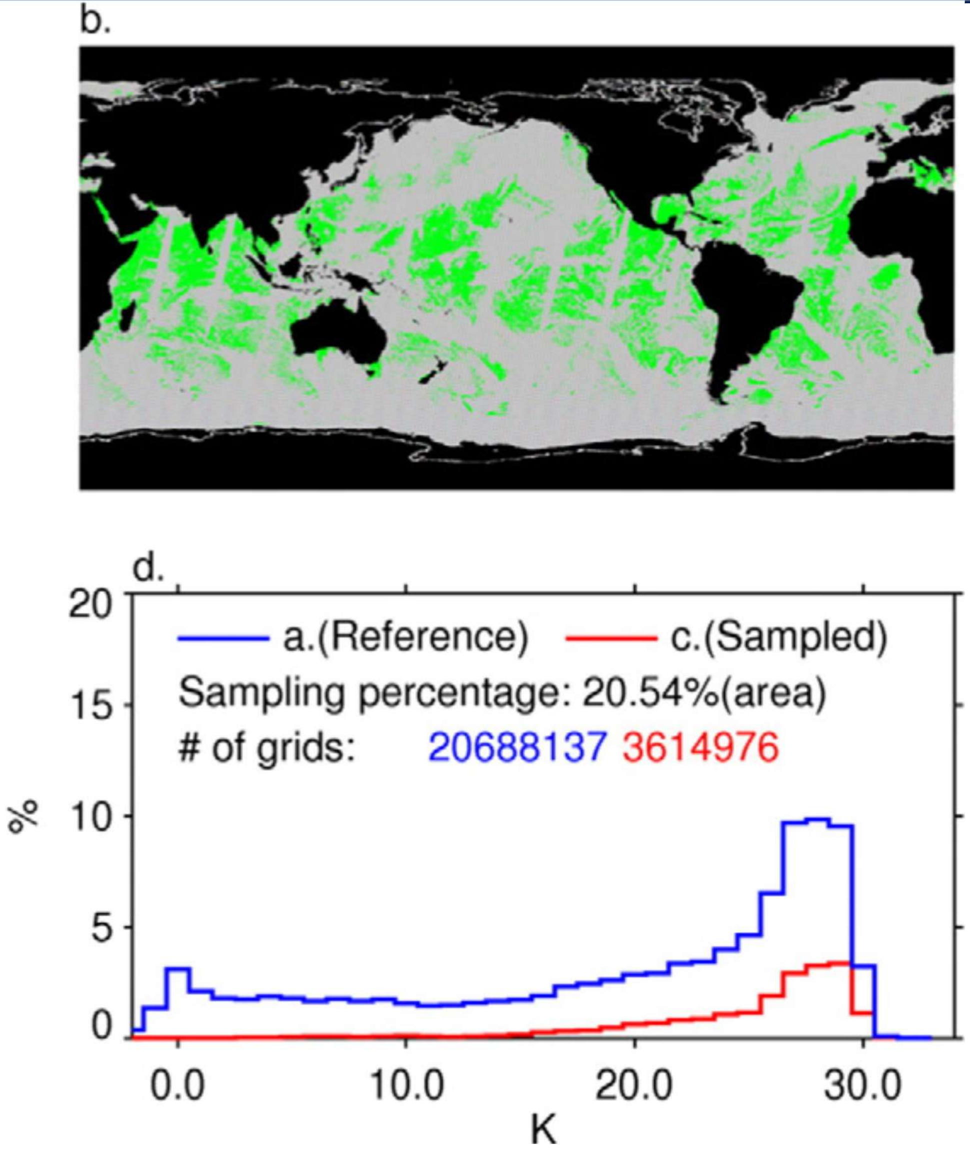


Clouds in the visible spectrum - day

Clouds in the infrared spectrum

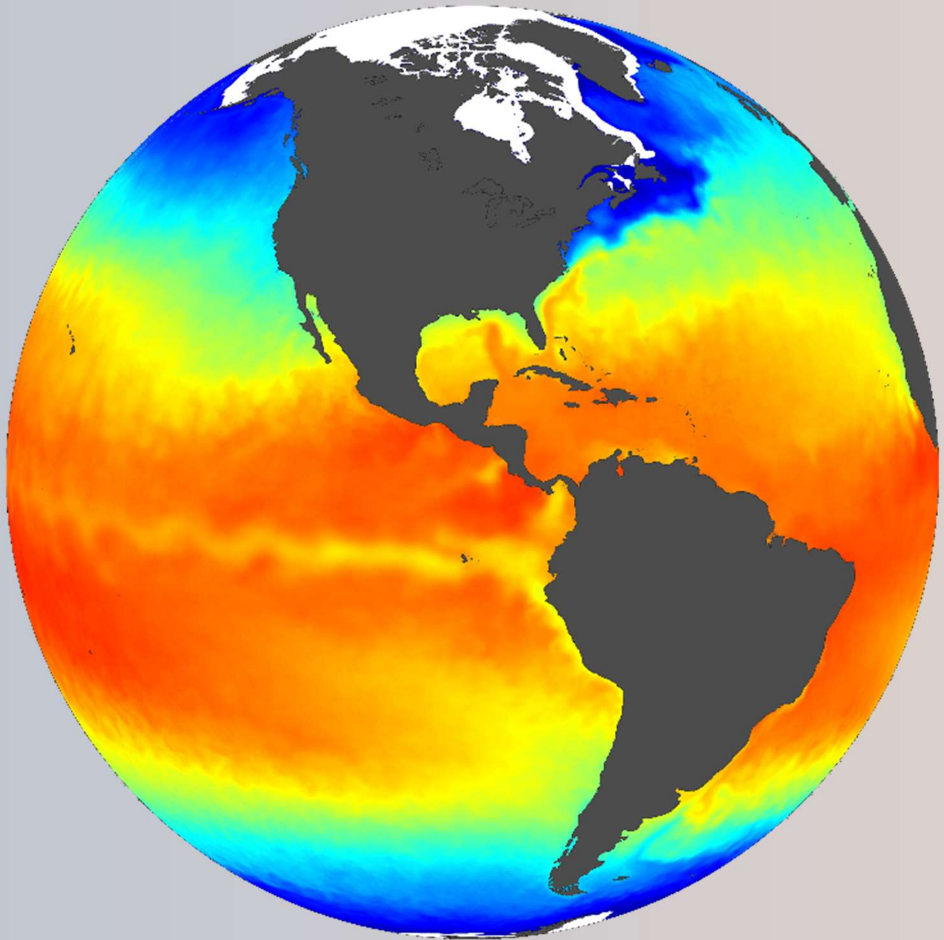


Clouds in the infrared spectrum



Cloud Screening for SST

- Infrared radiation from the sea surface does not propagate through clouds – similar to visible radiation
- Tests should be on a pixel-by-pixel basis.
- Spectral information is be a powerful means for cloud screening.
- Two approaches:
    - Decision trees
    - Bayesian algorithms



Multi-channel atmospheric correction algorithms

Peter Minnett

To provide operational users and the science community with the SST measured by the satellite constellation

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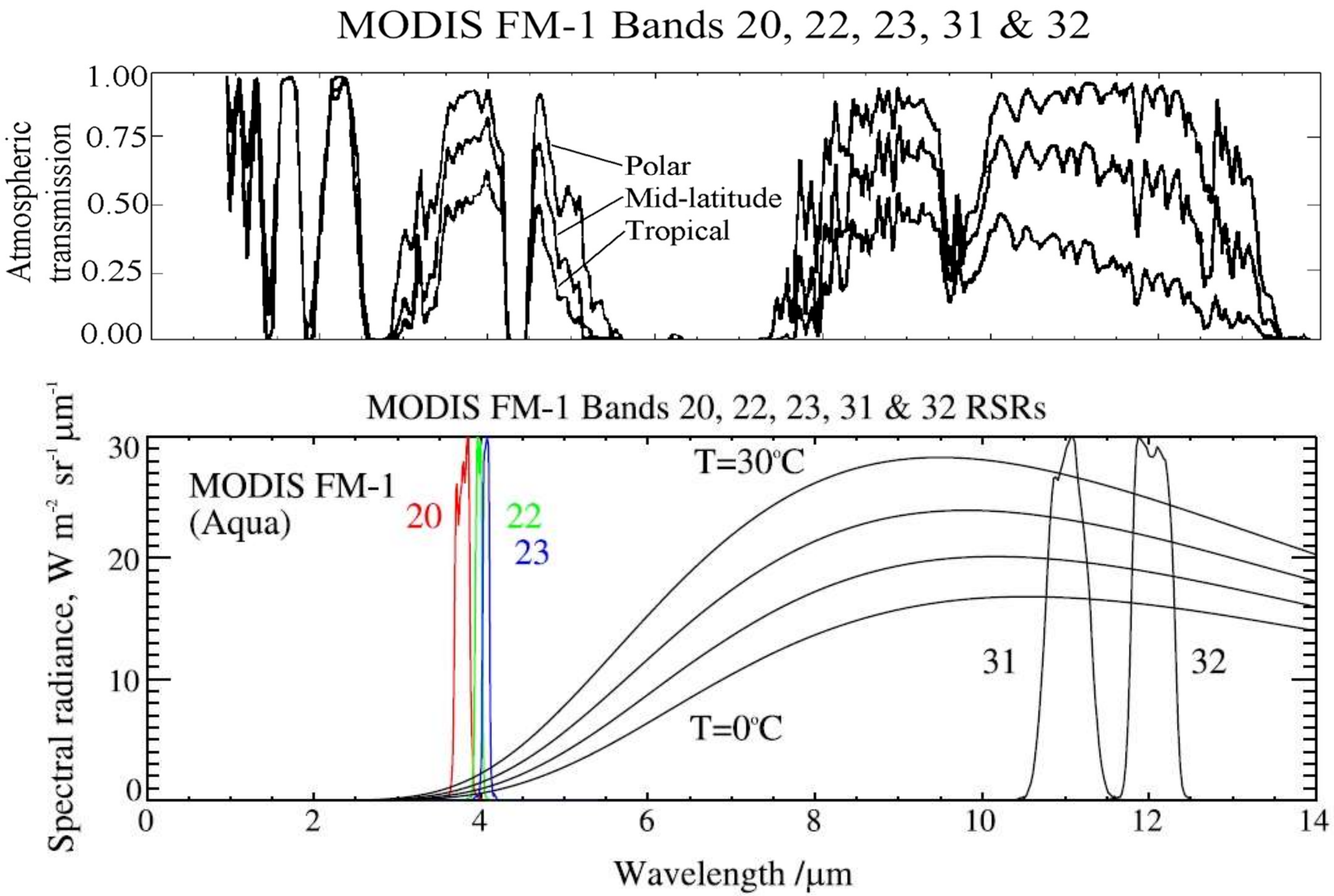
Accurate SSTs

- The accuracy target for satellite-derived SST for climate change research is ±0.1K and a decadal stability of better than 0.04K
- It is possible to build self-calibrating infrared radiometers that can meet these target on orbit*.
- But the accuracy of the derived SST is limited by how well the effects of the intervening atmosphere can be corrected.
- Once the satellite data have been successfully screened for the presence of clouds, the effects of the intervening clear atmosphere have to be corrected.

Minnett, P. J., and D. L. Smith (2014), Postlaunch Calibration and Stability: Thermal Infrared Satellite Radiometers, in *Experimental Methods in the Physical Sciences, Vol 47, Optical Radiometry for Ocean Climate Measurements*, edited by G. Zibordi, C. J. Donlon and A. C. Parr, pp. 201-243, Academic Press, doi:http://dx.doi.org/10.1016/B978-0-12-417011-7.00008-8

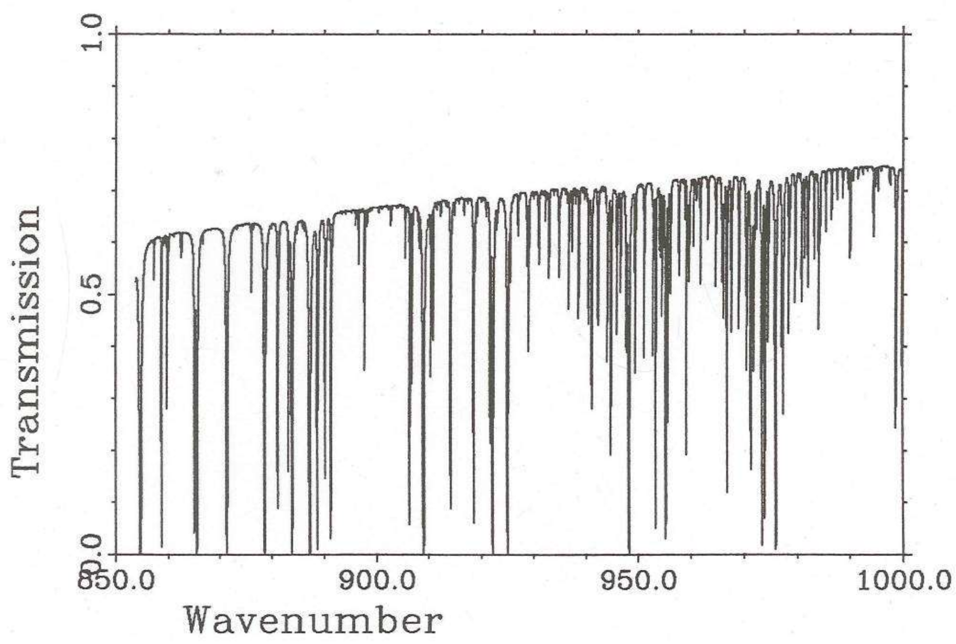
Atmospheric transmissivity in the infrared



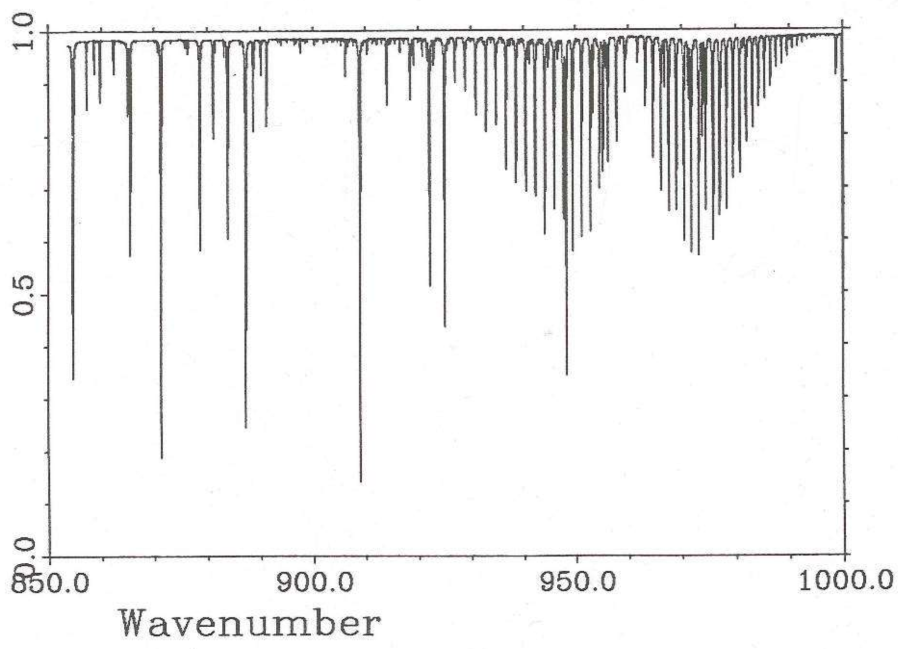
Spectral dependence of the atmospheric transmission for wavelengths of electro-magnetic radiation from about 1 to 14 µm, for three characteristic atmospheres (above), and (below) the black-body emission for temperatures of 0, 10, 20 and 30°C, and the relative spectral response functions of the bands MODIS (Flight Model 1) on *Aqua* used to derive SST.

Atmospheric Transmissivity

Moist summer mid-latitude atmosphere

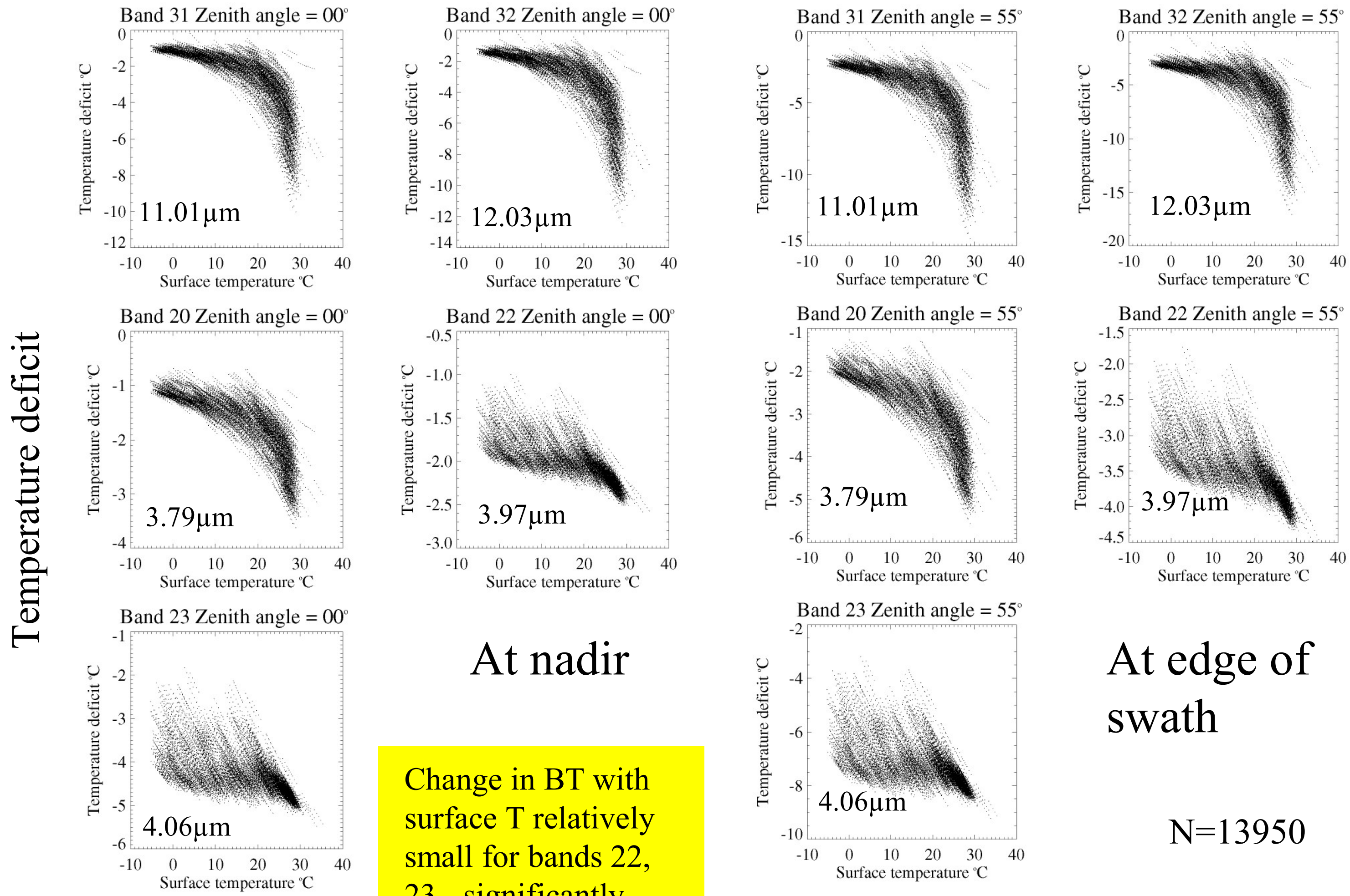


Dry winter atmosphere



Transmission spectra calculated for a moist summer mid-latitude atmosphere, and a very dry winter atmosphere.

Predicted MODIS brightness temperatures at satellite height



Change in BT with surface T relatively small for bands 22, 23 - significantly larger for bands 20, 31, 32

Surface temperature range, -10 to 40°C

Multichannel atmospheric correction

- We use the hypothesis that the difference in the brightness temperatures measured in two spectral channels, *i* and *j*, is related to the temperature deficit in one of them.
- The atmospheric correction algorithm for SST retrieval can be formulated:

$$SST - T_i = f\,(T_i - T_j)$$

- where SST is the derived SST, and T_i and T_j the brightness temperatures in channels *i* and *j*.

Linearize Planck Function and Radiative Transfer

- By assuming that the atmospheric attenuation is small in these channels, the radiative transfer can be linearized.
- If the channels are spectrally close Planck's function can also be linearized.
- The algorithm can then be expressed in the very simple form:

$$SST = a_0 + a_i T_i + a_j T_j$$

where a_0, a_i and a_j are coefficients determined by regression analysis either of coincident satellite and in situ measurements, such as from drifting buoys, or of simulated satellite measurements derived by radiative transfer modeling of the propagation of the infrared radiation from the sea surface through a representative set of atmospheric profiles.

MODIS SST atmospheric correction algorithms

The form of the daytime and night-time algorithm for MODIS measurements in the long wave atmospheric window is:

$$SST = c_1 + c_2 * T_{11} + c_3 * (T_{11}-T_{12}) * T_{sfc} + c_4 * (\sec(\theta)-1) * (T_{11}-T_{12})$$

where T_n are brightness temperatures measured in the channels at n μm wavelength, T_{sfc} is a 'climatological' estimate of the SST in the area, and θ is the satellite zenith angle. This is based on the Non-Linear SST algorithm.

[Walton, C. C., W. G. Pichel, J. F. Sapper and D. A. May (1998). "The development and operational application of nonlinear algorithms for the measurement of sea surface temperatures with the NOAA polar-orbiting environmental satellites." Journal of Geophysical Research **103** 27,999-28,012.]

The MODIS night-time algorithm, using two bands in the 4μm atmospheric window is:

$$SST4 = c_1 + c_2 * T_{3.9} + c_3 * (T_{3.9}-T_{4.0}) + c_4 * (\sec(\theta)-1)$$

Note, the coefficients in each expression are different. They can be derived in three ways:

- empirically by regression against SST values derived from another validated satellite instrument
- empirically by regression against SST values derived surface measurements from ships and buoys
- theoretically by numerical simulations of the infrared radiative transfer through the atmosphere.

Emissivity effects

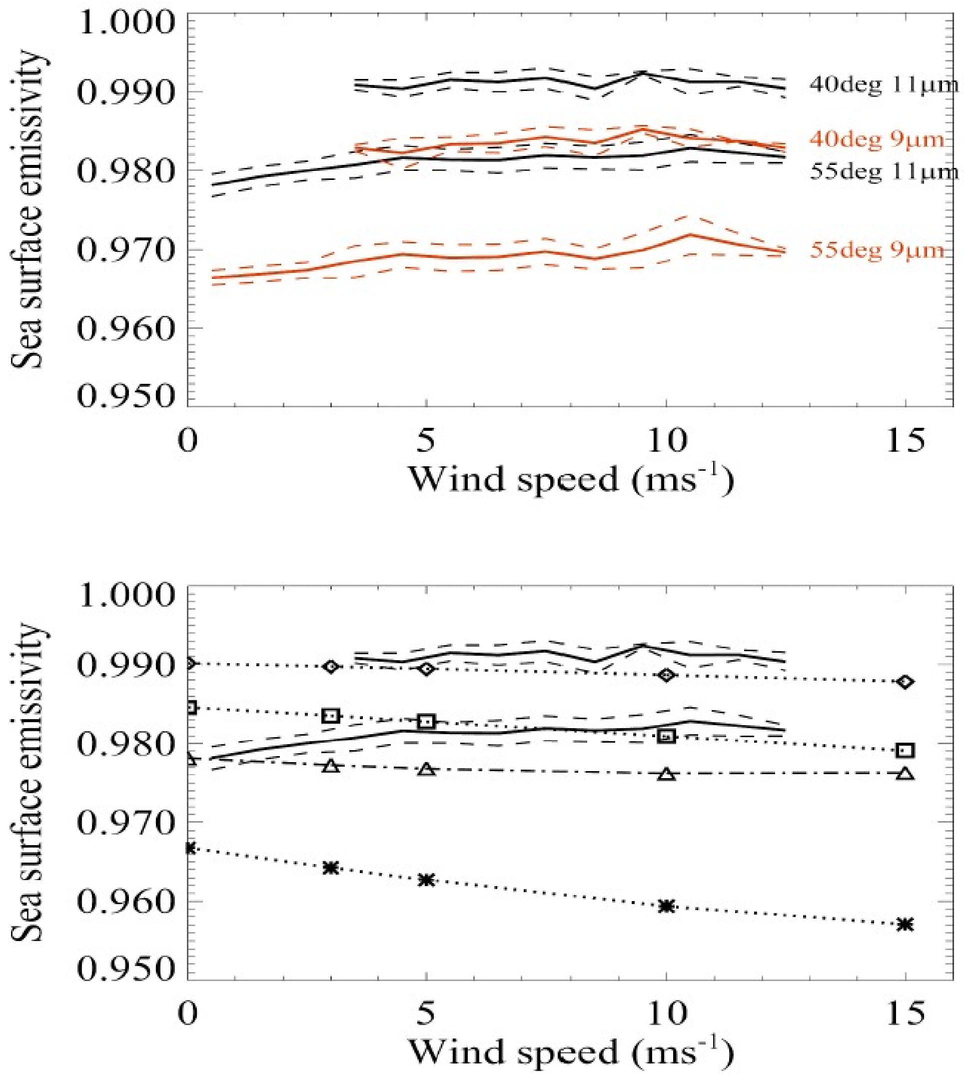
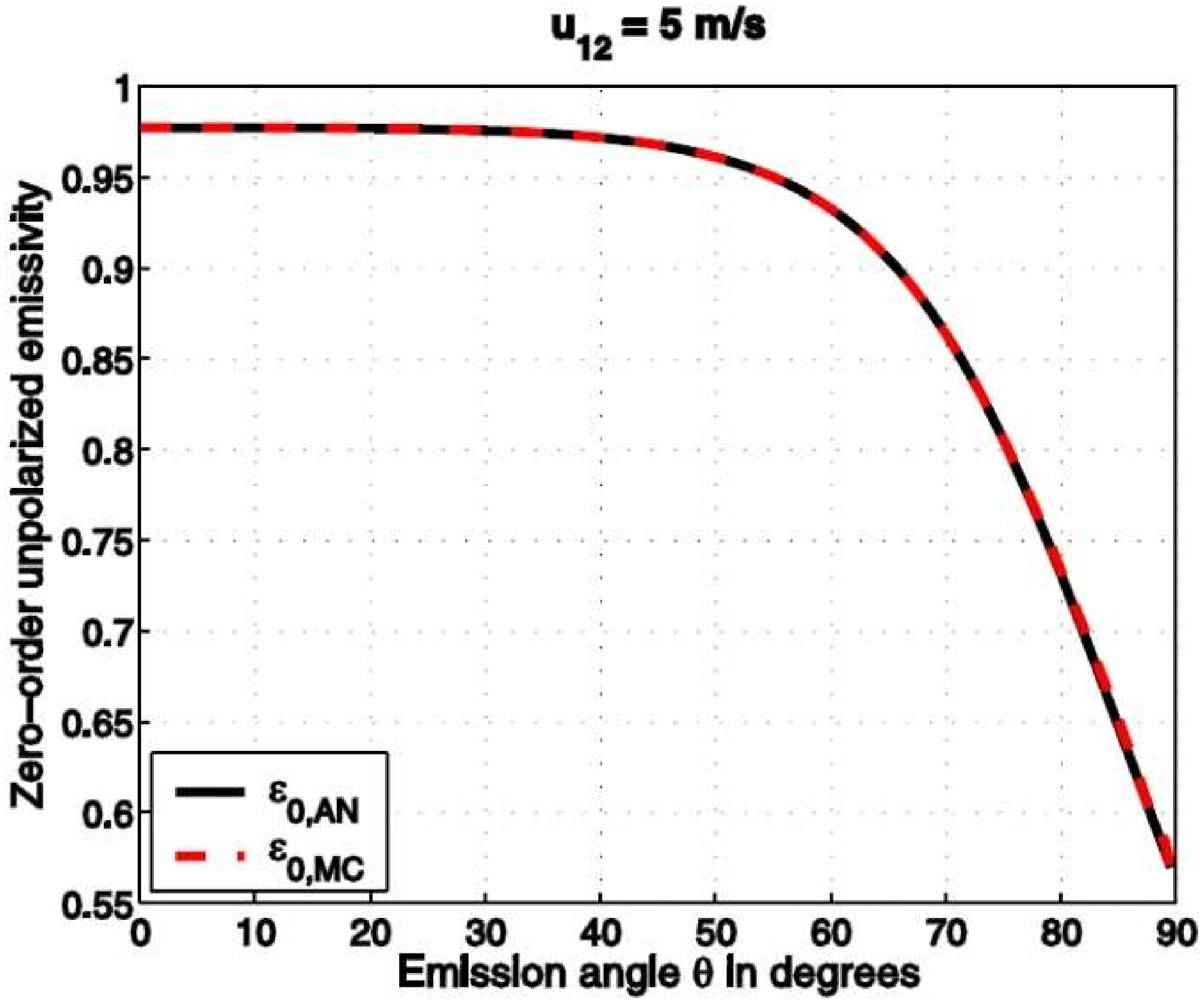


Figure 6. Observed mean (solid lines) and standard deviation (dashed lines) of sea surface emissivity in 1ms^{-1} wind speed bins for 9μm and 11μm at 40° and 55° incidence angles (top). Below, the solid lines are the measured 11μm emissivity for the 40° and 55° views, the dashed line with triangular markers represents values predicted by *[Watts et al., 1996]* for 55° at 11μm (the coefficients given in that paper are valid for 52°-55° viewing angle). The dotted lines are those predicted by *[Masuda et al., 1988]* for 40° (diamonds), 50° (squares) and 60° (asterisks). From: J.A. Hanafin, Ph.D. Thesis, University of Miami, 2002.

Emission angle dependence



Sea surface emissivities computed from an analytical approach (AN) and a Monte Carlo ray-tracing method (MC) versus the emission angle.

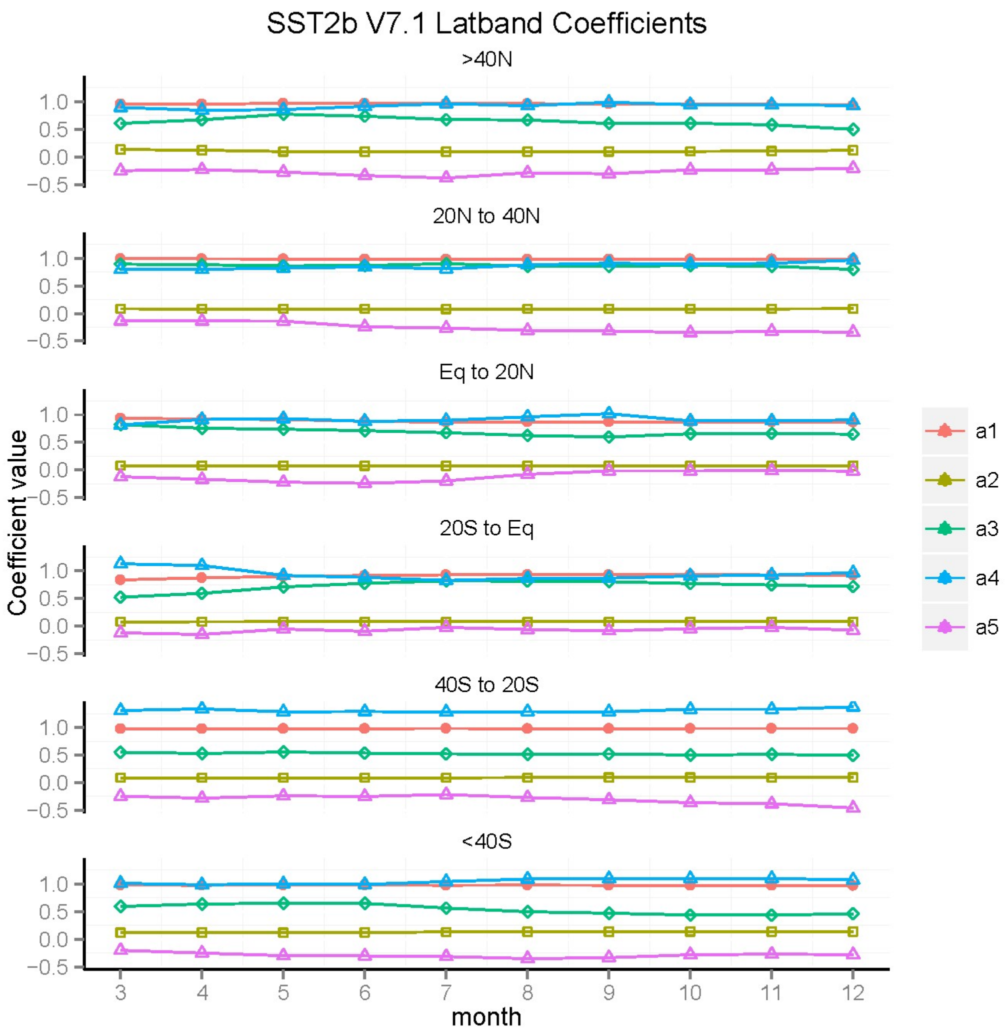
Wind u_{12} = 5 ms^{-1}; λ = 4 µm.

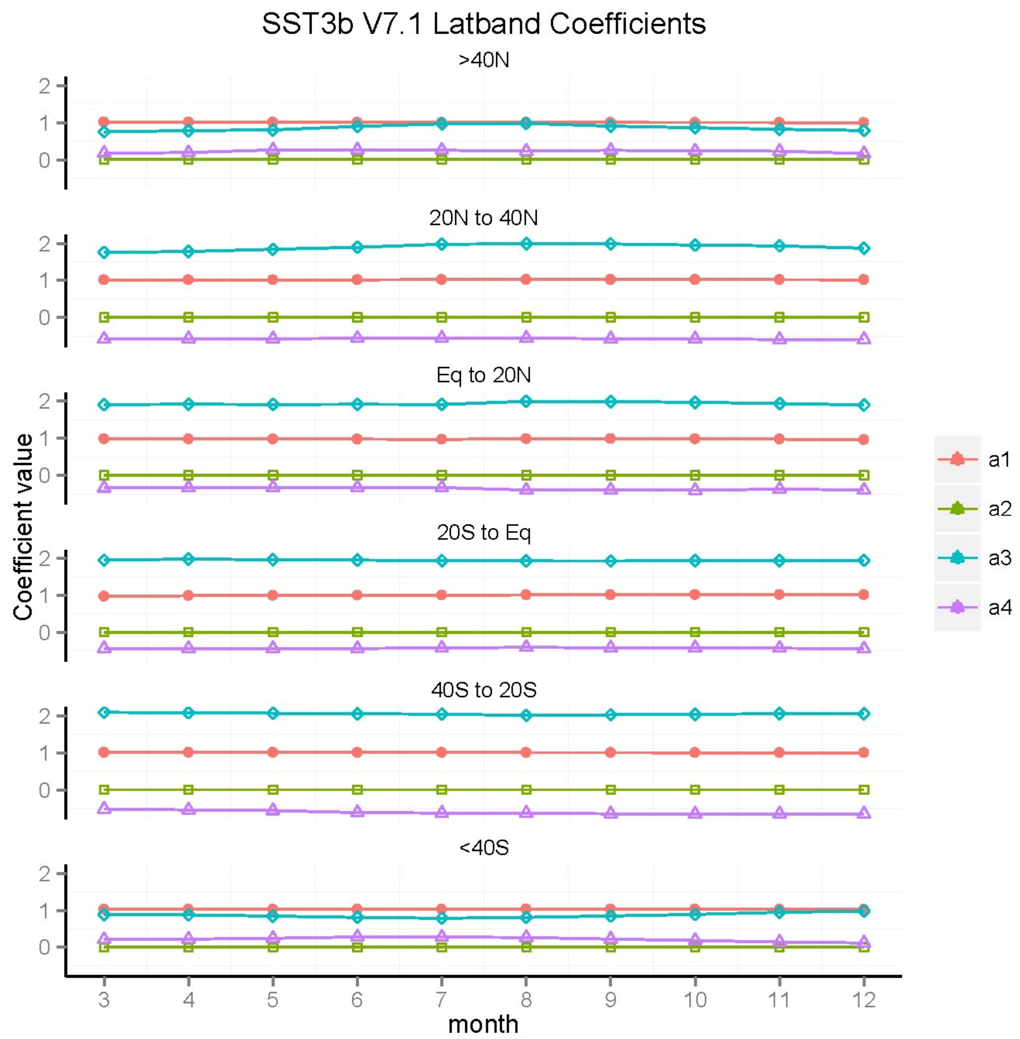
Bourlier, C. (2006), Unpolarized emissivity with shadow and multiple reflections from random rough surfaces with the geometric optics approximation: application to Gaussian sea surfaces in the infrared band, *Appl. Opt.*, *45*(24), 6241-6254.

Empirical improvements

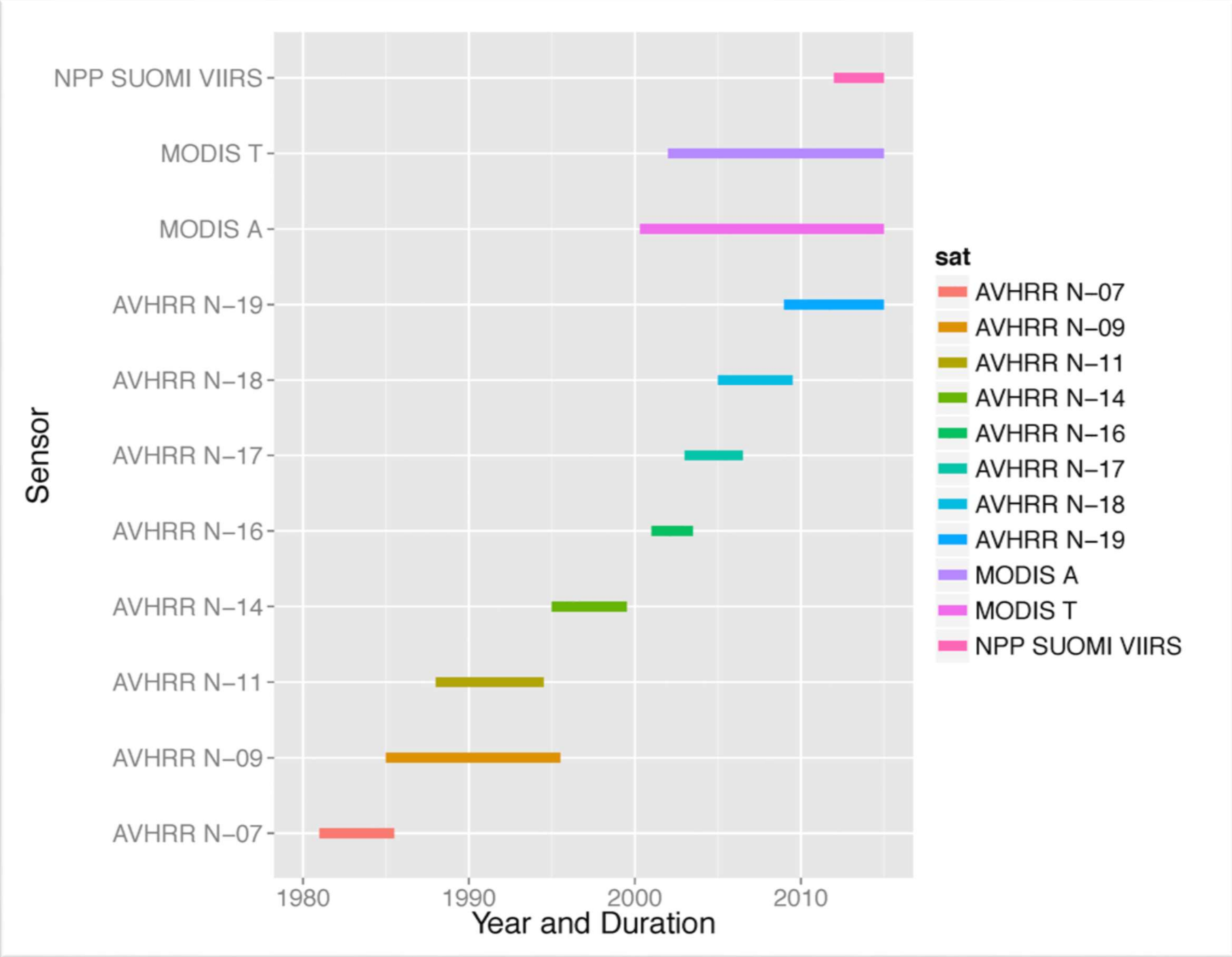
- Seasonal changes in the atmosphere can be accounted for by having monthly sets of coefficients.
- Regional changes in the atmosphere can be accounted for by having sets of coefficients in zones.

VIIRS Coefficients

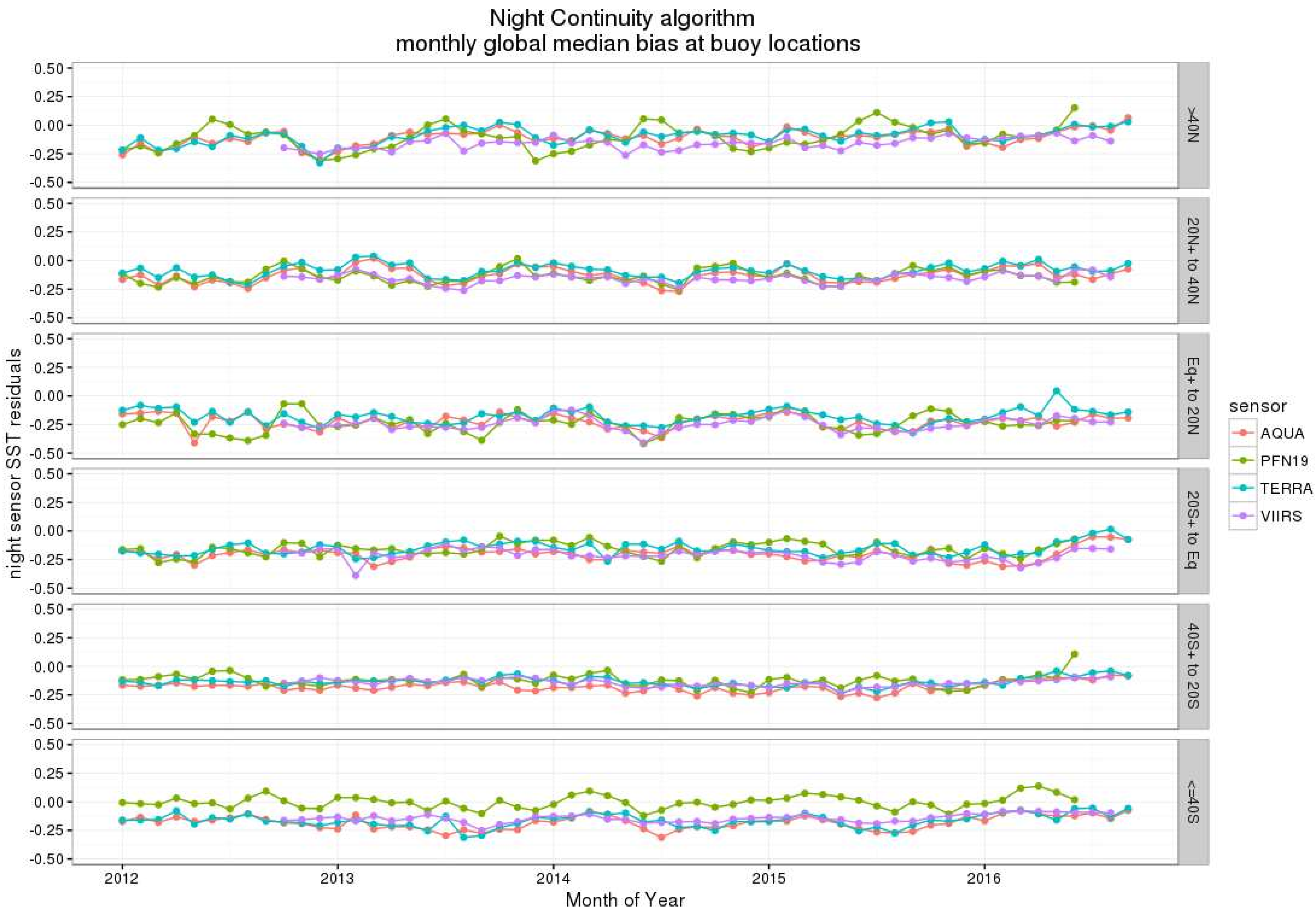




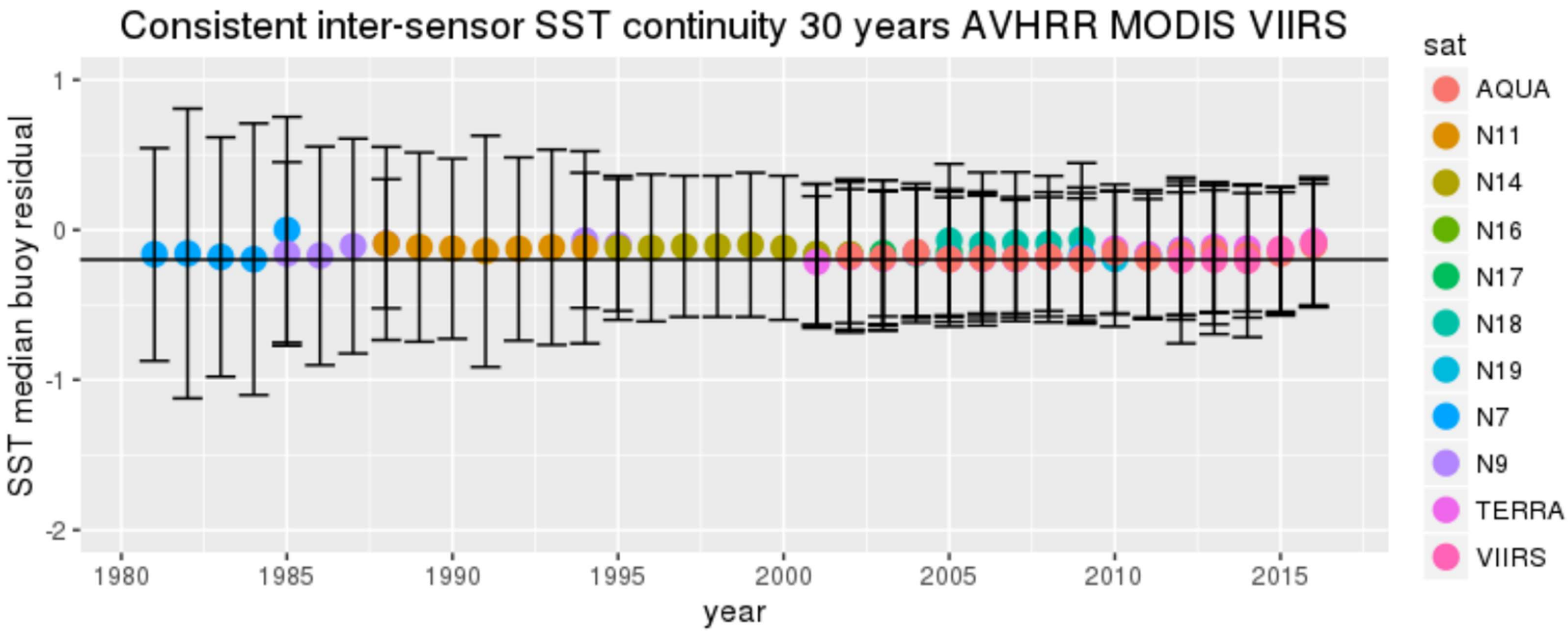
Benefits of continuity algorithms



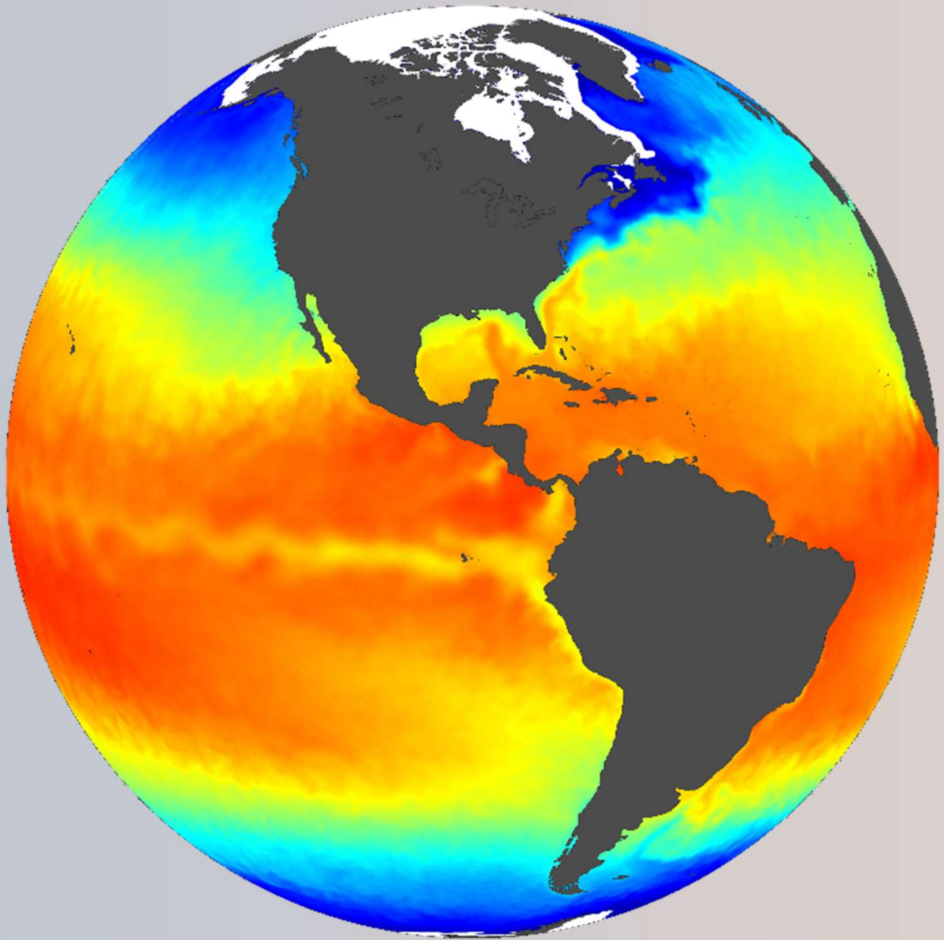
Monthly median bias errors – recent sensors



Monthly median bias errors – recent sensors



Annual median and robust standard deviation for 35 years of satellite IR SSTs. offset of the black horizontal line wrt zero is the canonical value of the cool skin effect (-0.17K) as the satellite SSTs are skin SSTs, whereas the buoy measurements are subsurface.



To provide operational users and the science community with the SST measured by the satellite constellation

SST retrieval using radiative transfer simulations

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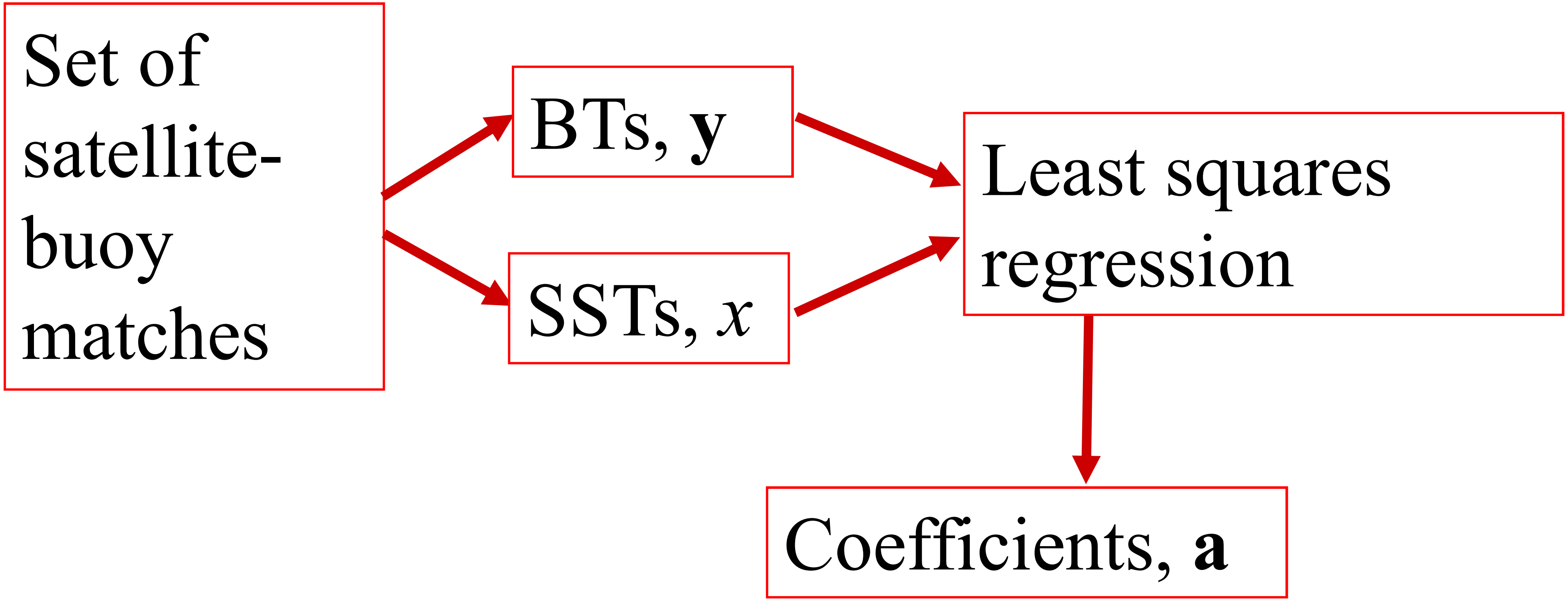
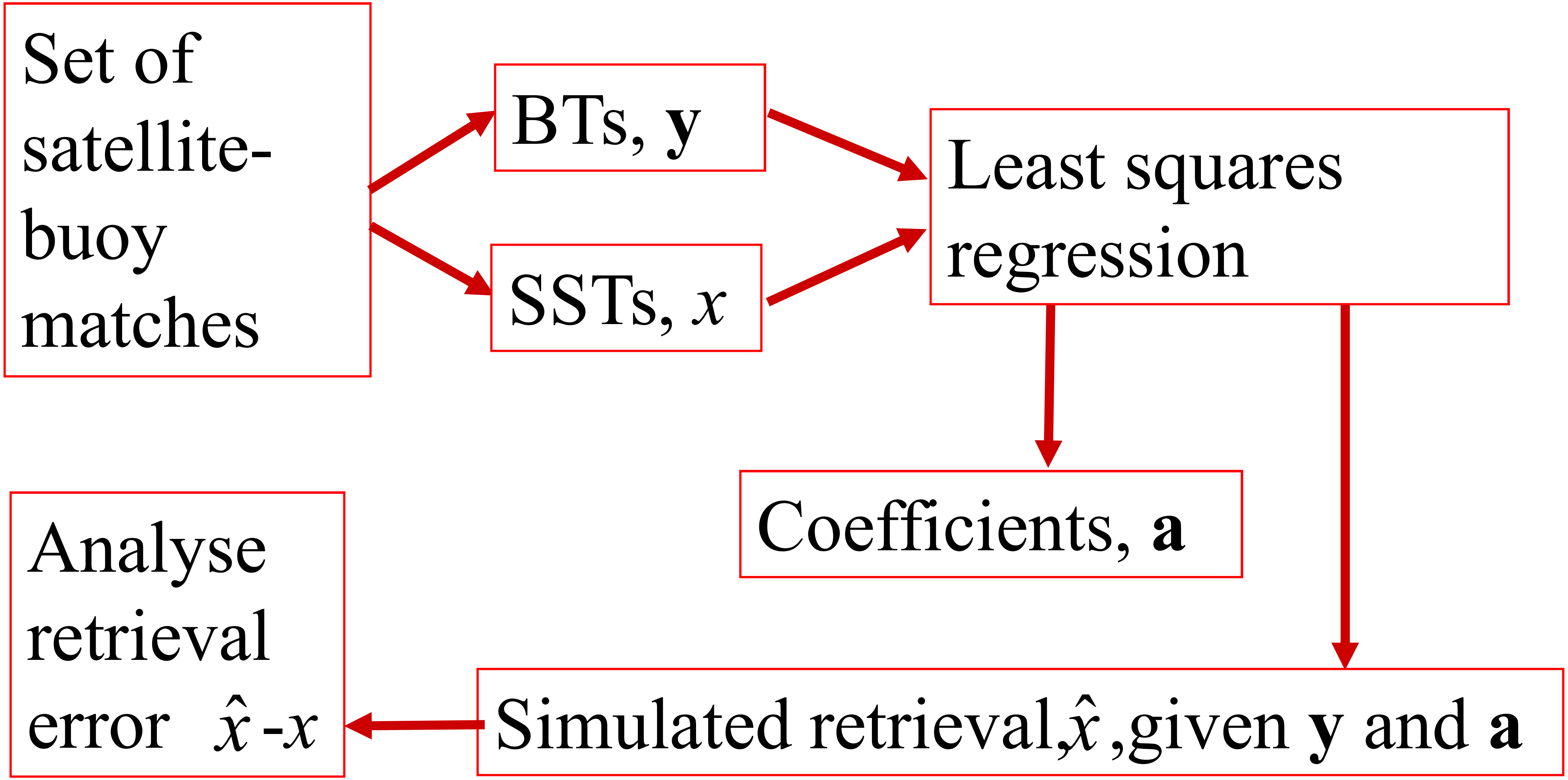
Questions addressed in this part

- What can radiative transfer modelling tell us about SST retrieval?
    - Preview of answer: apparently simple retrieval methods have surprising limitations
- Can radiative transfer modelling help us make better SST retrievals?
    - Preview of answer: yes, at least sometimes

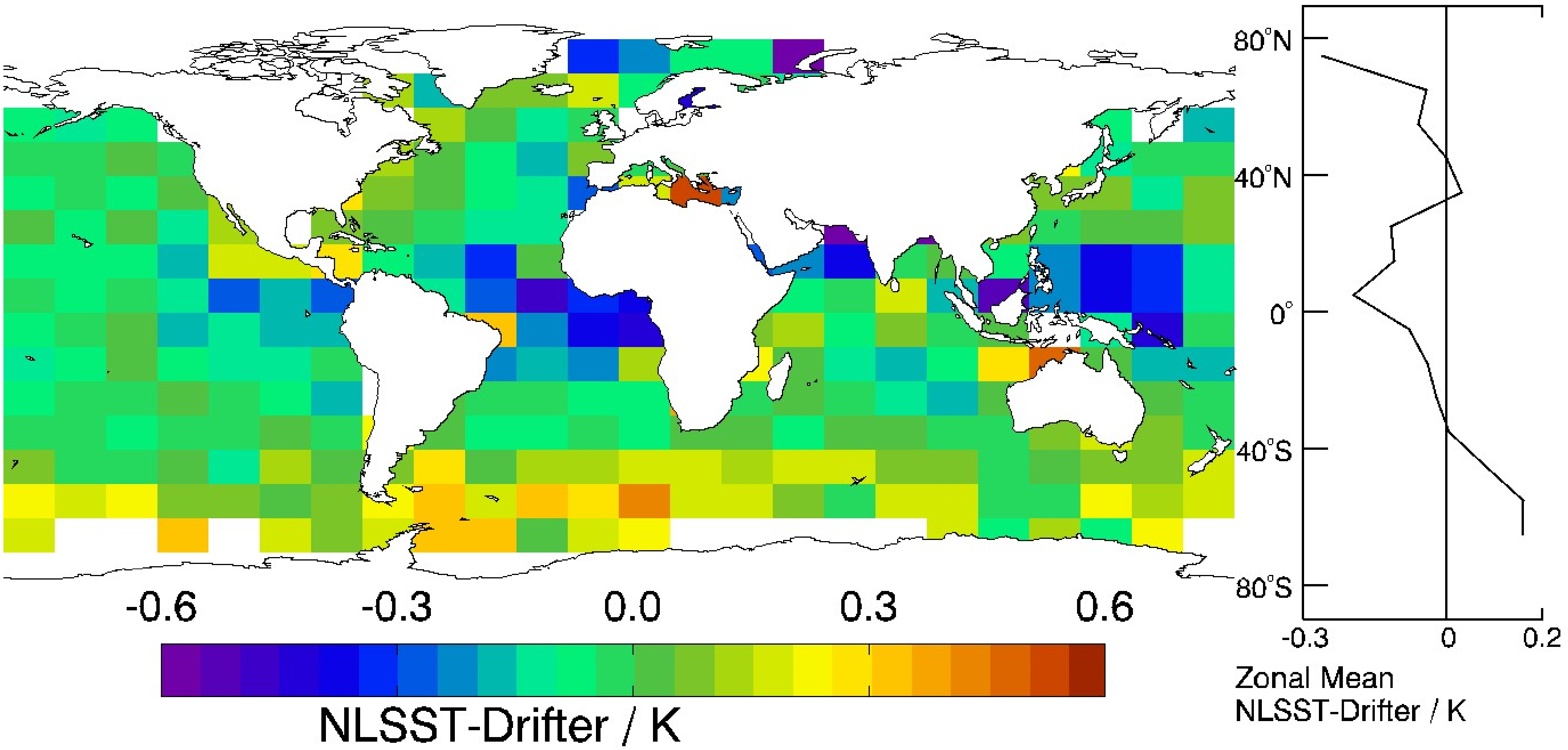
Recap: empirical retrieval coefficients



With RTM, this process can be simulated for a ‘perfect data’ study



Regional annual biases



Local (mis)behaviour

Algorithm

$$\hat{x} = a_0 + a_1 y_{11} + \left(a_2 S + a_3 x_b\right)\left(y_{11} - y_{12}\right)$$

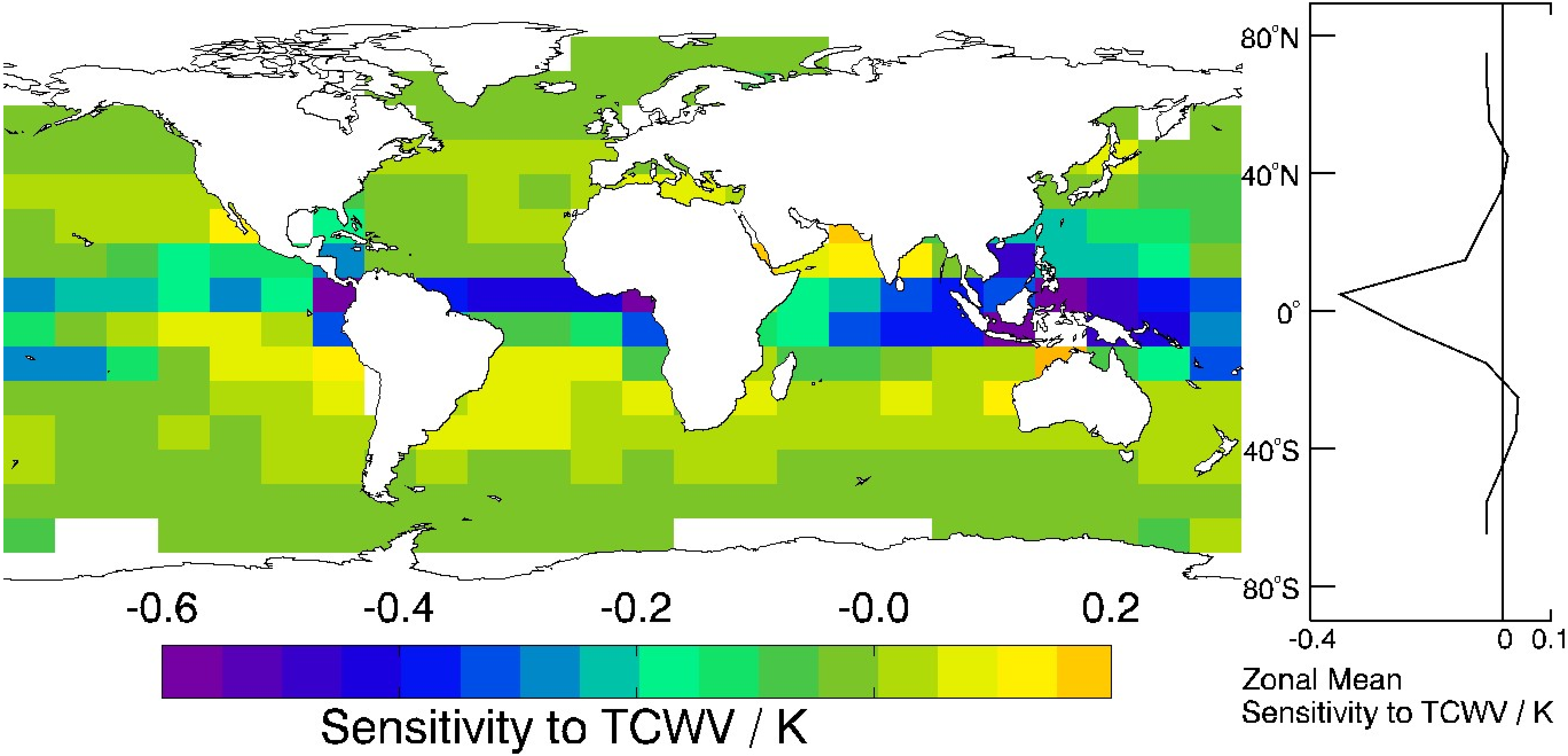
Sensitivity to water vapour, w

$$\frac{\partial \hat{x}}{\partial w} = \left(a_1 + a_2 S + a_3 x_b\right)\frac{\partial y_{11}}{\partial w} + \left(-a_2 S - a_3 x_b\right)\frac{\partial y_{12}}{\partial w}$$

Sensitivity to true SST, x

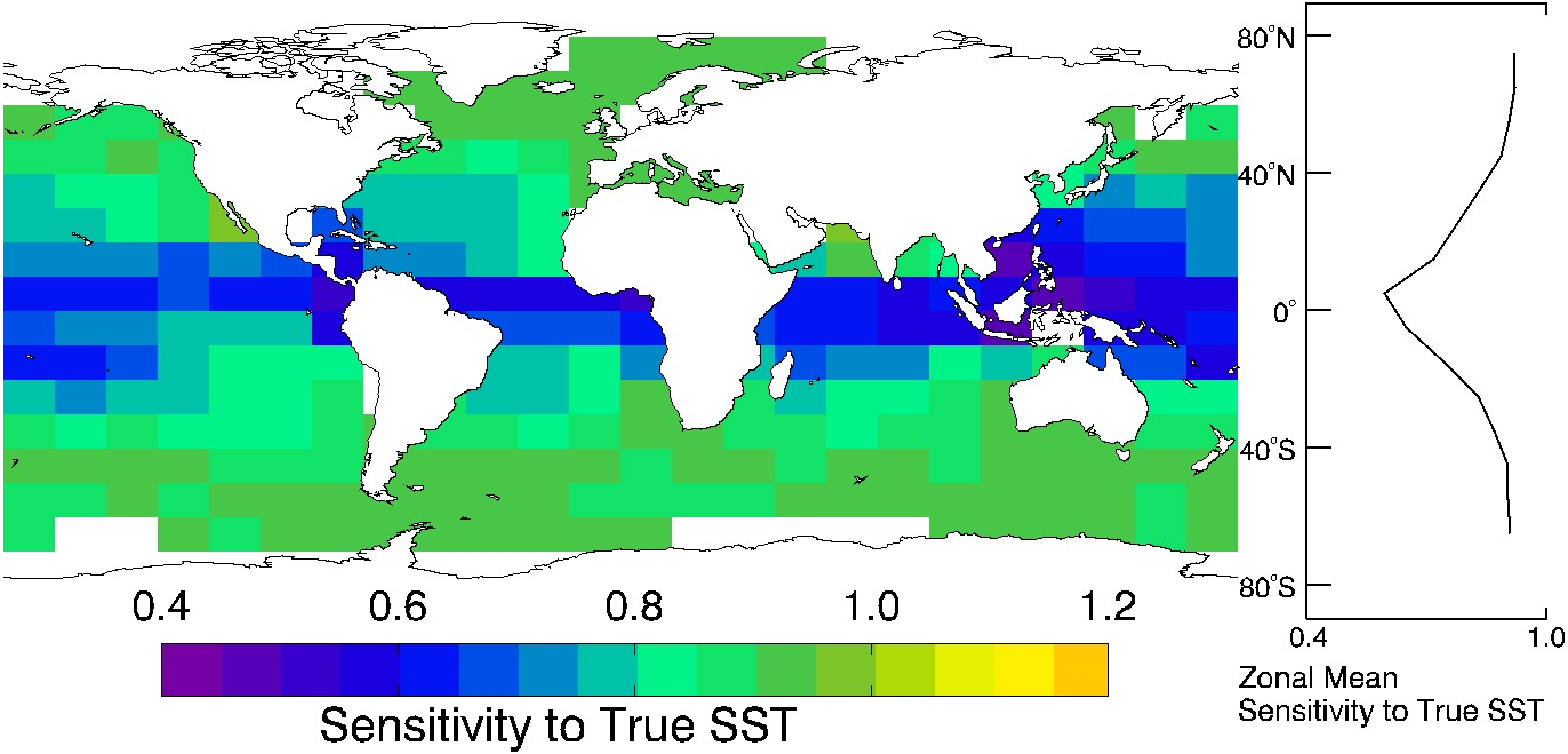
$$\frac{\partial \hat{x}}{\partial x} = \left(a_1 + a_2 S + a_3 x_b\right)\frac{\partial y_{11}}{\partial x} + \left(-a_2 S - a_3 x_b\right)\frac{\partial y_{12}}{\partial x}$$

Sensitivity to water vapour



Change in NLSST for 10% increase in TCWV, and no real SST change

Imperfect sensitivity to SST



Optimal estimation

- Essentially: calculation local coefficients "on the fly"
- Based on
  - **Local** atmospheric state
  - Physics of radiative transfer (via the RTM)

- What *should* OE give us?
  - Minimized random retrieval error
  - No regional biases
  - Reduced (and quantified) sensitivity to water vapour

- But, more complex and any RTM-calibration mismatch can introduce different biases

Optimal Estimation - Equations

Best estimate of the state variables in the vector **x**, given an initial estimate $\mathbf{x}_a$ with corresponding (modelled) observations $\mathbf{y}_a$ and new (real) observations **y**.

$$\hat{\boldsymbol{x}} = \boldsymbol{x}_a + \boldsymbol{S}_a\boldsymbol{K}^T\left[\mathbf{K}\mathbf{S}_a\mathbf{K}^T + \mathbf{S}_\varepsilon\right]^{-1}(\mathbf{y} - \mathbf{y}_a)$$

$$\boldsymbol{x} = \begin{pmatrix} SST \\ TCWV \\ \vdots \end{pmatrix}$$

State vector

Prior version from NWP
Posterior version is retrieved

$$\mathbf{y} = \begin{pmatrix} BT_1 \\ BT_2 \\ BT_3 \\ \vdots \end{pmatrix}$$

Observation vector

Prior version from RTM(NWP)
Compared to actual observation

Optimal Estimation - Equations

Best estimate of the state variables in the vector **x,** given an initial estimate $\mathbf{x}_a$ with corresponding (modelled) observations $\mathbf{y}_a$ and new (real) observations **y**.

$$\hat{\boldsymbol{x}} = \boldsymbol{x}_a + \boldsymbol{S}_a\boldsymbol{K}^T\,[\mathbf{K}\mathbf{S}_a\mathbf{K}^T + \mathbf{S}_\varepsilon]^{-1}(\mathbf{y} - \mathbf{y}_\mathbf{a})$$

$$\mathbf{K} = \begin{pmatrix} \frac{\partial BT_1}{\partial SST} & \frac{\partial BT_1}{\partial TCWV} & \cdots & \\ \frac{\partial BT_2}{\partial SST} & \frac{\partial BT_2}{\partial TCWV} & \cdots & \\ \vdots & \vdots & \vdots & \vdots \end{pmatrix}$$

Optimal Estimation - Equations

Best estimate of the state variables in the vector **x,** given an initial estimate $\mathbf{x}_a$ with corresponding (modelled) observations $\mathbf{y}_a$ and new (real) observations **y**.

$$\hat{\boldsymbol{x}} = \boldsymbol{x}_a + \boldsymbol{S}_a\boldsymbol{K}^T\,[\mathbf{K}\mathbf{S}_a\mathbf{K}^T + \mathbf{S}_\varepsilon]^{-1}(\mathbf{y} - \mathbf{y}_\mathbf{a})$$

$$\mathbf{S}_\mathrm{a} = \begin{pmatrix} \sigma_{SST}{}^2 & \sigma_{TCWV,\,SST}{}^2 & \cdots & \cdots \\ \sigma_{SST,\,TCWV}{}^2 & \sigma_{TCWV}{}^2 & \cdots & \cdots \\ \vdots & \vdots & & \\ \vdots & \vdots & & \end{pmatrix}$$

Metop-A study

- Showed that potential benefits of OE can largely be obtained in practice

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Remote Sensing of Environment

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Optimal estimation of sea surface temperature from split-window observations

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Abstract

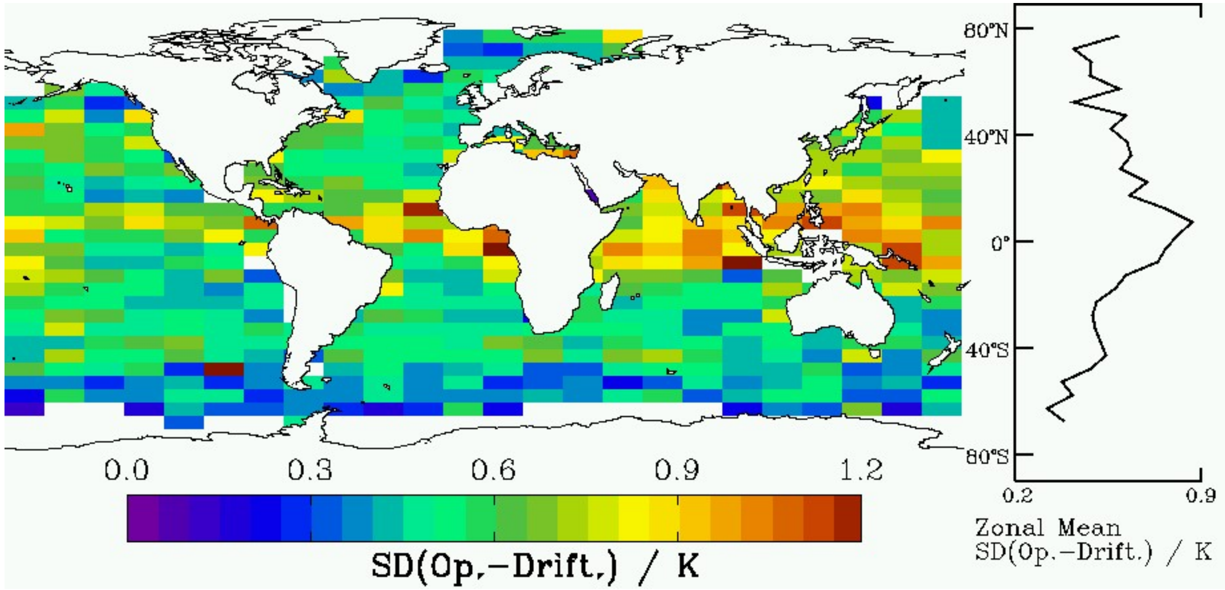
Optimal estimation (OE) improves sea surface temperature (SST) estimated from satellite infrared imagery in the "split-window", in comparison to SST retrieved using the usual multi-channel (MCSST) or non-linear (NLSST) estimators. This is demonstrated using three months of observations of the Advanced Very High Resolution Radiometer (AVHRR) on the first Meteorological Operational satellite (Metop-A), matched in time and space to drifter SSTs collected on the global telecommunications system. There are 32,175 matches. The prior for the OE is

Two main estimators

- **Maximum a posteriori – MAP (equations given)**
  - **Minimizes SST error variance**
  - **Explicitly embeds prior information in result**
  - **Probably appropriate for NWP, oceanography**

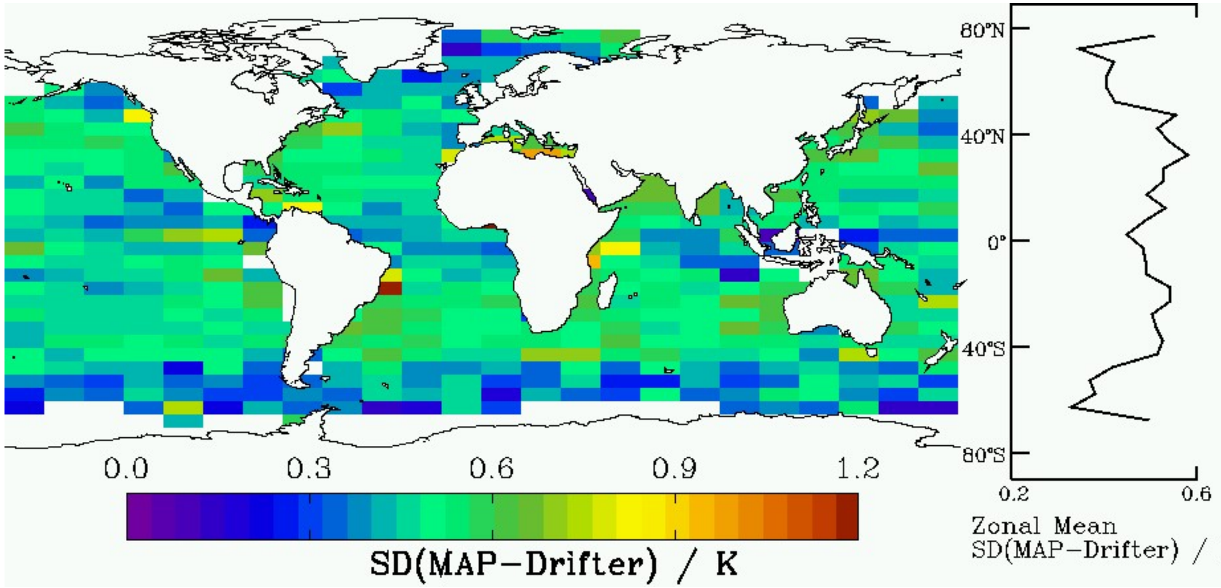
- Maximum likelihood – ML
  - Minimizes BT residuals (SST is noisier)
  - “Zero” prior influence in result
  - The only type of SST that should be used in climate re-analyses (if you are a purist)

Reduced SST spread of errors



Coefficients

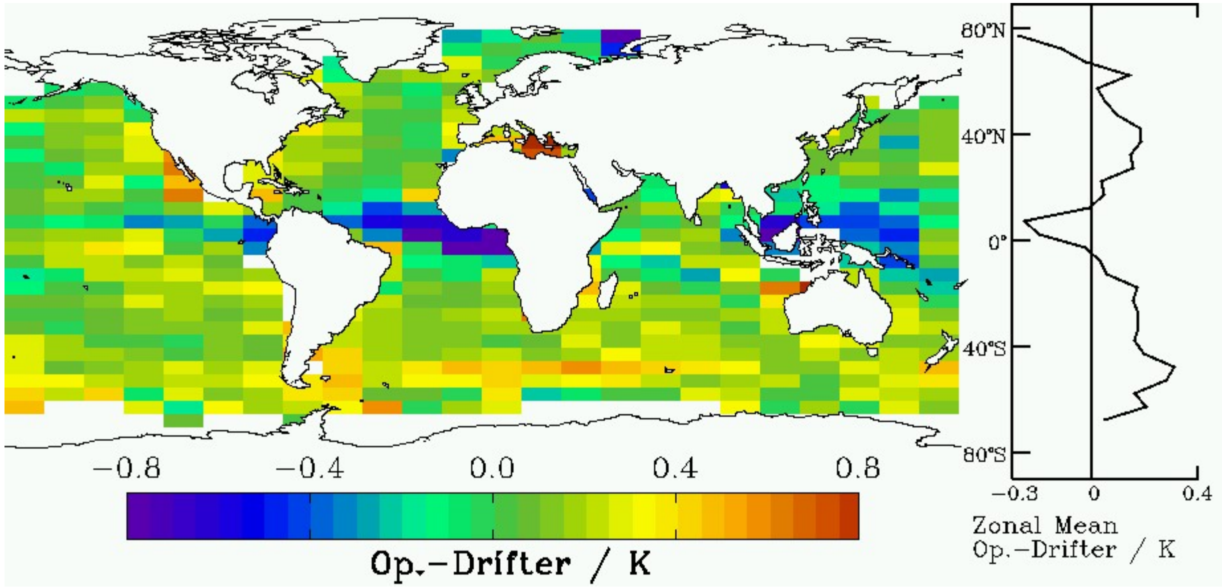
SD = 0.57 K



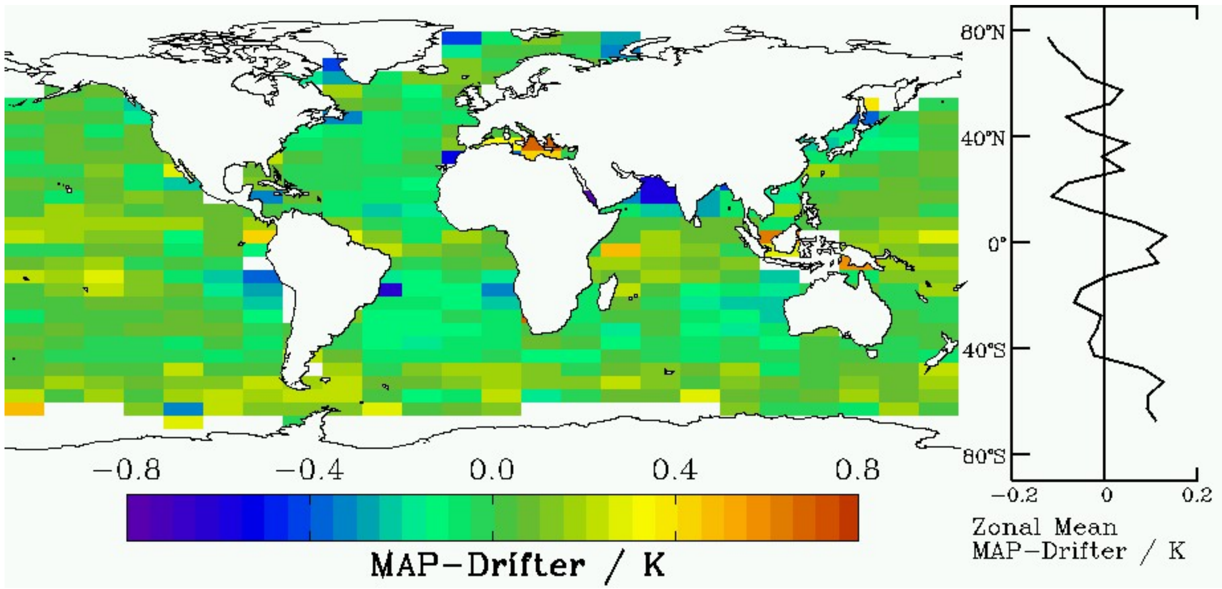
MAP optimal
est.

SD = 0.45 K

Reduced regional biases

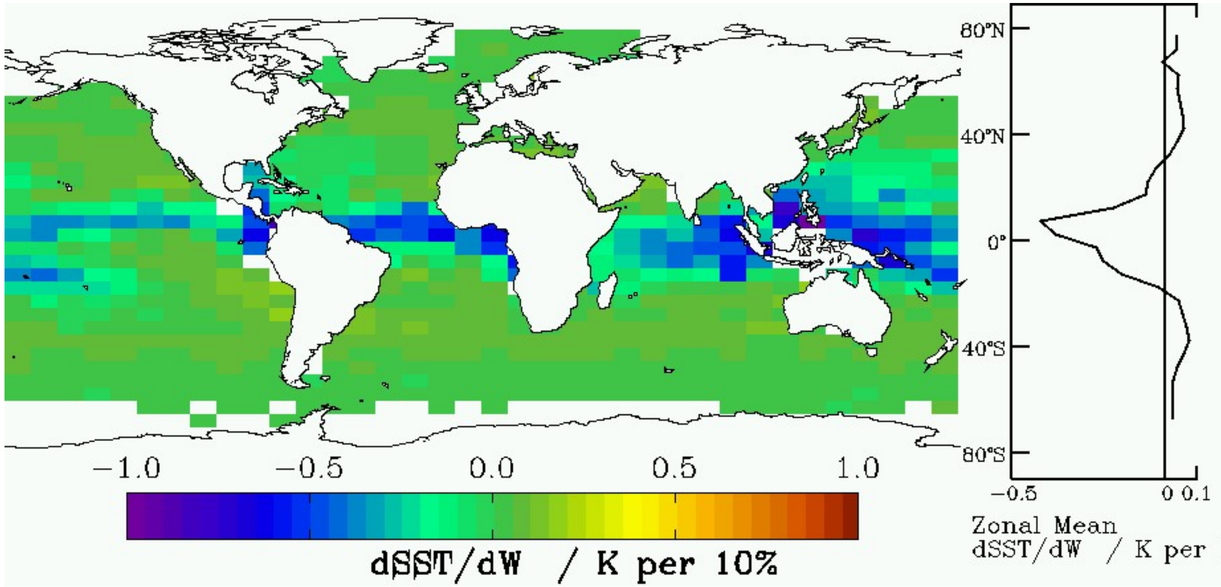


Coefficients

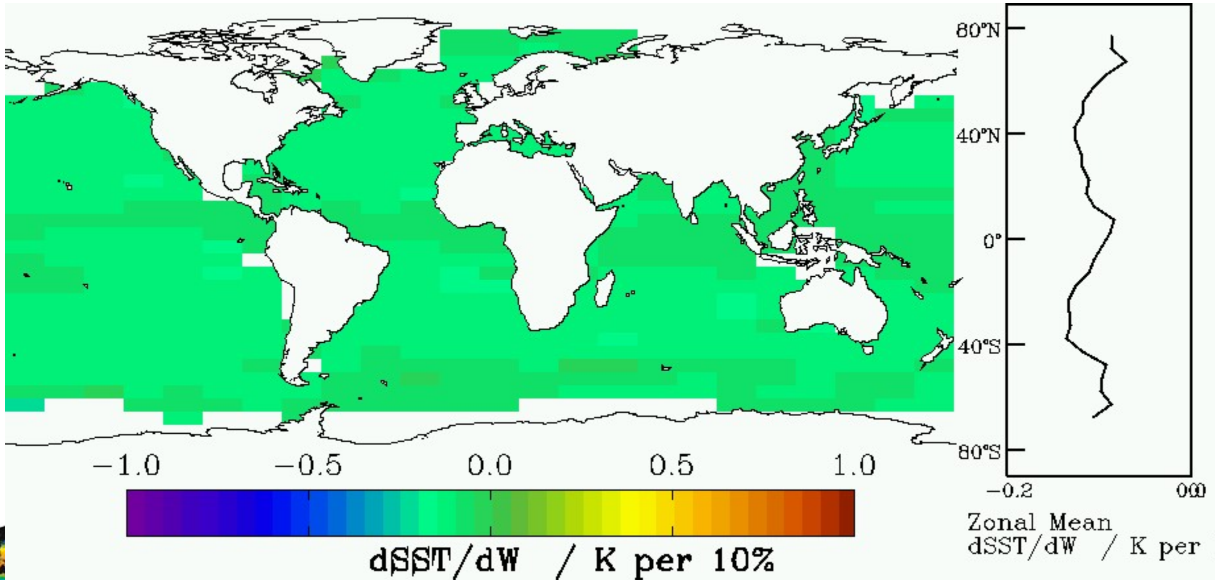


MAP OE

Reduced sensitivity to water vapour

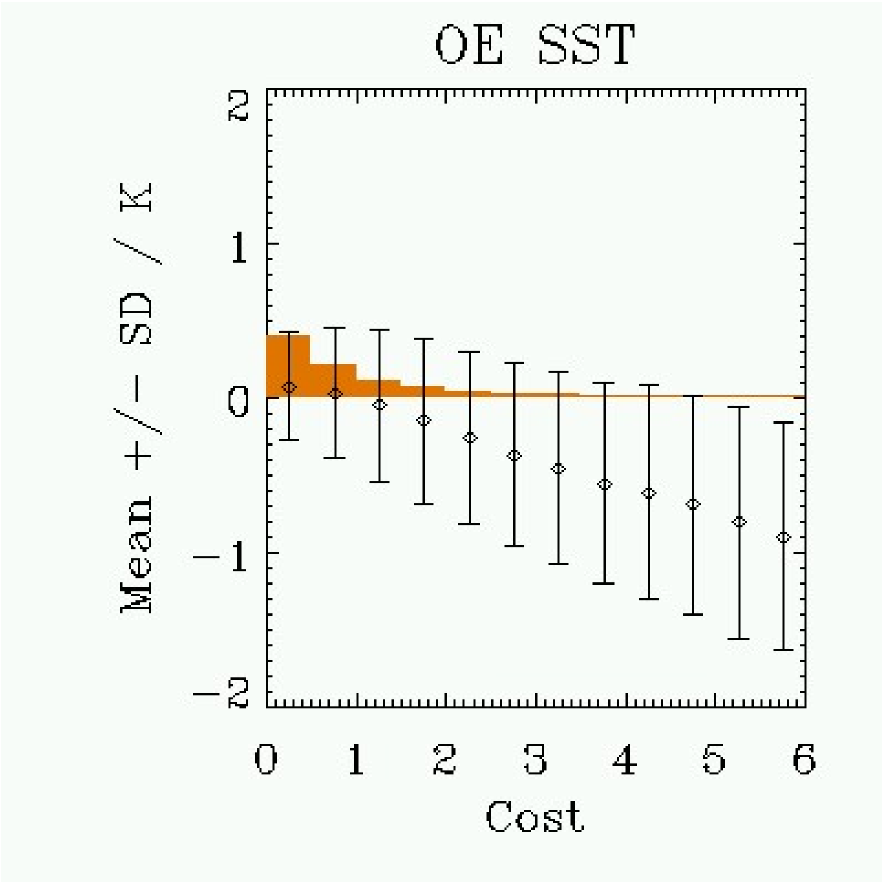


Coefficients



MAP OE

Retrieval cost: powerful quality indicator



MAP errors by cost

Lowest 44%	**+0.06 +/- 0.27**
Next 36%	**-0.03 +/- 0.36**
Poorest 19%	**-0.37 +/- 0.53**

Conclusions

- Coefficient-based retrieval
  - Deceptively simple
  - Built-in biases (bad for everyone)
  - Hidden influence of prior (bad for climate)
  - Very sensitive to water vapour in tropics
- Optimal estimation retrieval
  - Reduced bias, noise and sensitivity to TCWV
  - Cost is a powerful indicator of confidence in result
  - OE involves running a radiative transfer model, which is a lot of effort
  - Calibration of the sensor needs to be good (or estimated)