North Atlantic heat budget and its variability over the last 130 years from VOS observations

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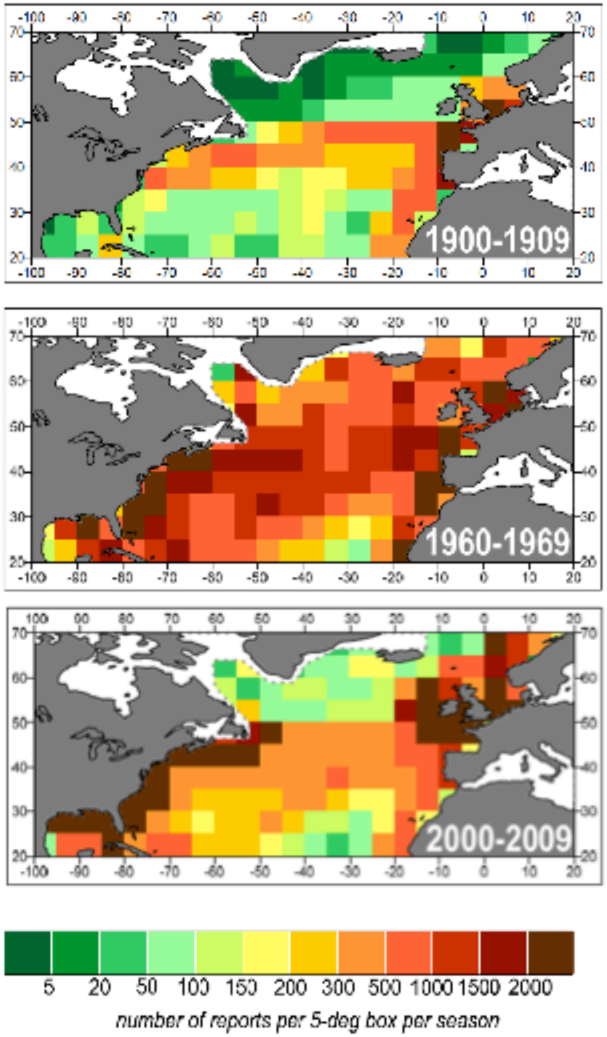
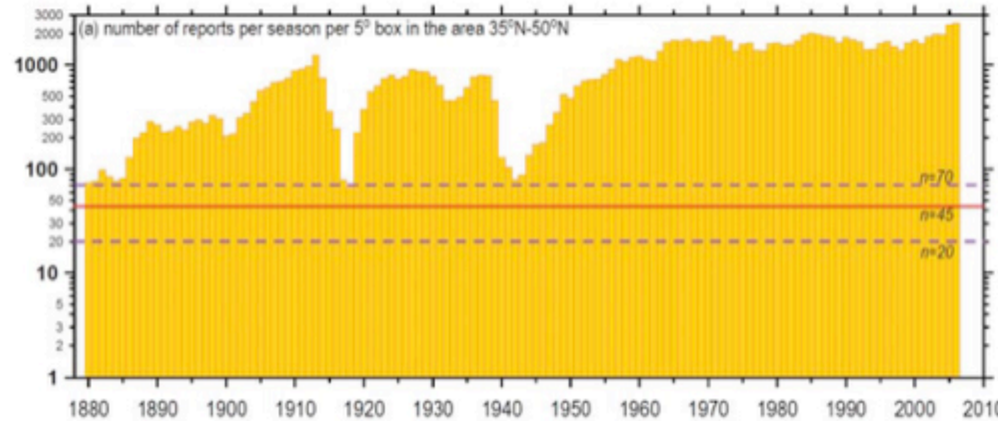
Outline:

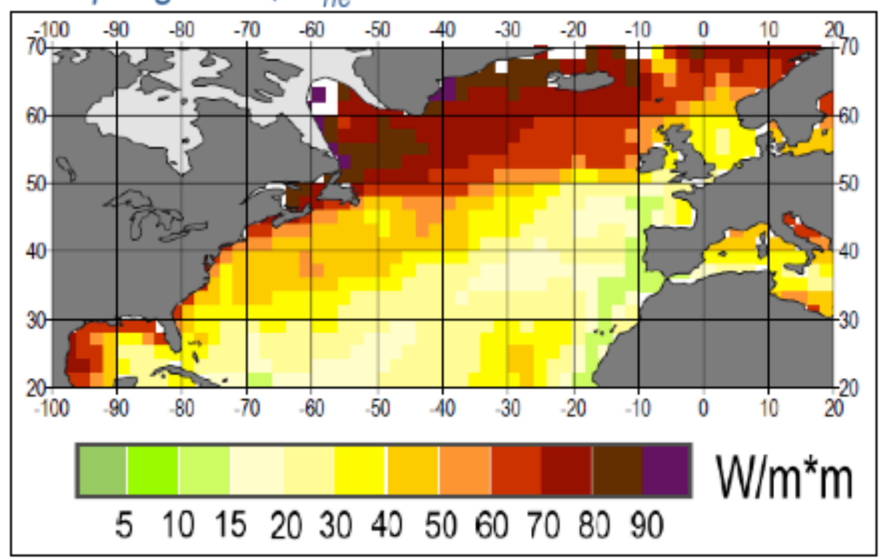
- Sampling problem in surface flux estimation from VOS
- Minimizing sampling uncertainty in turbulent fluxes using PDFs of fluxes
- Radiative fluxes over the North Atlantic for 1900+ - correcting biases in cloud cover for 1900-1950
- Long-term time series (1880+): turbulent and radiative fluxes together imply a prove for "*ocean control on surface flux*" concept
- Outlook

Regionally averaged fluxes and sampling in ICOADS



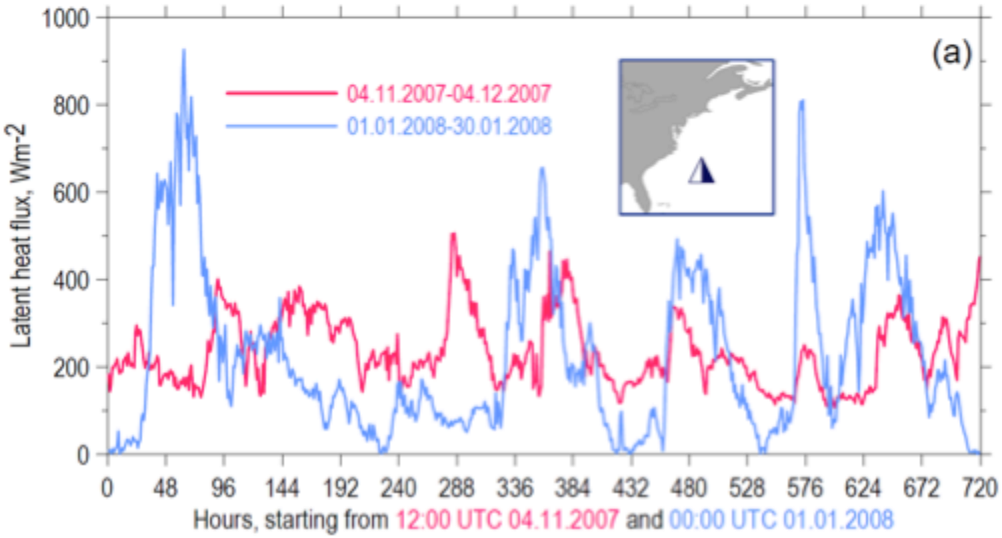


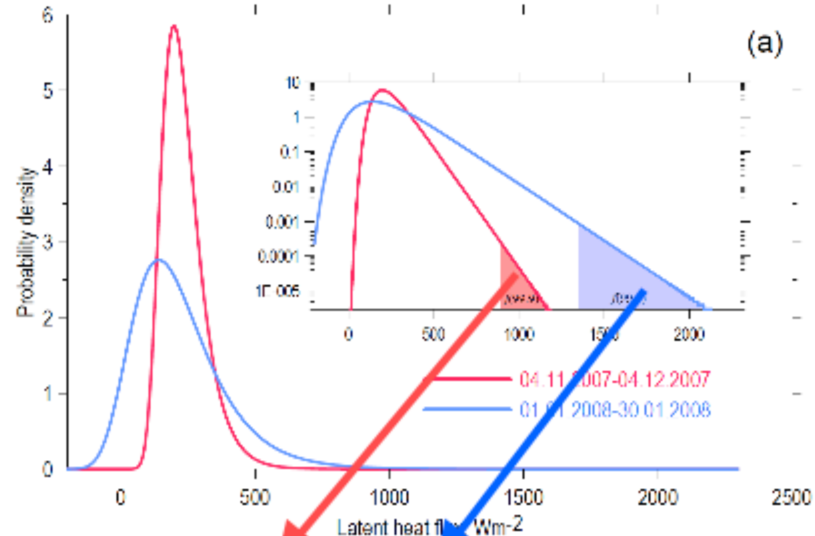
Sampling error, Q_{he}



- Up to 80 W/m^2 in subpolar NA
- Time dependent
- Affects integrated fluxes, especially in the areas of extreme fluxes

Probability distribution of turbulent fluxes





MEAN (04.11.2007-04.12.2007) = **234.6 W/m²**

MEAN (01.01.2008-30.01.2008) = **225.1 W/m²**

How these tails can be accounted for in large-scale integrations?

2-parameter MFT PDF (*Gulev and Belyaev 2012, J. Climate*)

$$P(x) = (\alpha \cdot \beta) \cdot e^{\beta x} \cdot e^{-\alpha \cdot e^{\beta x}}$$

Turbulent fluxes: 1880+:
Producing homogeneous time series of turbulent fluxes applying censored sample theory to MFT distributions

- Sampling in 1960s+ should be as “bad” as before WW2
  - sub-sampling for all year using MC-generator (15-25 obs/mon)
- Impact of parameterizations should be minimized
  - no humidity, some features of COARE-3 scheme are switched off
- Impact of changes in obs. practices should be minimized
  - Beaufort winds only, bucket SST only

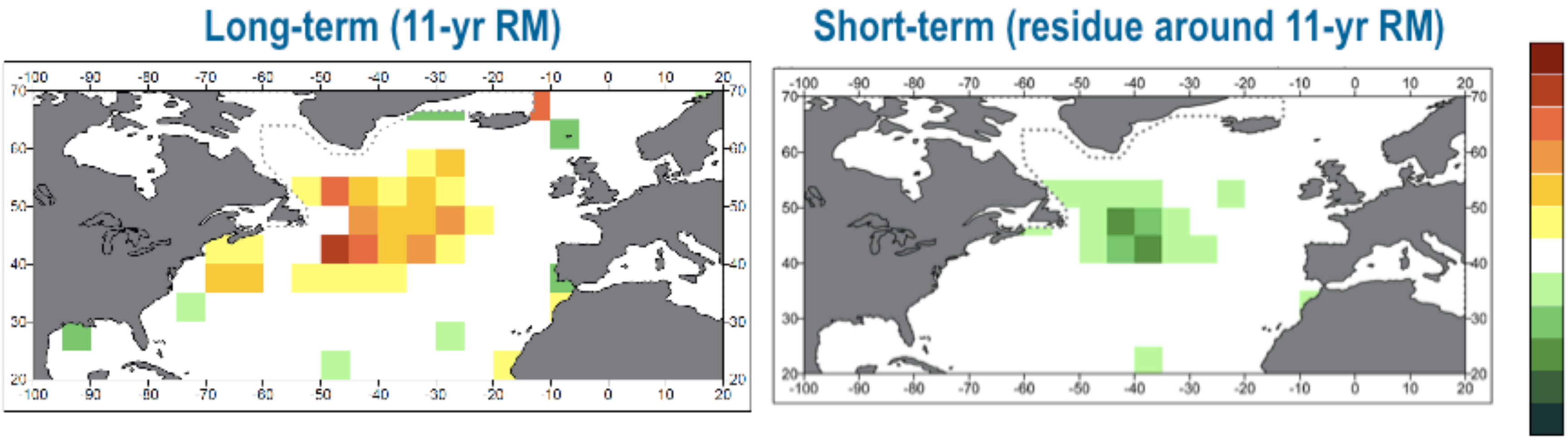
↓

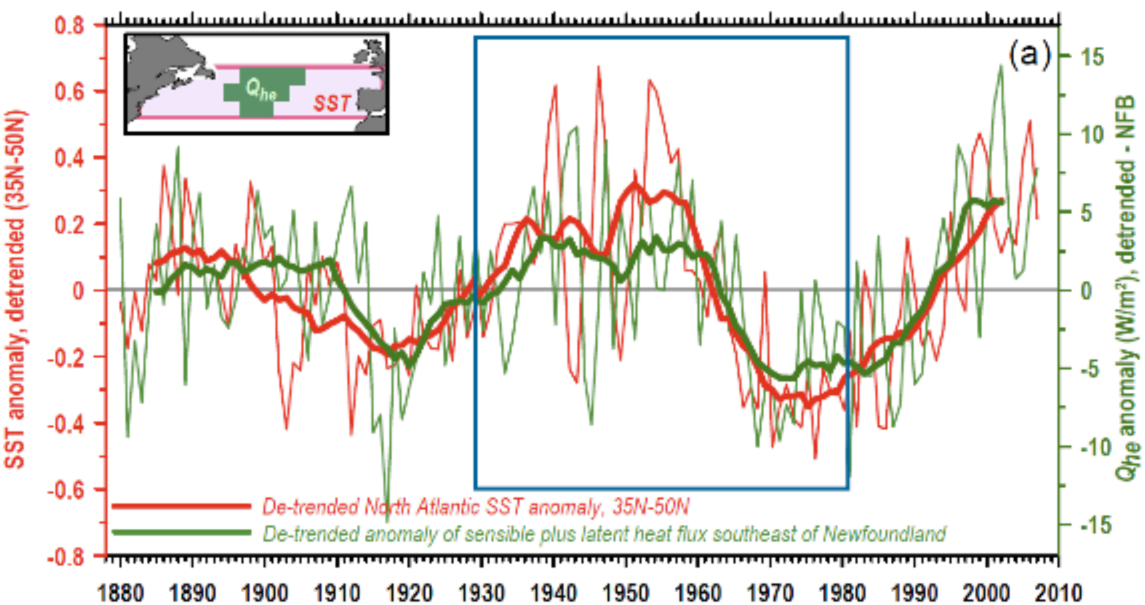
Integration of PDFs of fluxes using MFT distribution

↓

The fluxes will not be correct, but variability might be reliable

Testing the Bjerknes conjecture: reconstructed VOS fluxes vs HADSST





Correlation between SST and heat flux:

negative (short-term scales)

→ atmosphere drives SST

positive (long-term scales)

→ ocean drives heat flux

Gulev et al. 2013

Major caveat:

Radiative fluxes (SW and LW) **were not considered**, they may contribute significantly to the net flux anomalies and change their relation to the SST anomalies implying both warming (SW) and primarily cooling (LW) signals.

Need to incorporate SW and LW radiation into analysis:

(i) observations of cloud cover (driving SW and LW) are very limited before WW2
(ii) it is unclear how to deal with SW radiative fluxes, as it relies on astronomy (solar altitude)

Radiative fluxes

If we want to do this properly, the key-issue is availability of cloud cover and cloud types data

$$SW = Q_o(T_a, e_z, h_o) \times F(C, C_{type}) \times (1-\alpha)$$

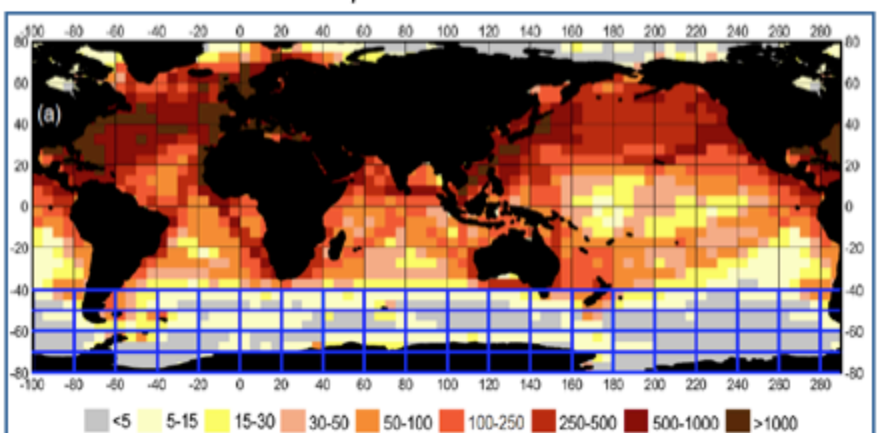
clear skies — cloud transmission — albedo

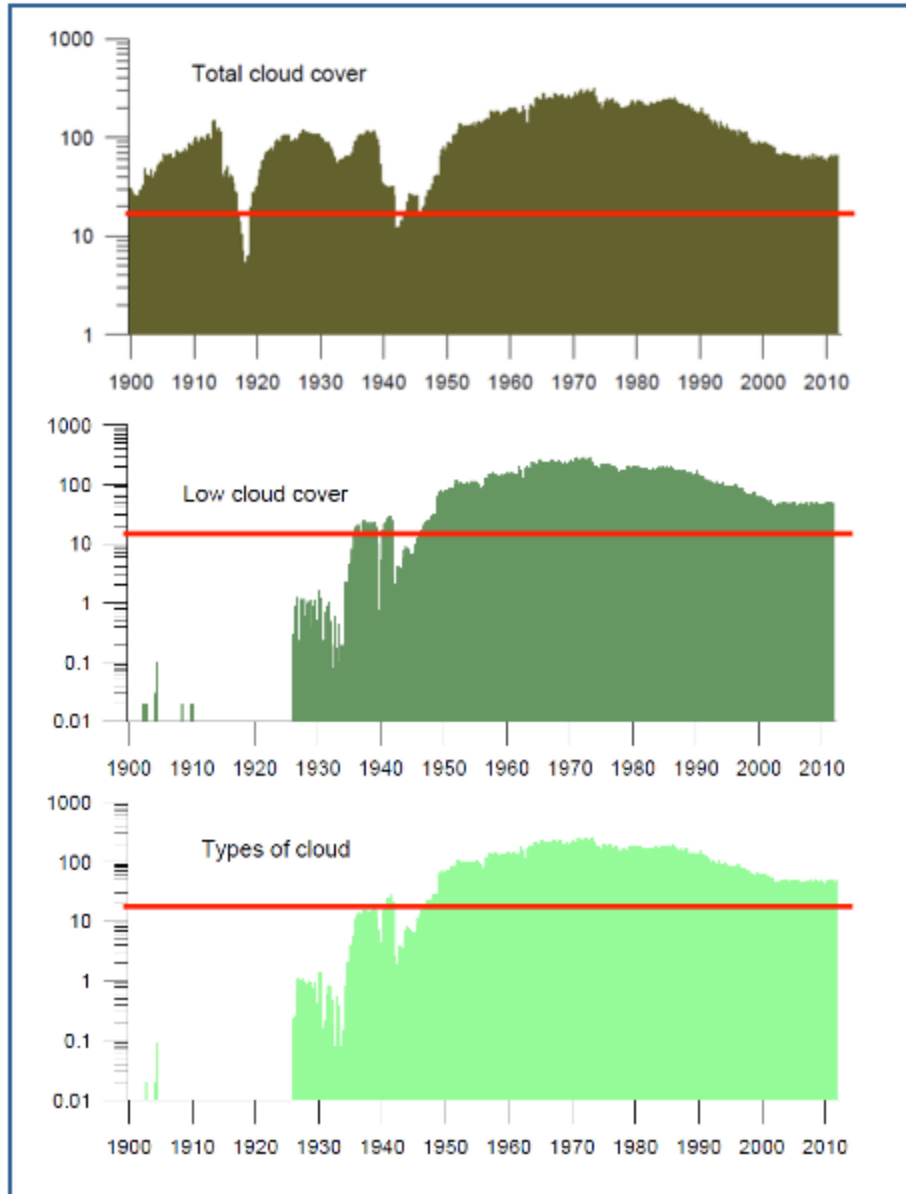
Effective emmisivity + LW albedo

$$LW = \varepsilon \, [\sigma SST^4 + F(C, C_{type}, T_a, e_z)]$$

upward — downward

Total number of cloud reports





Strategy on SW and LW:

Period: 1900+

Sampling: sub-sampling for all year using MC-generator (15-25 obs/mon)

Parameterizations (SW)

- *log* - clear sky SW dependence on h_{sol}
- rotation around the clock (48 steps, 30 min), throughout the month (30 steps, daily) and span over all latitudes inside 5º cell to account for uneven distribution of observations and biased solar altitude

$$\langle Q \rangle_l^{t,\theta,\varphi} = \frac{\sum_{i=1}^{30} \sum_{j=1}^{48} \sum_{k=1}^{120} Q_{i,j,k}(c_l, e_l, T_l, t_i, \theta_j, \varphi_k)}{30 \times 48 \times 120}$$

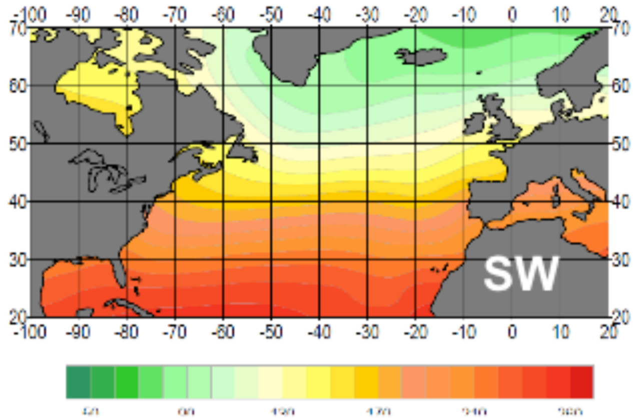
- no cloud types impact on atmospheric transmission factor

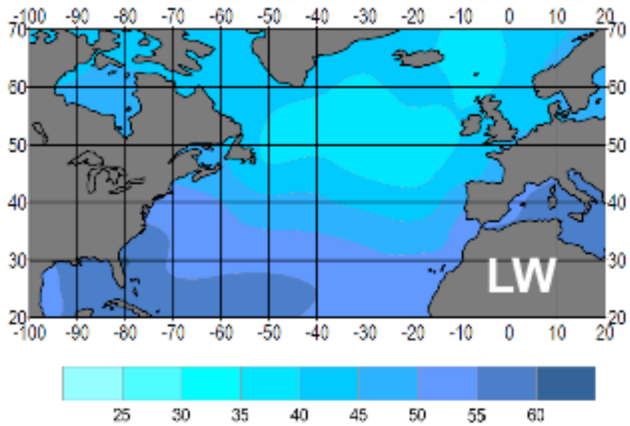
Parameterizations (LW)

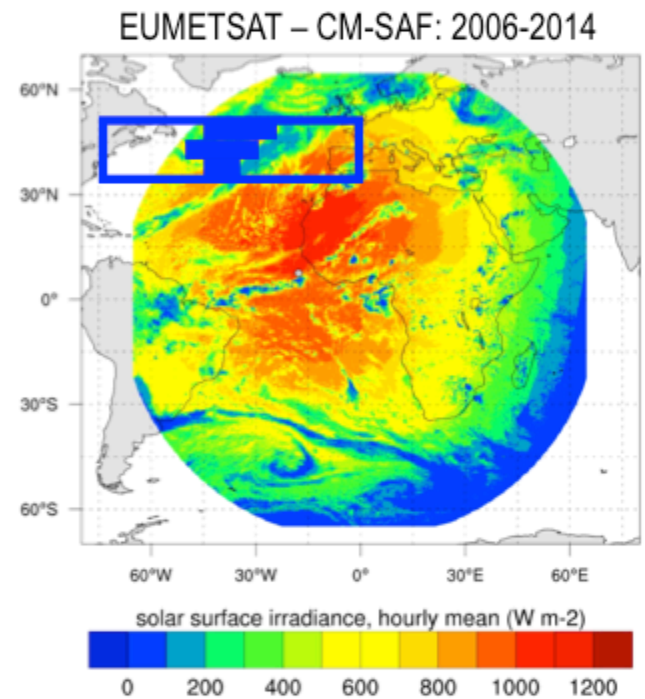
- no cloud type impact on the downward LW radiation
- Malevsky et al. (1992) and Josey et al. (2003) schemes

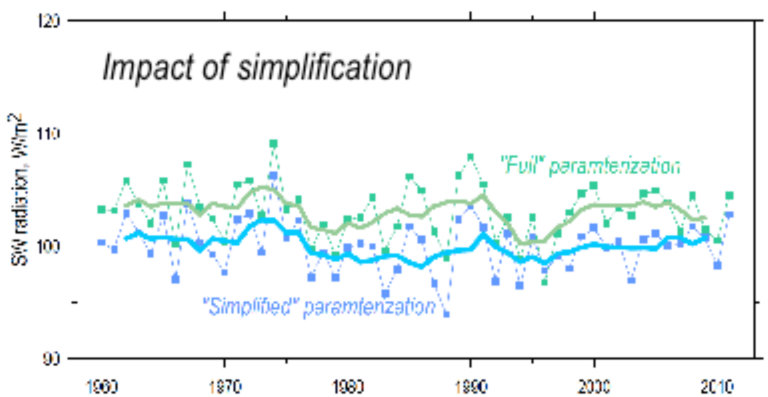
As for Qh, Qe, the fluxes will not be correct, but their variability might be reliable

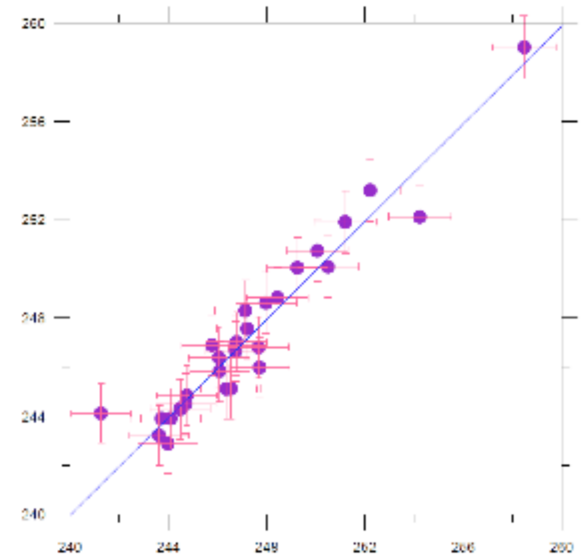
Validation:


SW

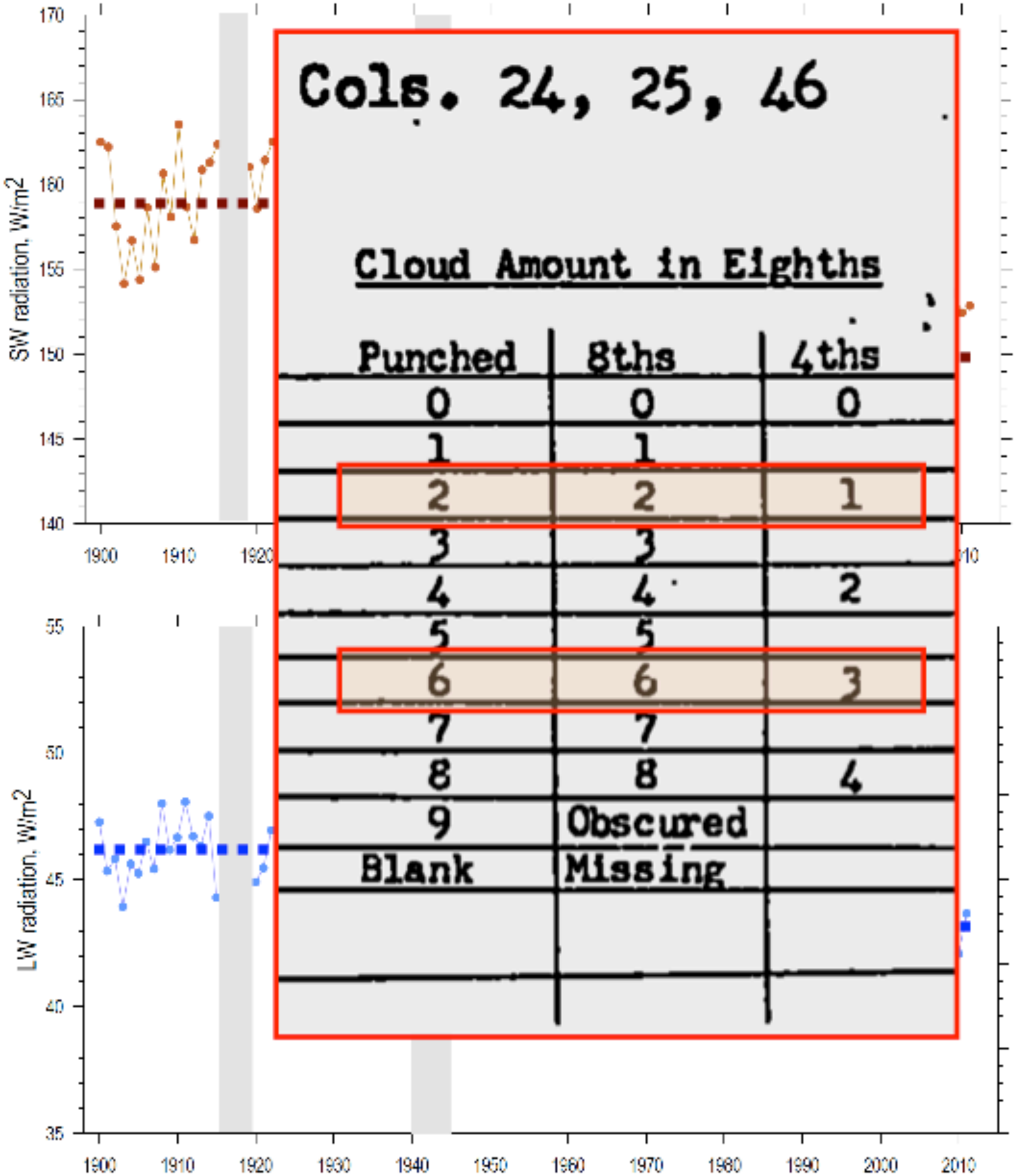

LW
25 30 35 40 45 50 55 60


EUMETSAT – CM-SAF: 2006-2014
60°N
30°N
0°
30°S
60°S
60°W 30°W 0° 30°E 60°E
solar surface irradiance, hourly mean (W m-2)
0 200 400 600 800 1000 1200


Impact of simplification
SW radiation, W/m2
"Full" parameterization
"Simplified" parameterization



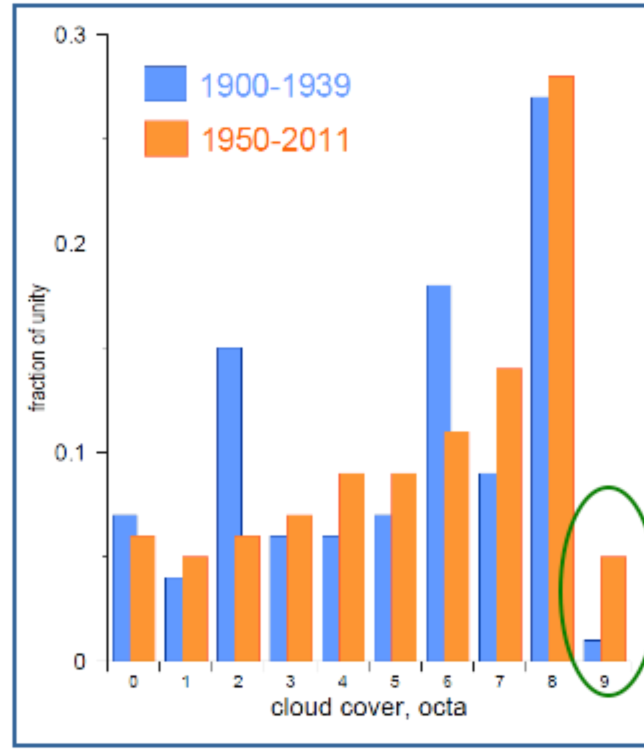
SW and LW time series (35-50N) – biases 1900-1940 vs 1946+



Cols. 24, 25, 46

Cloud Amount in Eighths

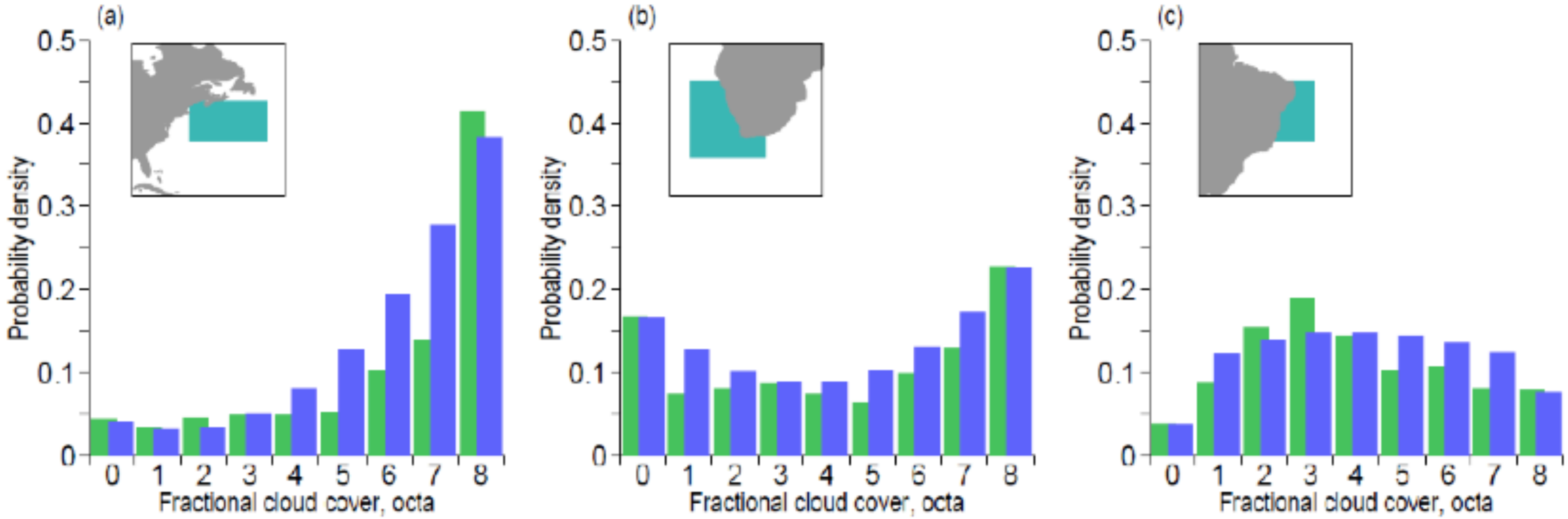
Punched	8ths	4ths
0	0	0
1	1	
2	2	1
3	3	
4	4	2
5	5	
6	6	3
7	7	
8	8	4
9	Obscured	
Blank	Missing	



Considerable part of ICOADS reports before WW2 was based on 4 categories:

Clear skies	→	0 octa
Low amount	→	~2 octa
High amount	→	~6 octa
Overcast	→	8 octa

Correction of bias using 3-parameter cloud cover PDF



PDF for the fractional cloud cover (Aleksandrova et al. 2018, J. Climate):

Continuous form:

$$P(x) = C(\alpha,\beta)\cdot\left[\theta(1-x)^{\alpha}\exp(-\beta(1-x)) + (1-\theta)x^{\alpha}\exp(-\beta x)\right]$$

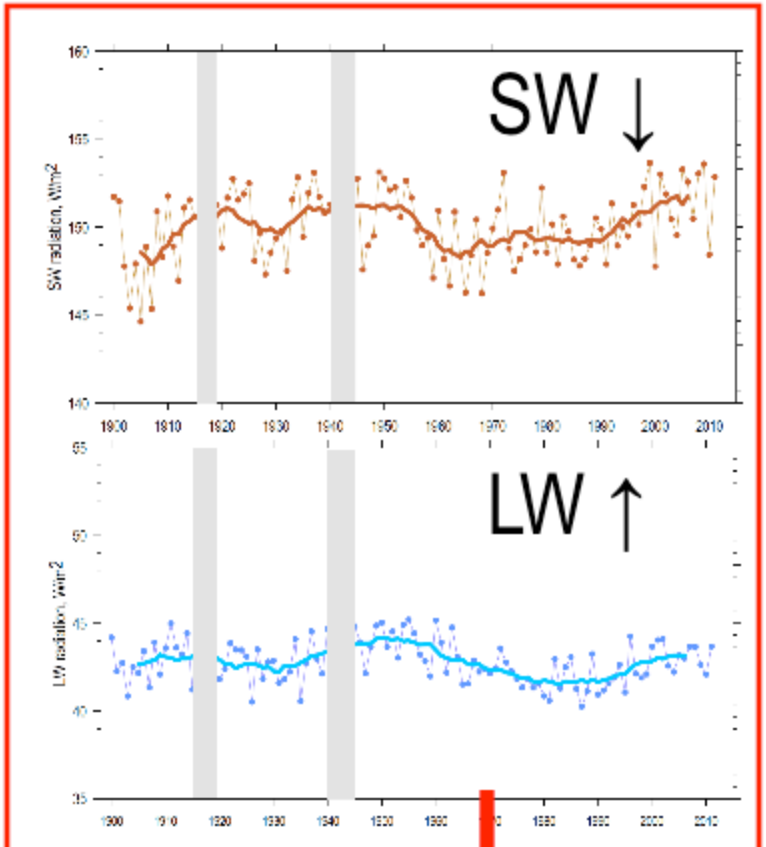
Discrete form:

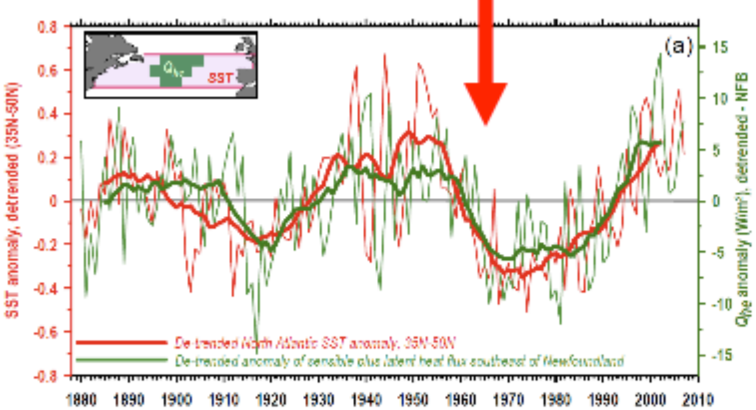
$$P(k) = \beta^{(\alpha+1)}\gamma^{-1}(\alpha+1,\beta)\times\frac{1}{n}\times\left[\theta\left(1-\frac{k}{n}\right)^{\alpha}\exp\left(-\beta\left(1-\frac{k}{n}\right)\right) + (1-\theta)\left(\frac{k}{n}\right)^{\alpha}\exp\left(-\beta\frac{k}{n}\right)\right],$$

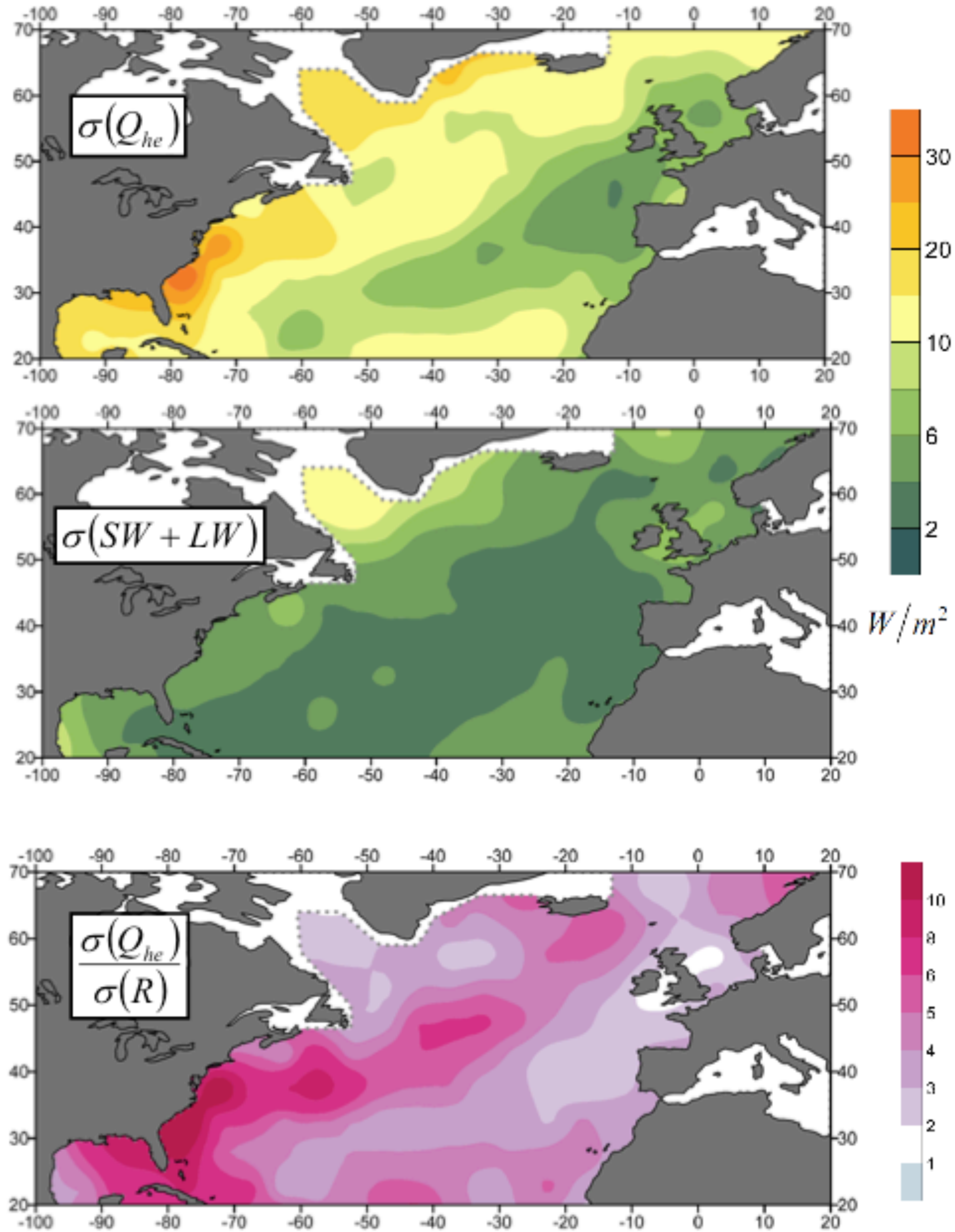
$$k = 0,1,\ldots.,8$$

After correction

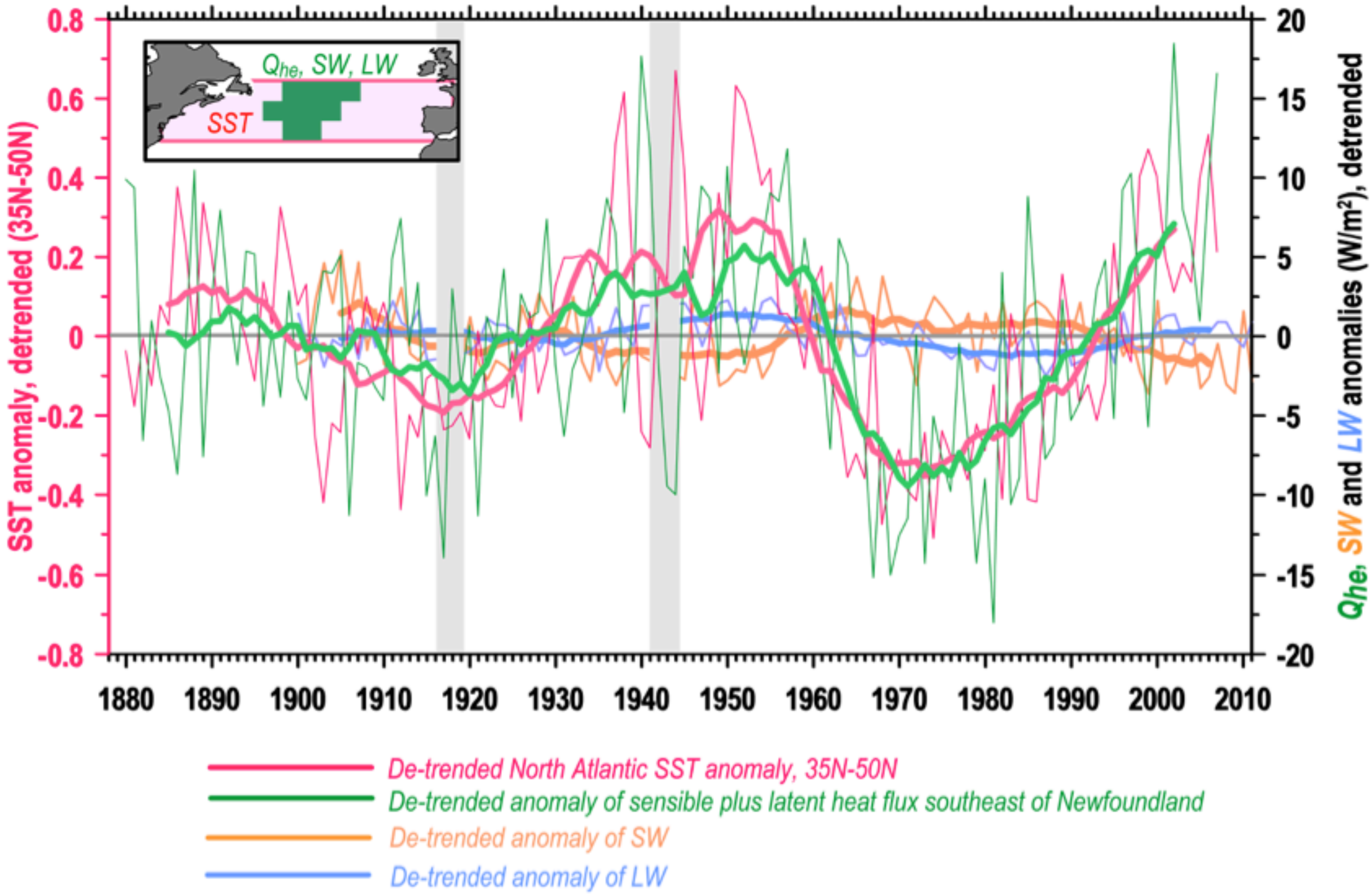
Interannual standard deviations



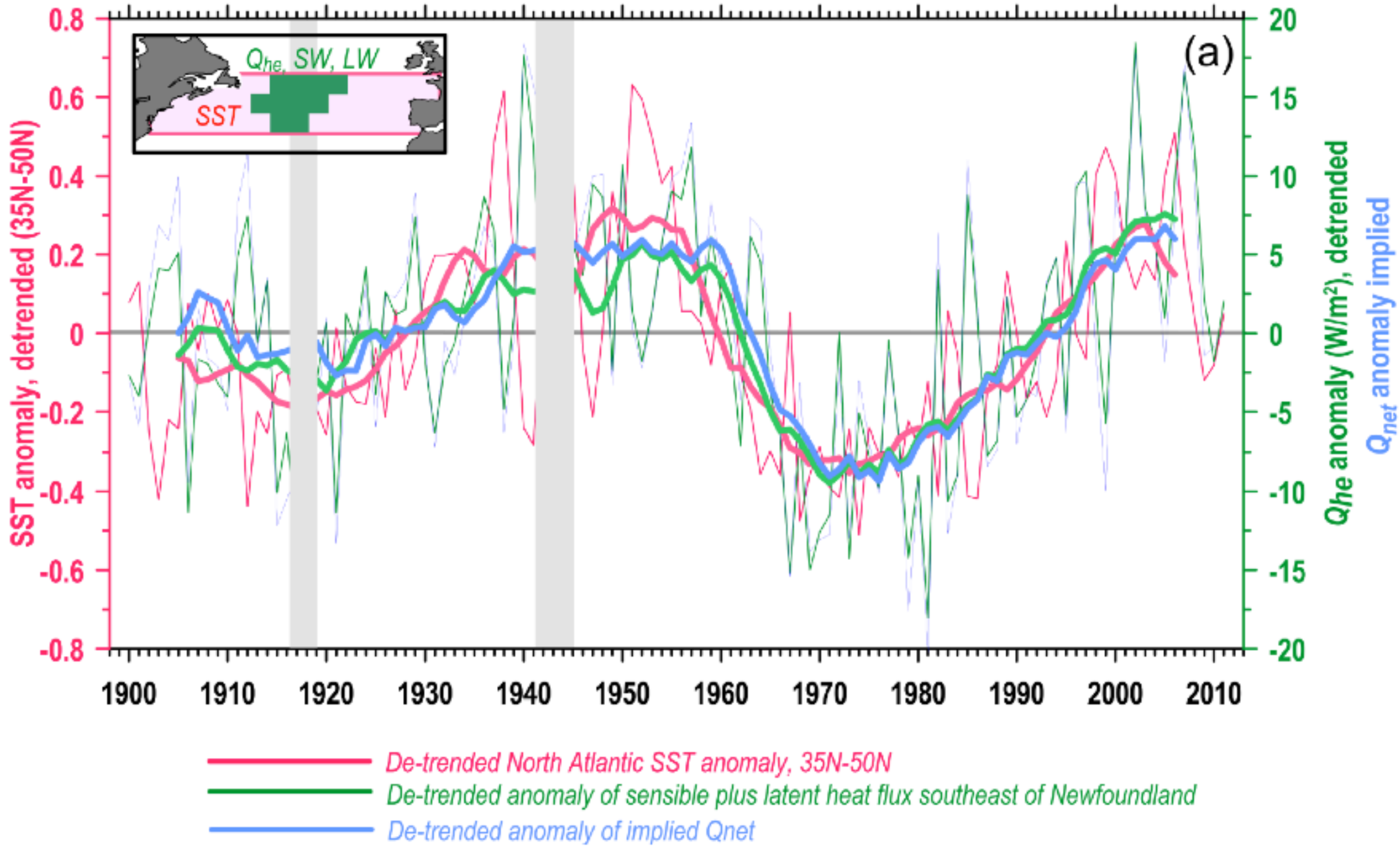




All fluxes together



Implied anomaly of the net flux



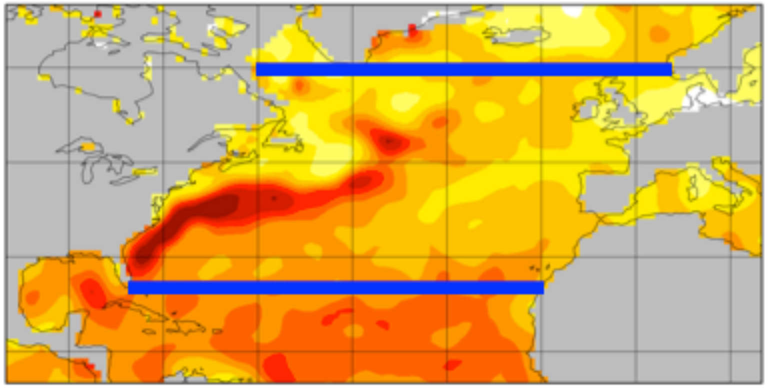
Conclusions :

Multidecadal variations in SST (AMV) in the Gulf Stream extension play **an active role** in air-sea interaction providing diabatic heating of the lower atmosphere. At interannual timescales, the atmosphere **drives changes in SST.** **Caveat – no radiative fluxes**

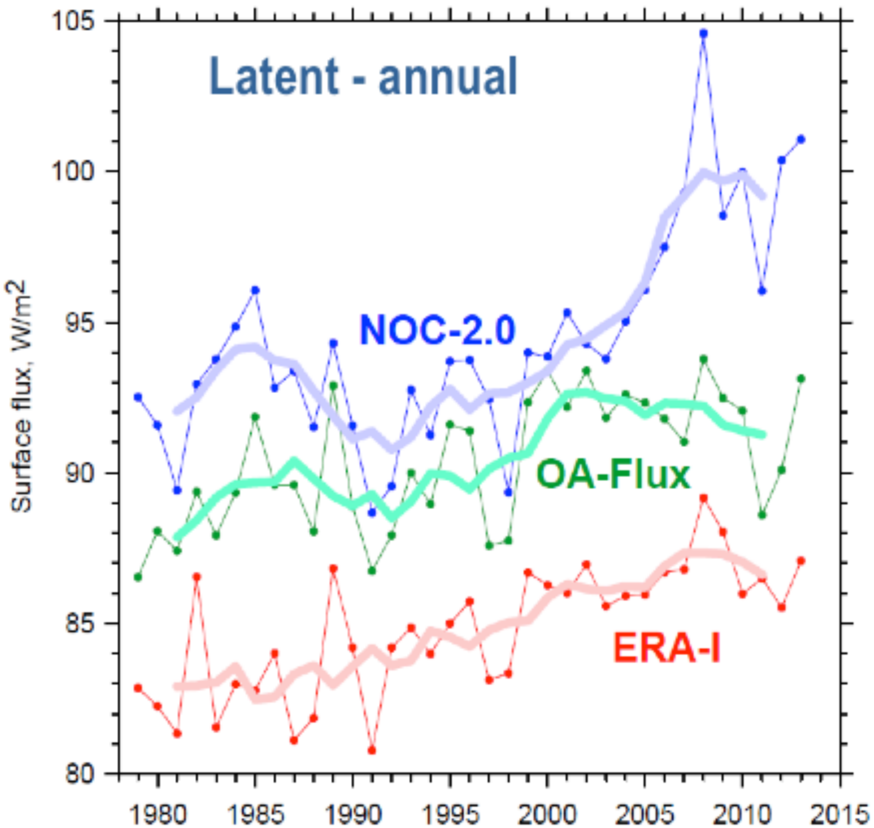
New time series of radiative fluxes (1900+) were developed →

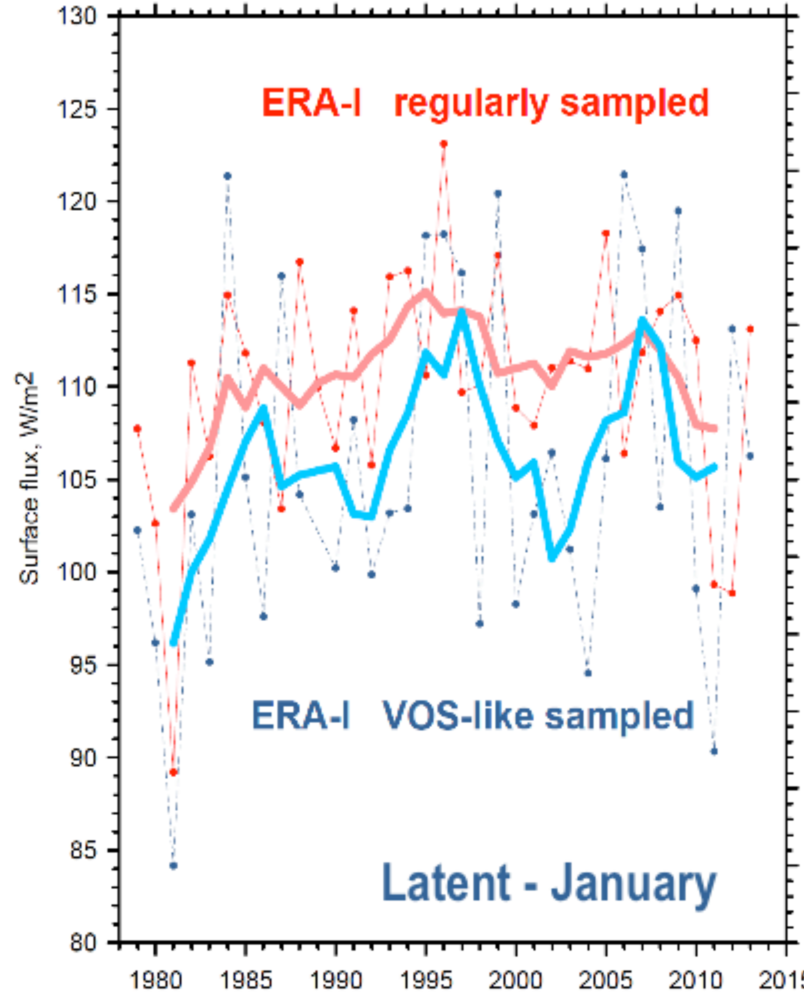
SW and LW anomalies on the top of turbulent fluxes do not change the conclusion, as the magnitudes of changes in radiative fluxes are considerably smaller compared to the turbulent fluxes

Flux averaging (25N-60N) over lat-lon space

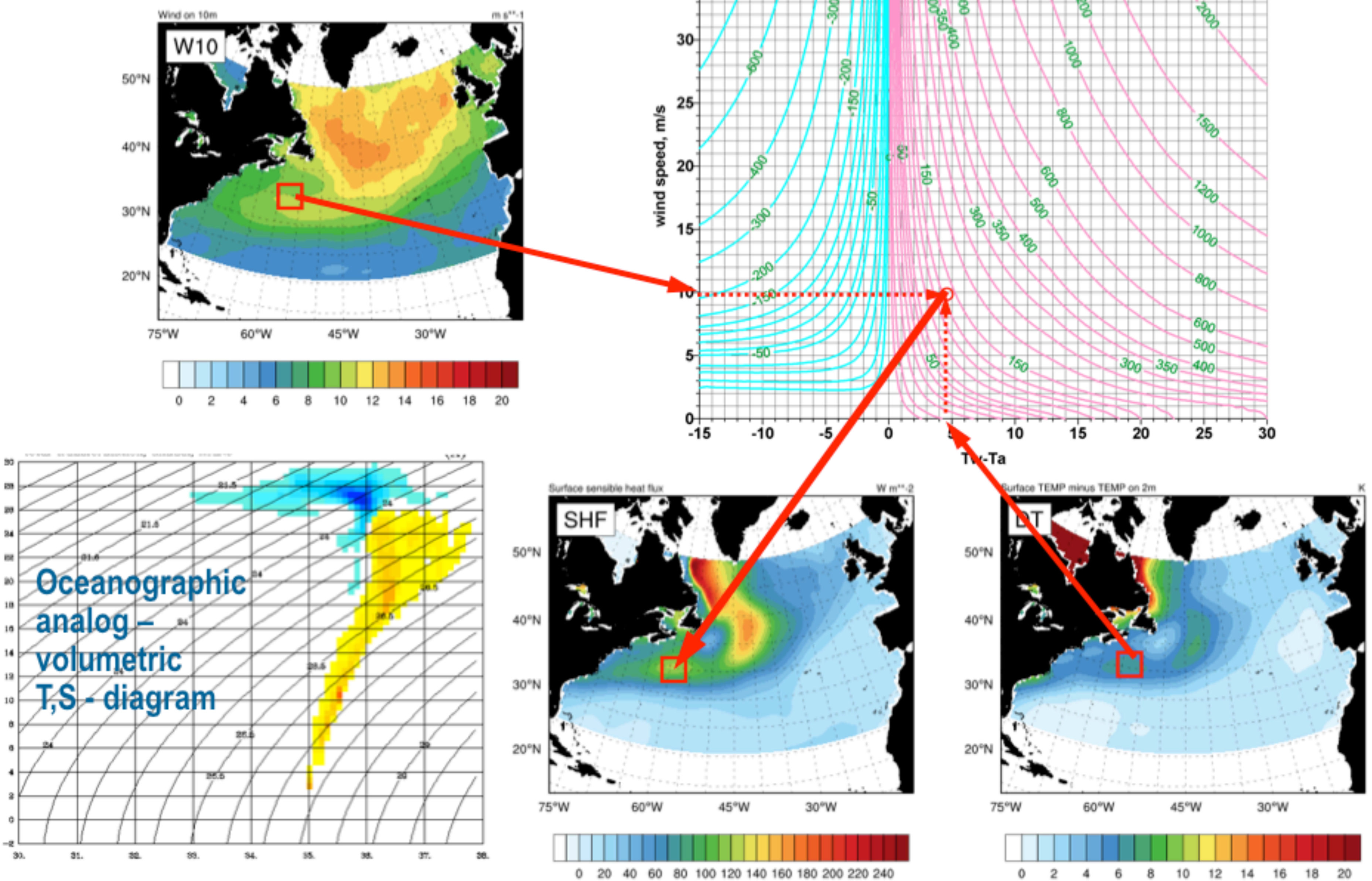


Long-term annual sampling error: 4.83 W/m^2
Long-term January sampling error: 7.79 W/m^2
Max sampling error: 19.45 W/m^2

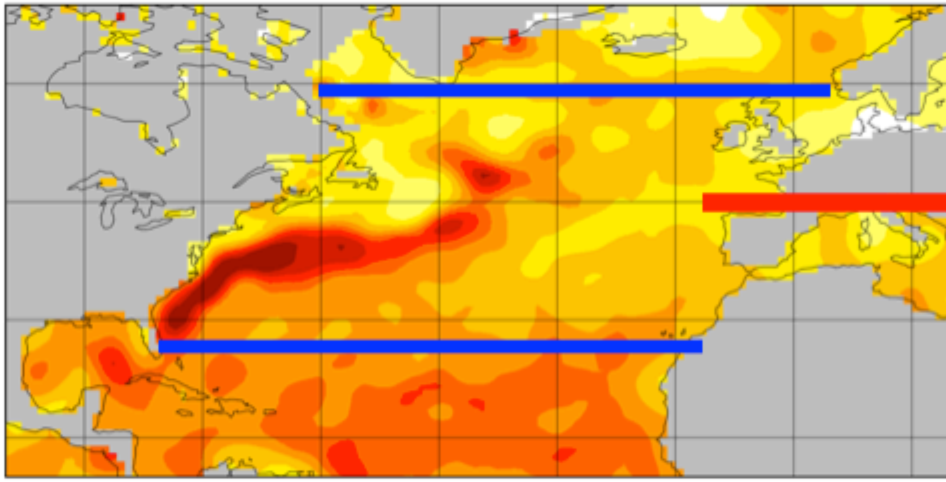


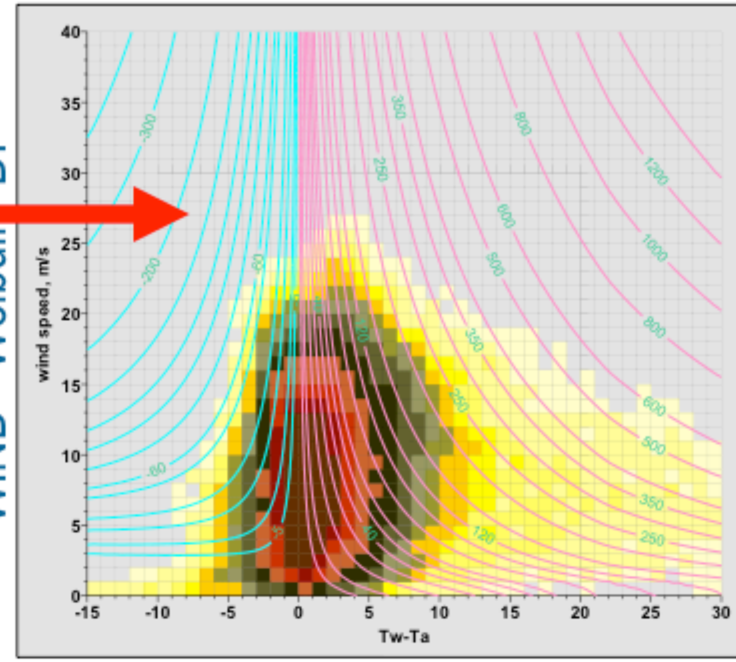


Surface turbulent fluxes in "δT (δq) – V" space



From "*lat-lon*" space to "dt(dq) –V" space





WIND - Weibull PDF

SST-Tair – MFT PDF

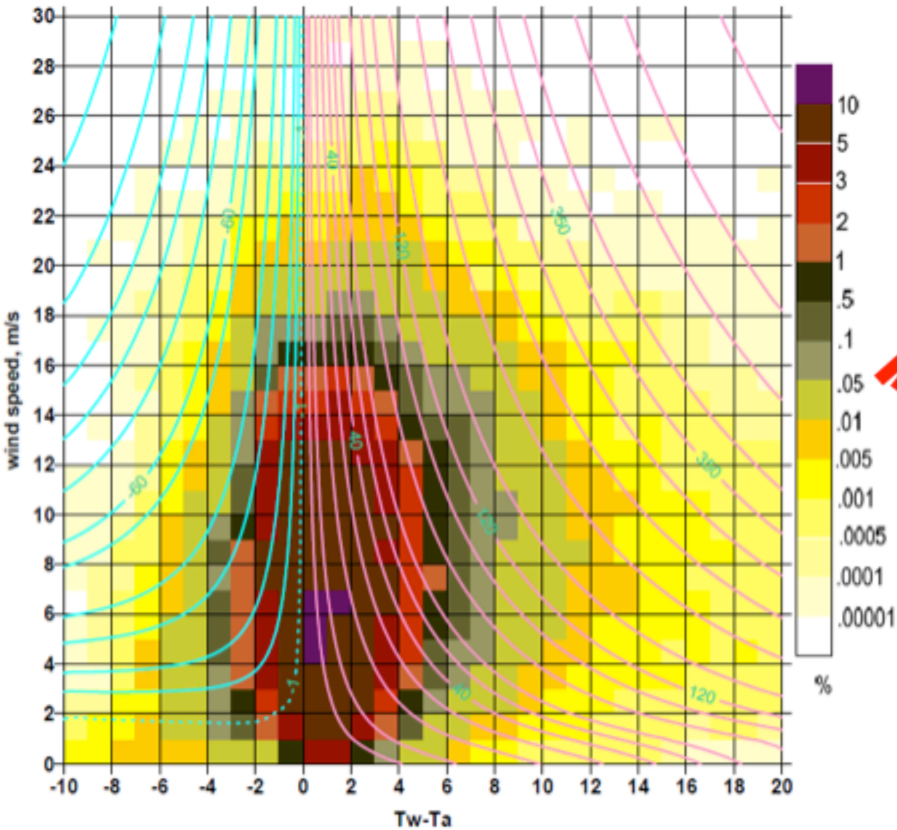
$$Q_{\Sigma} = \int_{t} dt \int_{S} Q dS = \int_{V} dV \int_{\delta T} Q d(\delta T)$$

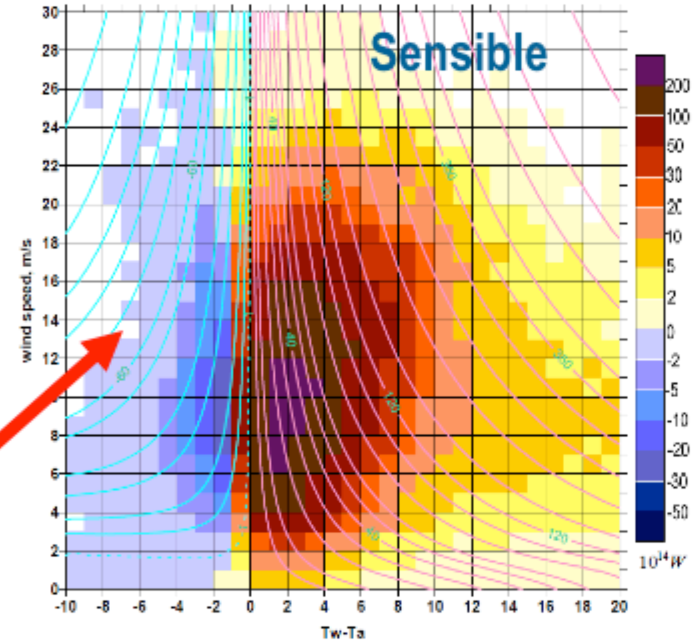
$$P(V \mid \delta T) \cdot P(\delta T) = \frac{\alpha_V}{\beta_V}\left(\frac{V}{\beta_V}\right)^{\alpha_V - 1} \cdot e^{-\left(\frac{V}{\beta_V}\right)^{\alpha_V}} \cdot (\alpha_T \cdot \beta_T) \cdot e^{-\beta_T \delta T} \cdot e^{-\alpha_T \cdot e^{-\beta_T \delta T}}$$

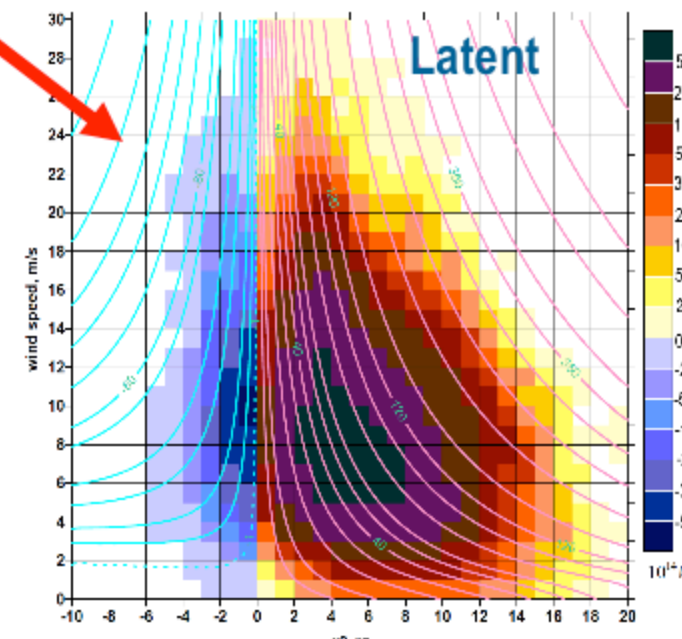
Weibull

MFT

From probabilities to fluxes in "$\delta T(\delta e) - V$" space

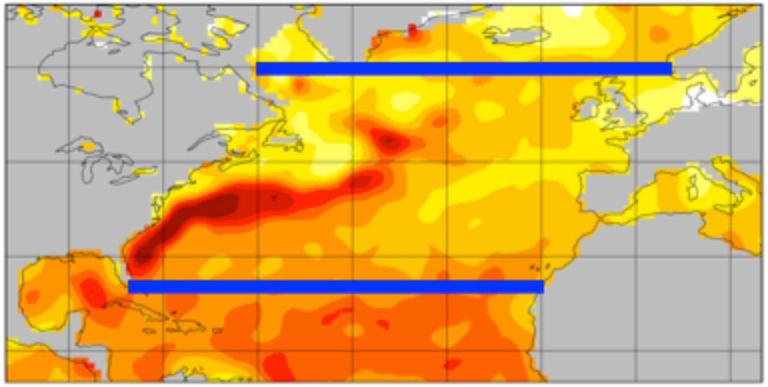






$$\sum_{dT}\ \sum_{V}\left[P(dT_i \mid V_j)\times Q_{dT_i,V_j}\right]$$

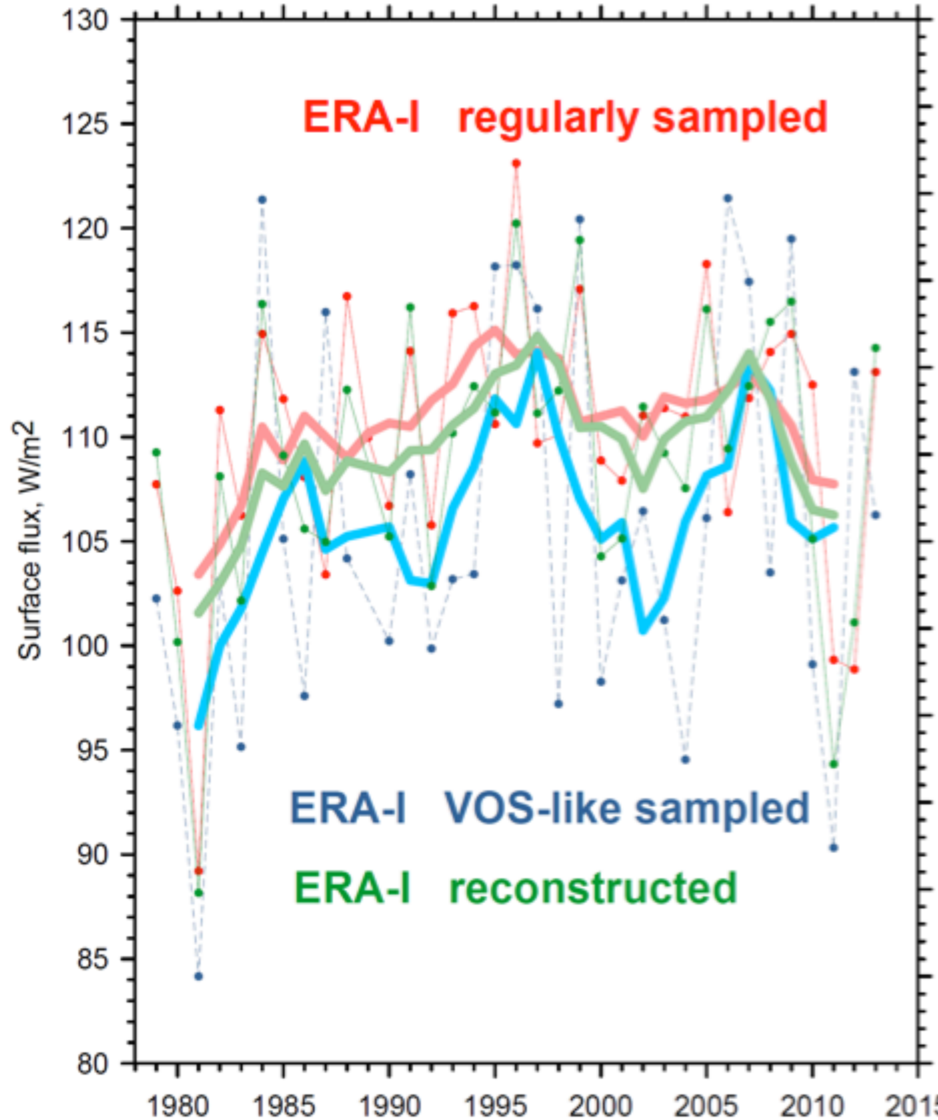
Reconstructed time series (25N-60N)



- ❑ ~8 times smaller uncertainties, strong biases removed

Long-term annual sampling error:
0.51 W/m^2 (was 4.83)
Long-term January sampling error:
1.36 W/m^2 (was 7.79)
Max sampling error:
4.24 W/m^2 (was 19.45)

- ❑ More realistic interannual variability



Conclusions (25-60N, 1979+):

2D PDF for flux related variables (dT, V) allows for the accurate integration of surface turbulent fluxes in space and time →

Reducing uncertainty associated with sampling in the area-integrated turbulent fluxes by ~8 times

Summary (25-60N):

Probability distributions for flux related variables (dT, V) allow for accurate integration of surface turbulent fluxes in space and time (joint MFT-W distribution), application of the algorithm allows for reducing uncertainty associated with sampling in the area-integrated turbulent fluxes by ~8 (3-10) times

Computations based on VOS variables (including radiative fluxes provide net flux estimates of ~25.3 W/m2 (0.6 PW) – uncertainty is large to discuss interannual changes

Approach

1. Generating flux data:

ERA-I (1979-2013) state variables →
computed SHTF and LHTF (COARE-3)

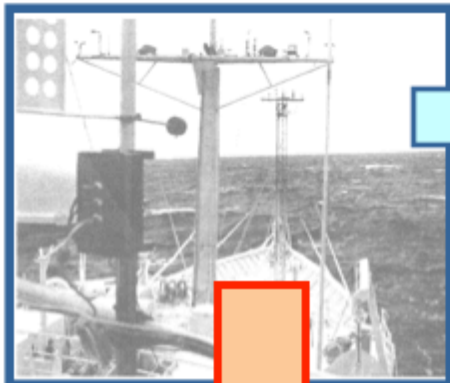
$$Q_h \sim C_h(\delta T, V) \cdot \delta T \cdot V \quad Q_e \sim C_e(\delta q, V) \cdot \delta q \cdot V$$

2. Space-time integration in *dt* – *W* space:

Integrating PDFs instead of averaging flux values

Q1: How scalar wind is distributed? → Weibull (known)
Q2: How dT (dq) is distributed? → MFT (as fluxes) - proven

What is VOS-based surface flux product?



Pre-processing and variable corrections:

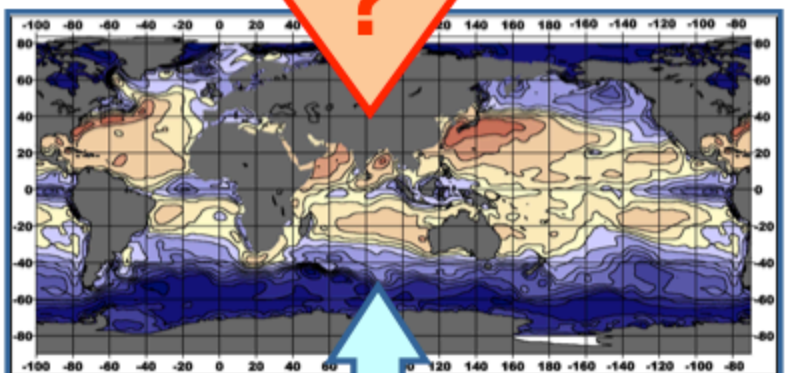
SST, T_a, q, SLP, V, cloud cover, wave characteristics

Parameterizations:

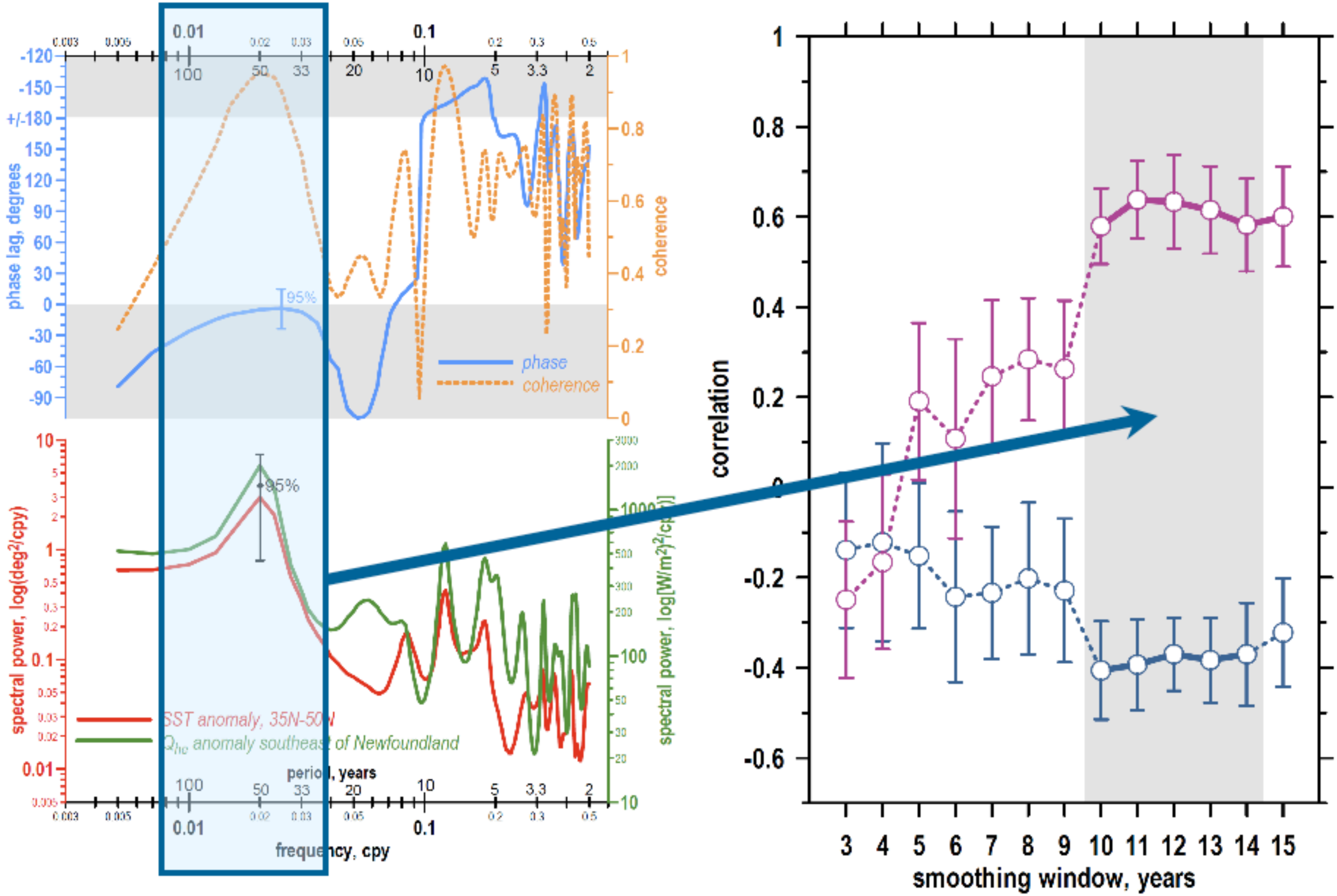
$$LW = \varepsilon\sigma SST^4 F_{lw}(Cn, T_a, e_z),$$
$$SW = Q_o F_{sw}(C_n, T_a, e_z, h_o)(1-\alpha),$$
$$Q_h = C_p C_t \rho (SST - T_a\gamma)V,$$
$$Q_e = L C_e \rho (0.622/P)(e_o - e_z)V,$$
$$H = SW - LW - Q_h - Q_e$$
$$\tau = \rho C_v (V, h_w) V^2$$

Gridding, objective analysis and interpolation:

Global surface flux fields

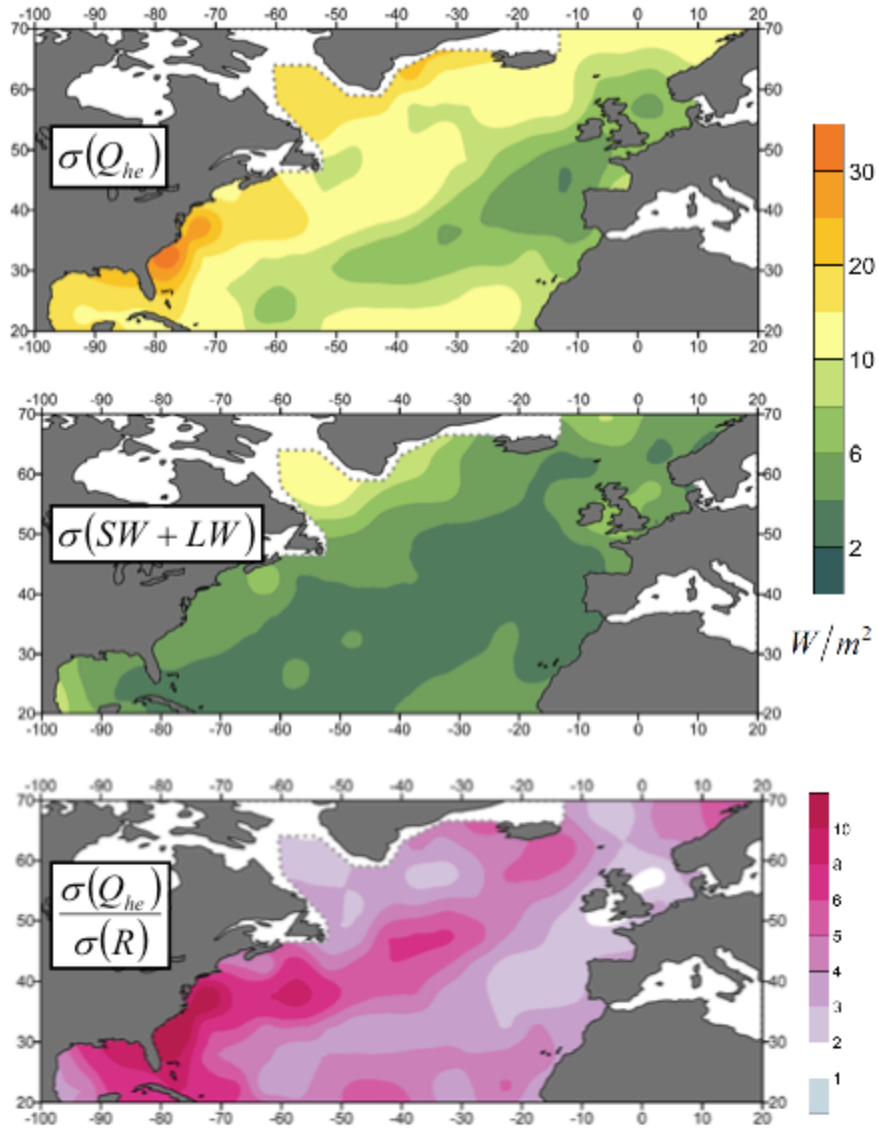


Co-spectral analysis



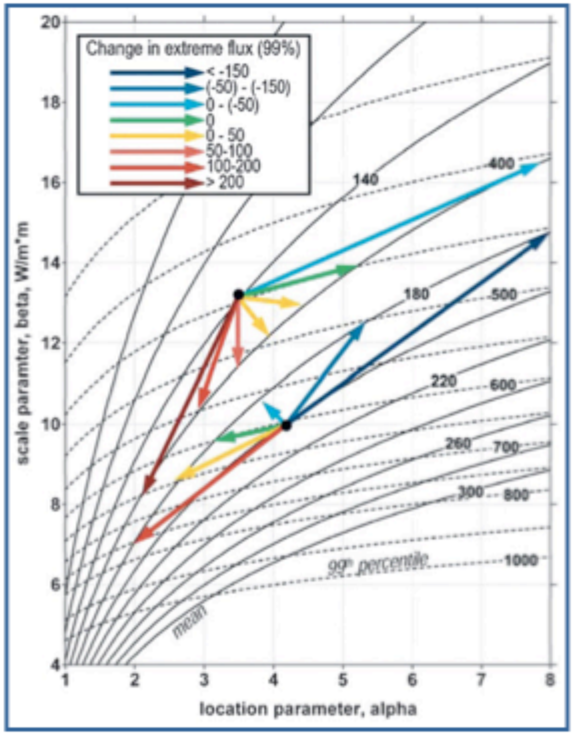
Gulev et al. 2013

Correction of bias using 3-parameter cloud cover PDF

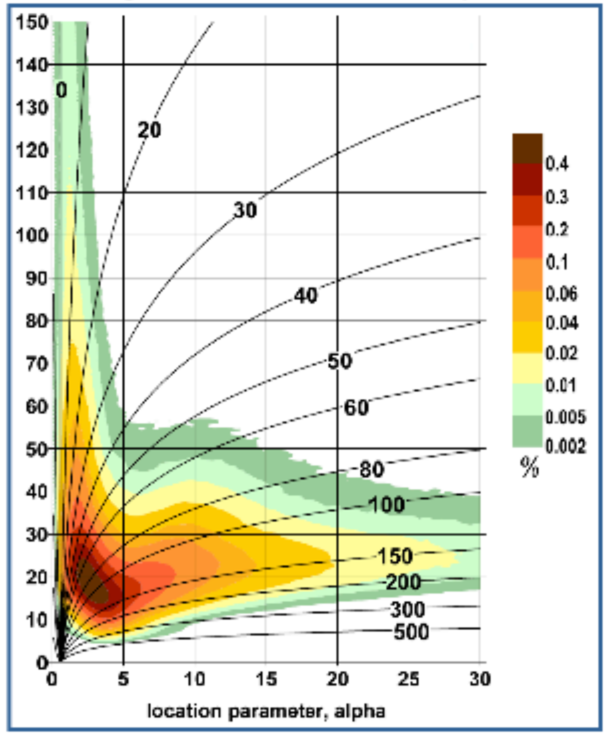


Properties of the MFT distribution

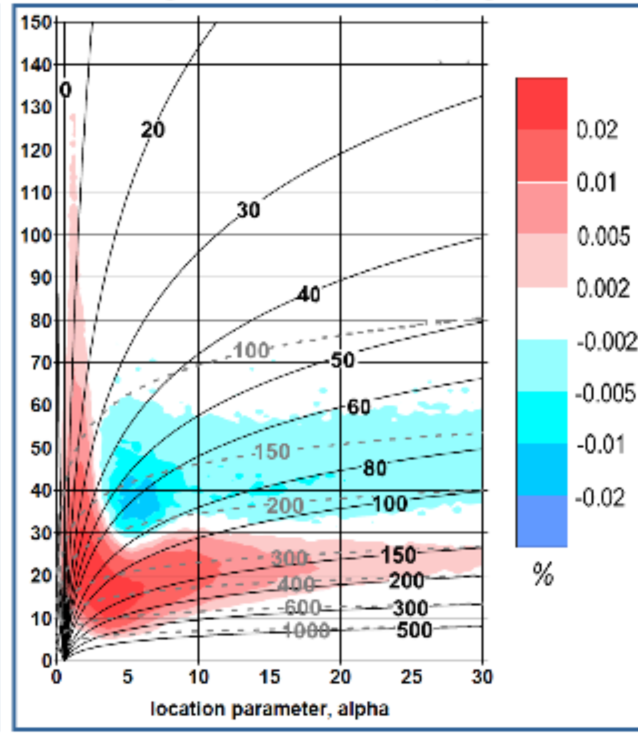
Same mean → different extremes



Integration of fluxes in α, ▯ *-space*



Integrated effect of sampling bias



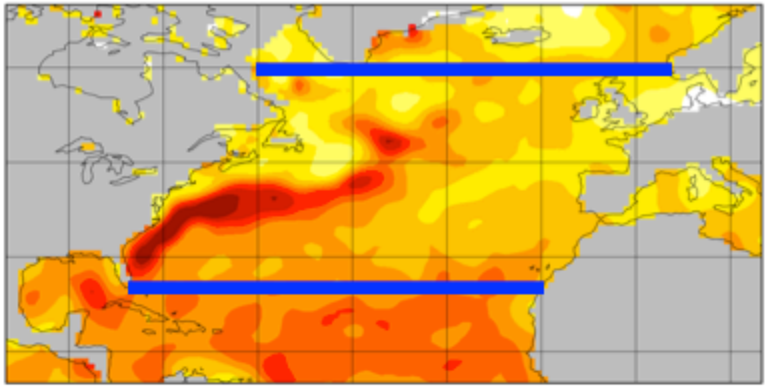
Minimization of sampling error: Integration of MFT PDF applying censored sample theory for estimating parameters:

$$P(x) = (\alpha \cdot \beta) \cdot e^{\beta x} \cdot e^{-\alpha \cdot e^{\beta x}}$$

$$\bar{x} = \int_{-\infty}^{\infty} P(x) \cdot x dx = \frac{C + \ln \alpha}{-\beta} \qquad \mathrm{var}\, x = \int_{-\infty}^{\infty} P(x) \cdot x^2 dx - \bar{x}^2 = \frac{\pi^2}{6\beta^2}$$

$$\frac{n}{\alpha} = n_1 + \sum_{i=n_1+1}^{n} \exp(-\beta x_i); \qquad -\frac{n}{\beta} - \frac{n_1}{\beta}(C + \ln \alpha) + \sum_{i=1}^{n} x_i = \frac{2}{\alpha^2 \beta}\left(\frac{3}{2} - C - \ln \alpha\right) + + \sum_{i=n_1+1}^{n} x_i \exp(-\beta x_i)$$

Flux averaging (25N-60N) over lat-lon space



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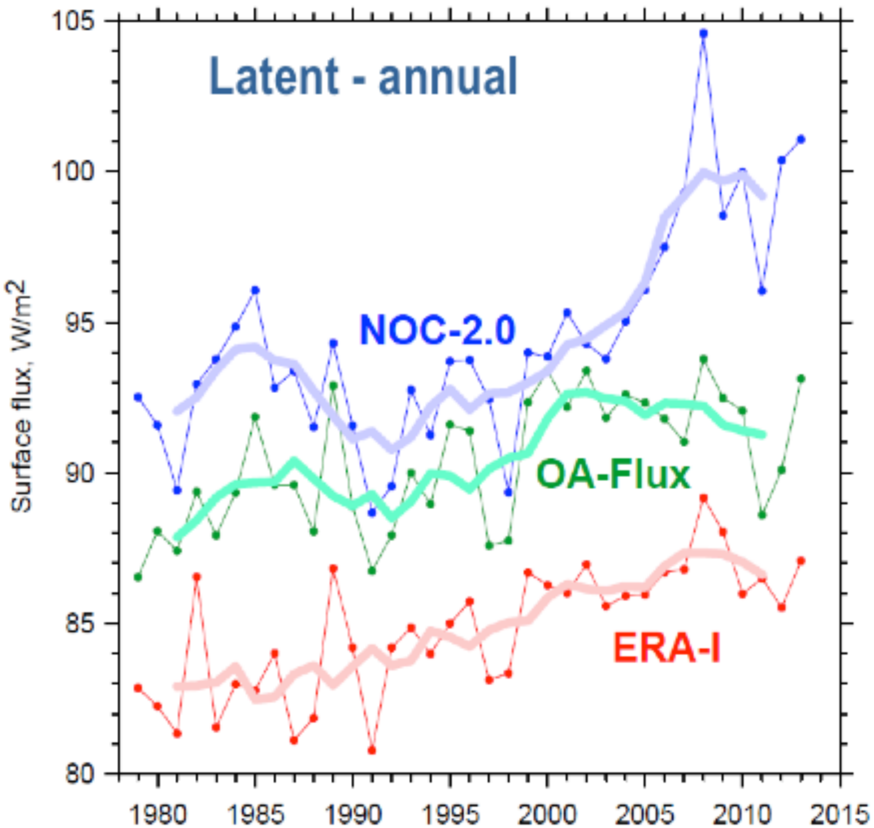

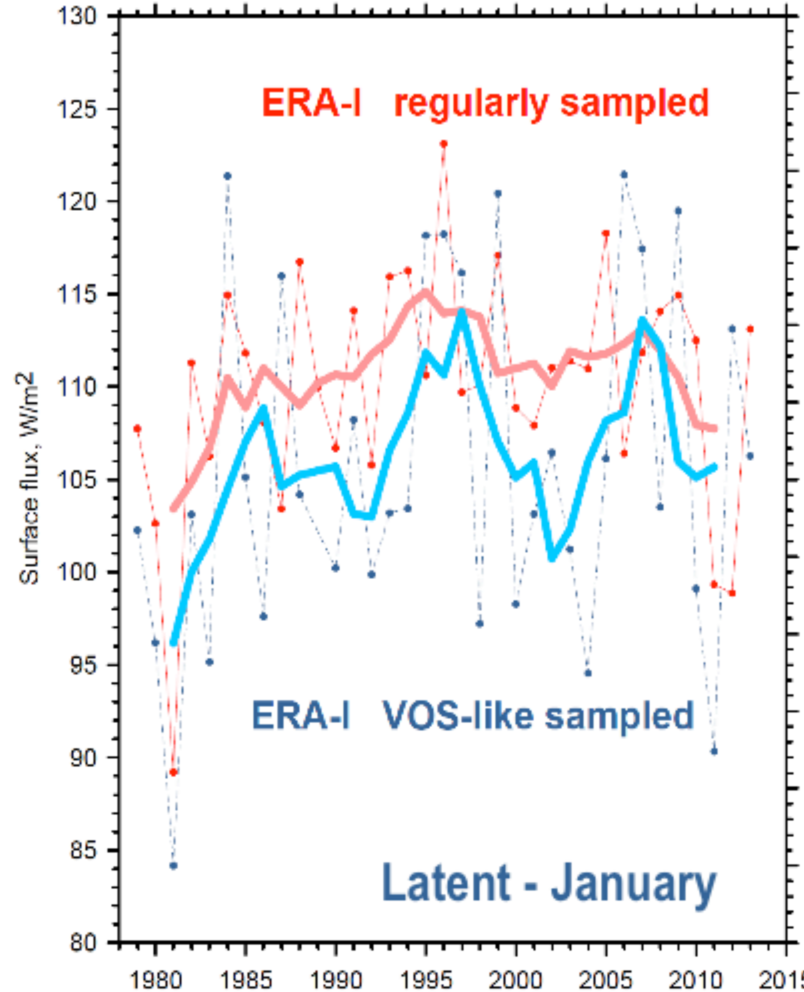

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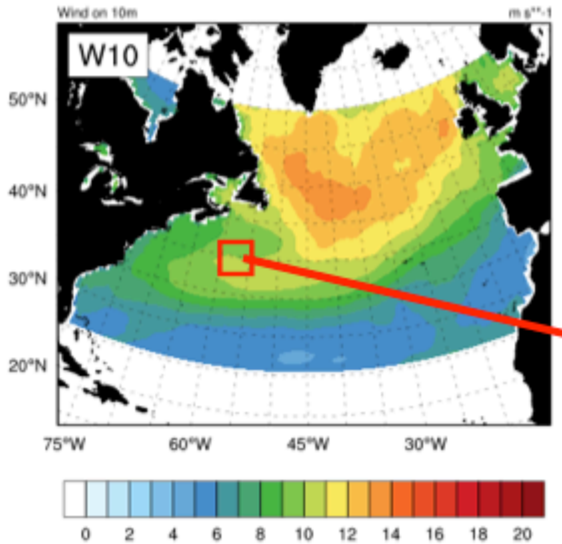
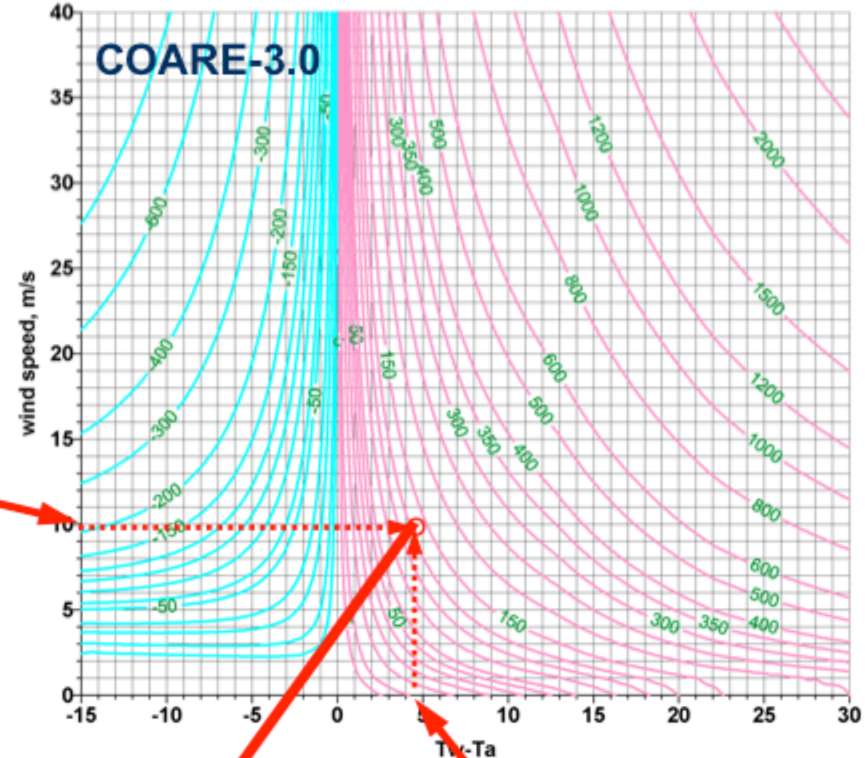
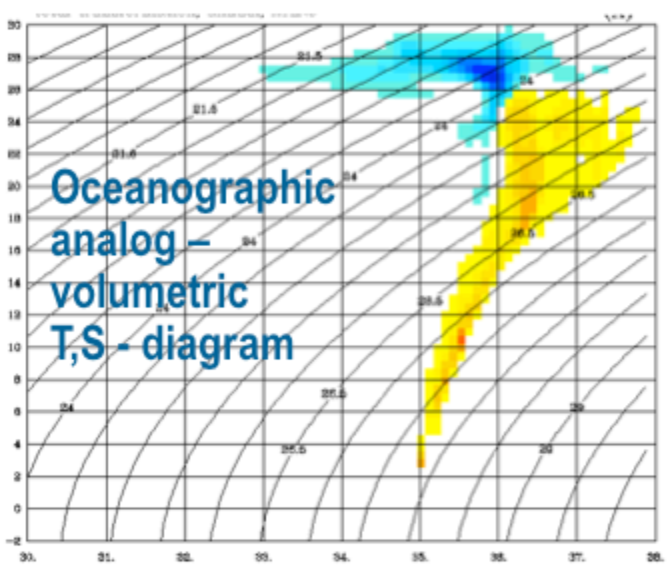
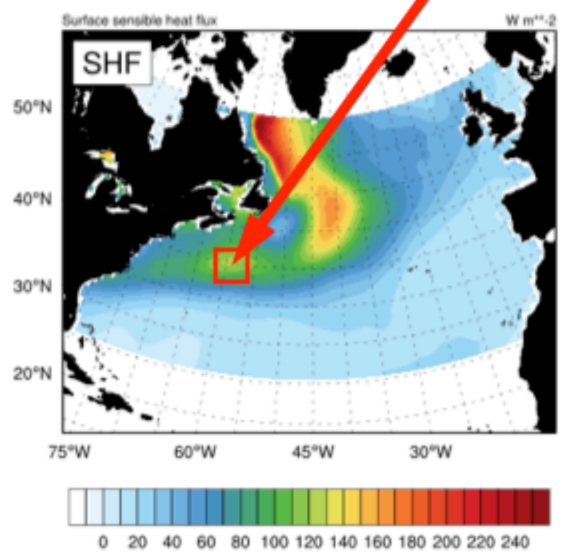
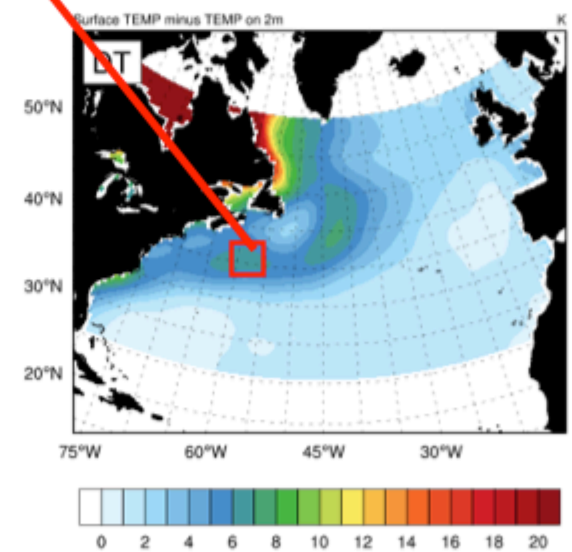


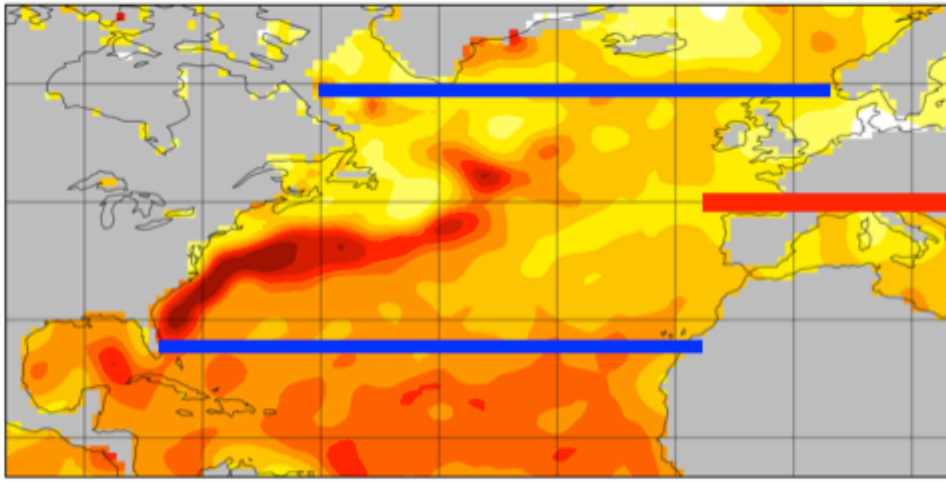


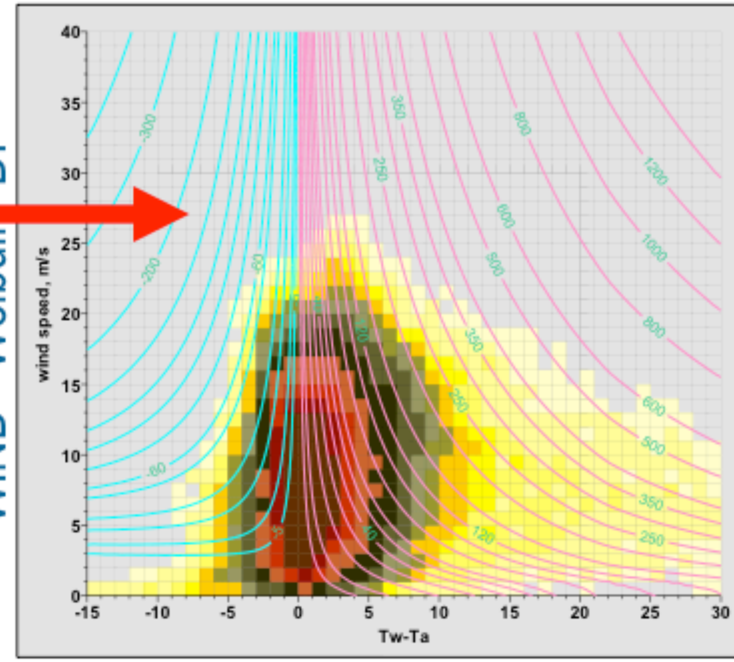






From "*lat-lon*" space to "dt(dq) –V" space





WIND - Weibull PDF

SST-Tair – MFT PDF

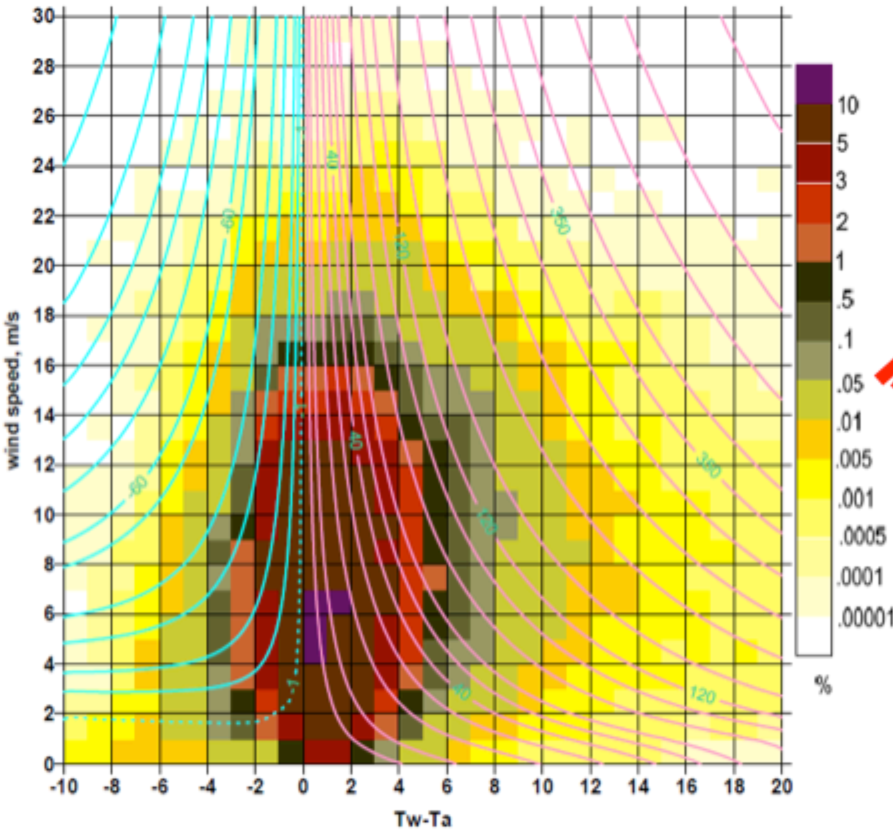
$$Q_\Sigma = \int_t dt \int_S Q\,dS = \int_V dV \int_{\delta T} Q\,d(\delta T)$$

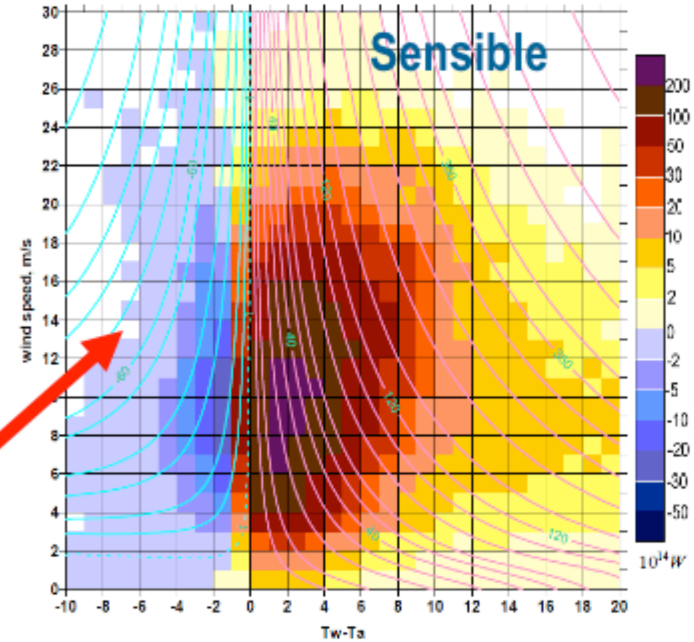
$$P(V \mid \delta T)\cdot P(\delta T) = \frac{\alpha_V}{\beta_V}\left(\frac{V}{\beta_V}\right)^{\alpha_V-1}\cdot e^{-\left(\frac{V}{\beta_V}\right)^{\alpha_V}} \cdot (\alpha_T\cdot\beta_T)\cdot e^{-\beta_T\,\delta T}\cdot e^{-\alpha_T\cdot e^{-\beta_T\delta T}}$$

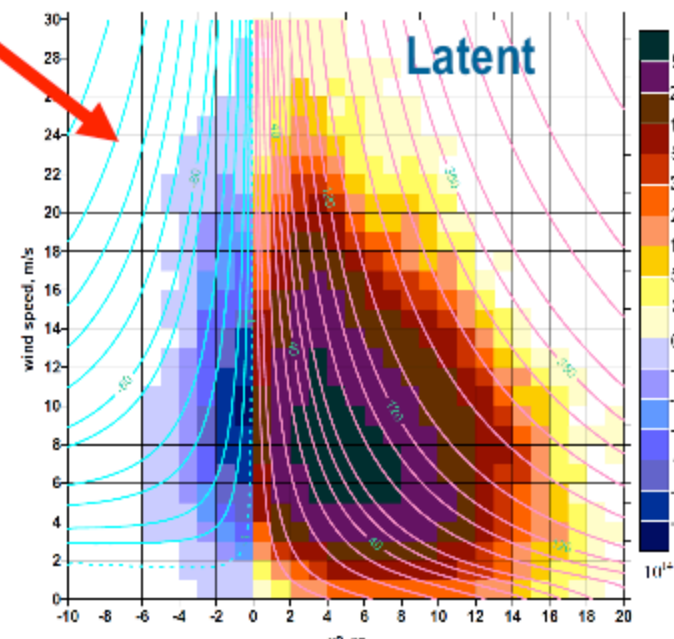
Weibull

MFT

From probabilities to fluxes in "$\delta T(\delta e)$ –V" space

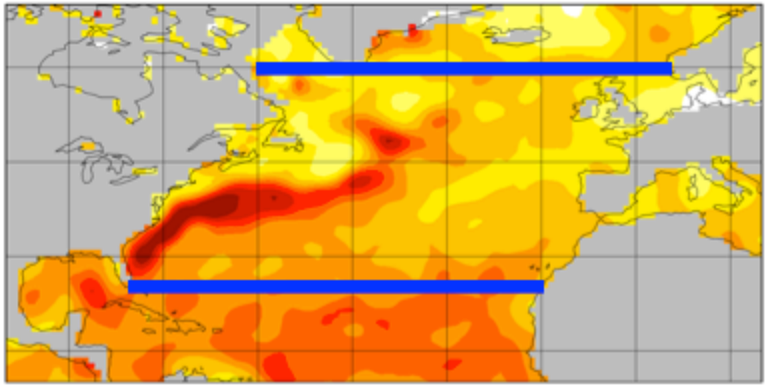






$$\sum_{dT}\ \sum_{V}\left[P(dT_i \mid V_j)\times Q_{dT_i,V_j}\right]$$

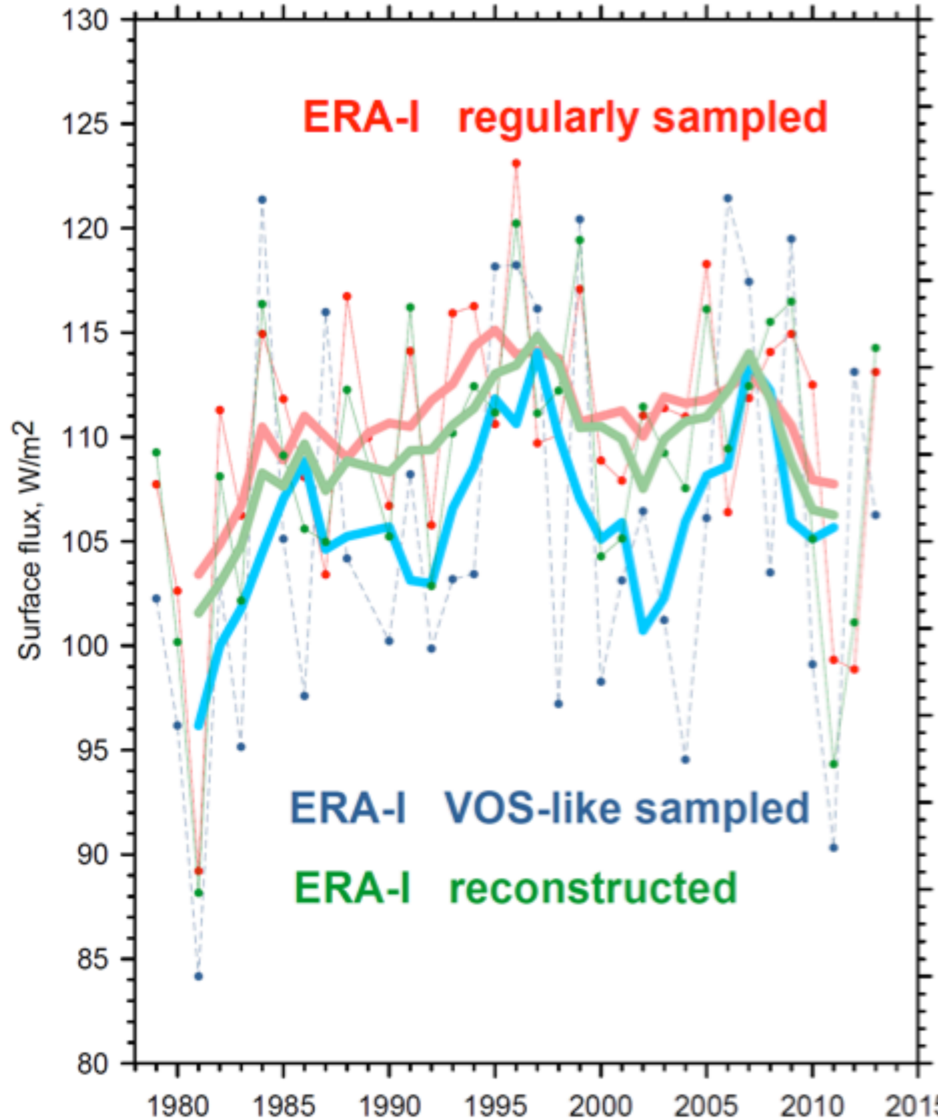
Reconstructed time series (25N-60N)



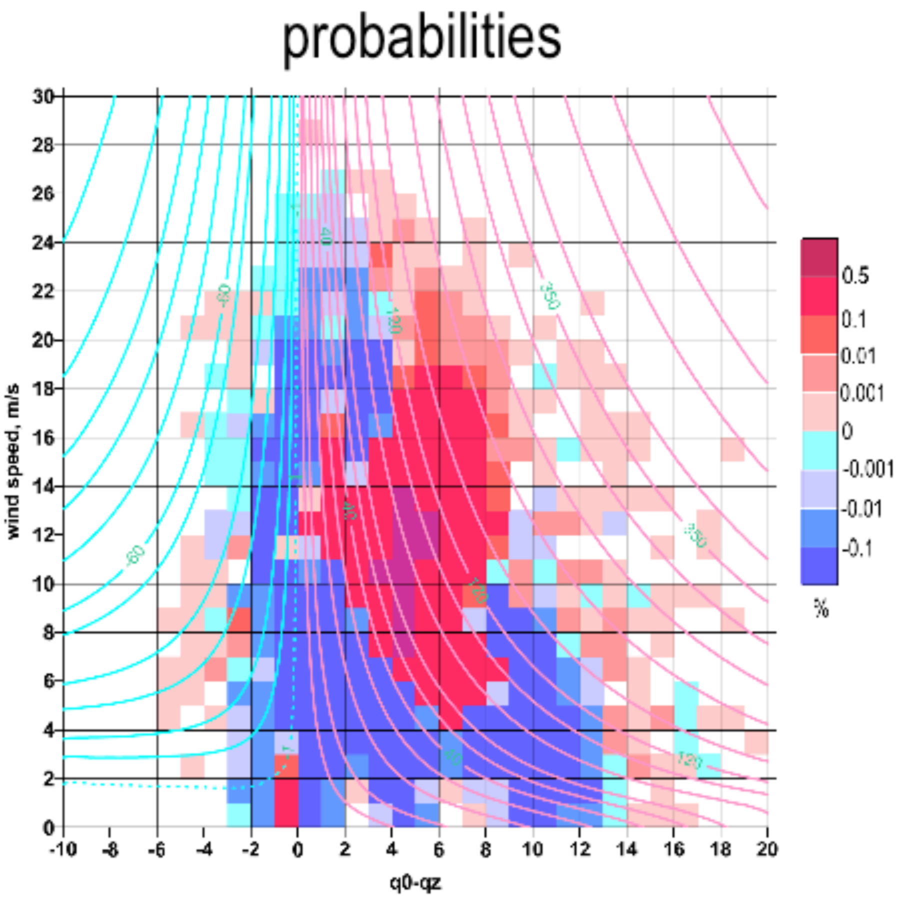
- ~8 times smaller uncertainties, strong biases removed

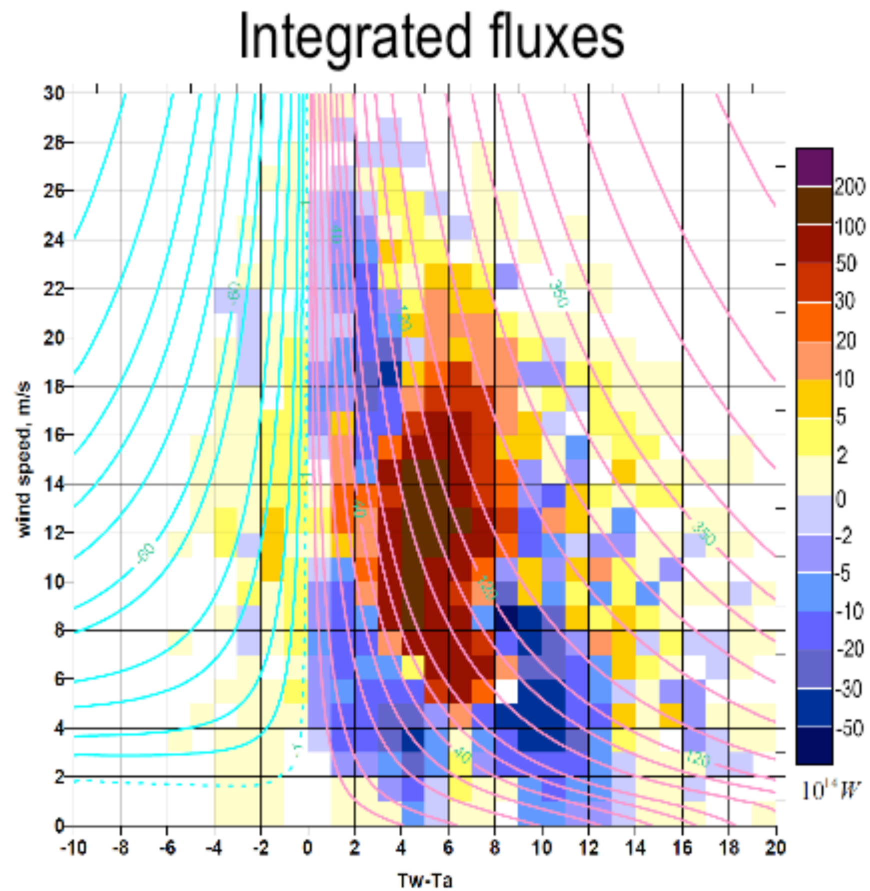
Long-term annual sampling error:
0.51 W/m² (was 4.83)
Long-term January sampling error:
1.36 W/m² (was 7.79)
Max sampling error:
4.24 W/m² (was 19.45)

- More realistic interannual variability

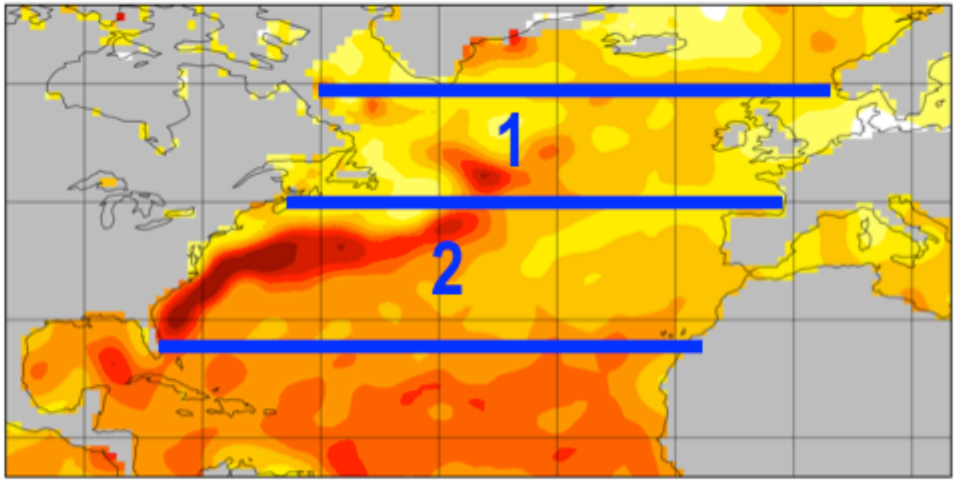


Differences between fully sampled and undersampled fluxes





Regionally integrated fluxes (25 – 60 N)



Sampling uncertainty of the regionally integrated surface flux (SH+LH)	1	2	1+2
Real VOS sampling	6.72%	5.84%	6.14%
2-D reconstruction (Weibull + MFT)	0.92%	0.75%	0.81%