Toward a Balanced Net Heat Flux at the Ocean Surface

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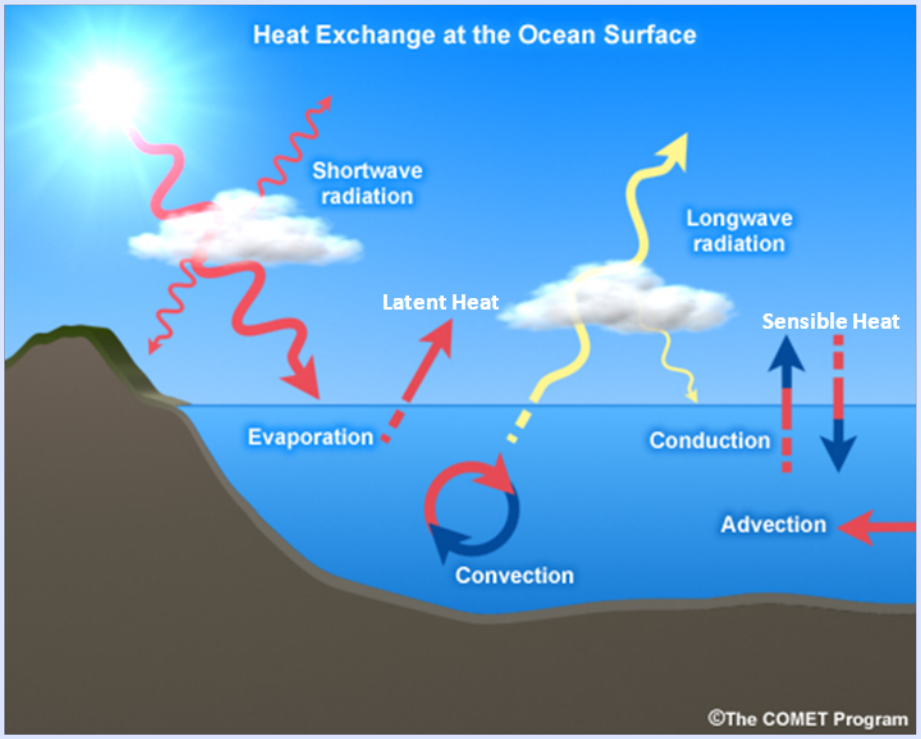
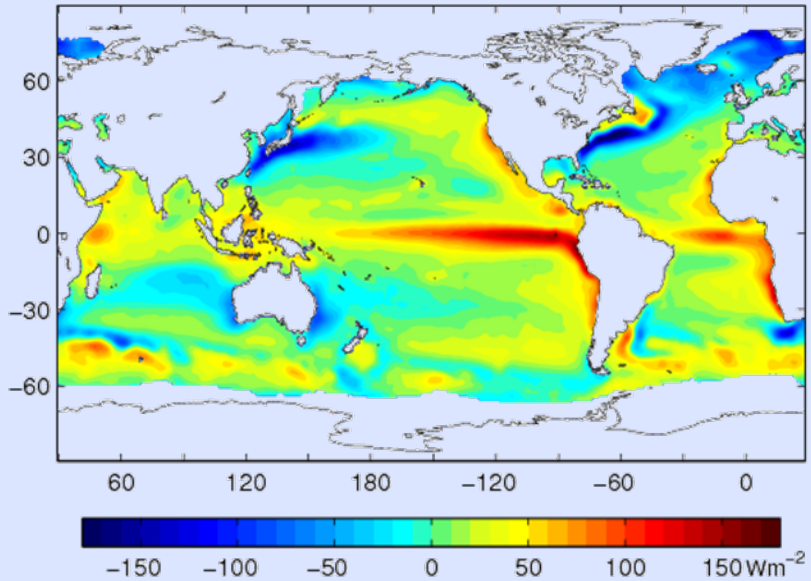
Heat exchange at the Ocean Surface



Qnet (average of 11 products)



Net Heat Flux: Qnet = sum of (SW, LW, LH, SH)

SW → SWD and SWU

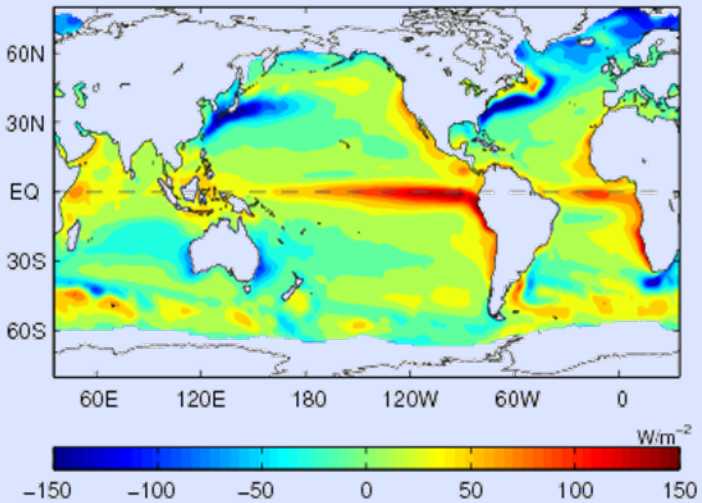
LW → LWD and LWU

Qnet is the sum of 6 terms →

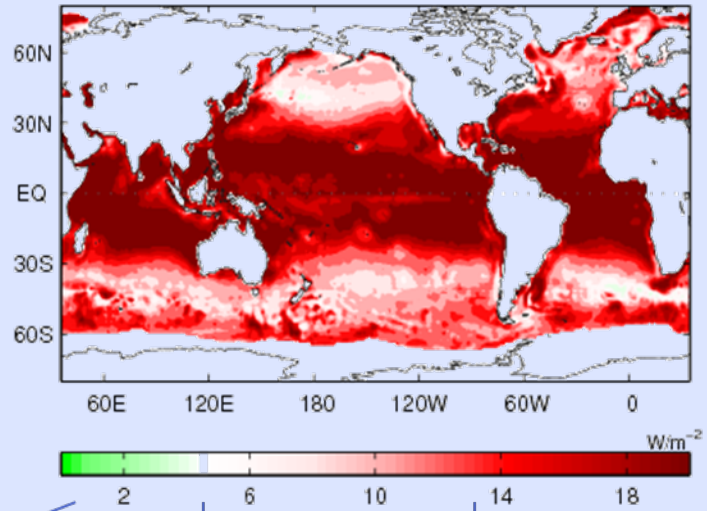
The accuracy of the Qnet estimate is affected by error in each term and error combination.

Mean difference between 11 Qnet products

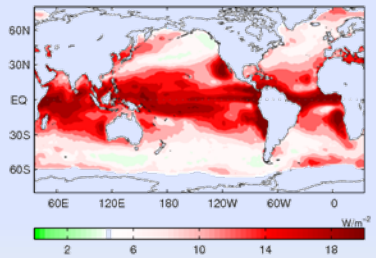
Mean Qnet
(average of 11 products)



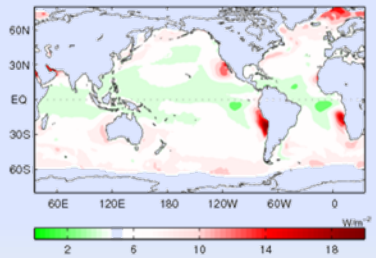
STD Qnet (11 products)



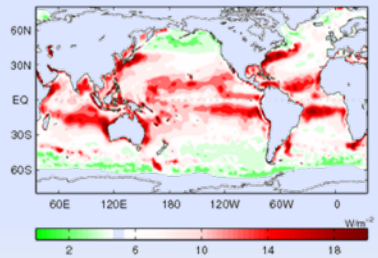
STD SW



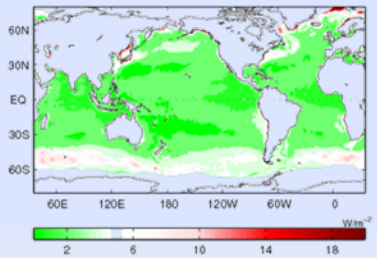
STD LW



STD LH



STD SH

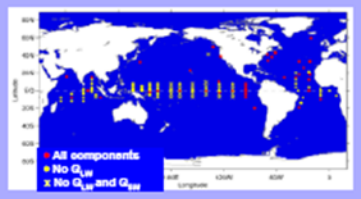


List of the air-sea flux products

Type	Name	Variables	Resolution & Data period
NWP Reanalyses	NCEP1 NCEP2 ERA40	Qnet, SW, LW, LH, SH, Also SWD, SWU, LWD, LWU	6 hourly, 1948 - 6 hourly, 1979 - 6 hourly, 1957 - 2002
Recent NWP Reanalyses	CSFR ERAinterim MERRA	Qnet, SW, LW, LH, SH Also SWD, SWU, LWD, LWU	Hourly, 1979 - 6 hourly, 1979 - Hourly, 1979 -
Ship-based analysis	NOCS2	Qnet, SW, LW, LH, SH	Monthly, 1973 -
Blended analysis	CORE2	Qnet, SW&LW(ISCCP), LH&SH (Satellite and NCEP1)	Monthly, 1948-2006
Satellite-based analyses	FLASHFlux SRB ISCCP	SW, LW Also SWD, SWU, LWD, LWU	Hourly & daily, 2009 - Daily, 1983 - Daily, 1983 -
Objective analysis	OAFlux	LH, SH	Daily, 1958 -

The WHOI OAFlux Project: Methodology and Strategy

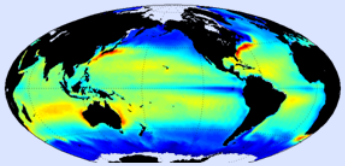
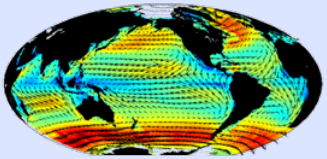
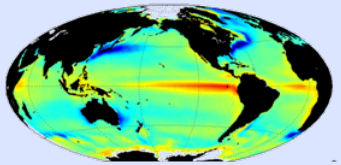
Global air-sea fluxes of heat, freshwater, and momentum are computed from bulk flux parameterizations using observed/modeled air-sea variables as inputs.

Existing Problems	Our Remedies
Not all flux-related variables can be observed by satellites.	Use atmospheric reanalyses to fill in missing information.
All data have errors, particularly the reanalyzed variable fields.	Obtain the best possible estimate through **objective synthesis** of all available sources (least-squares estimation based on the Gauss-Markov theorem)
Error in each dataset needs to be quantified for optimization.	Global flux buoys as validation database 

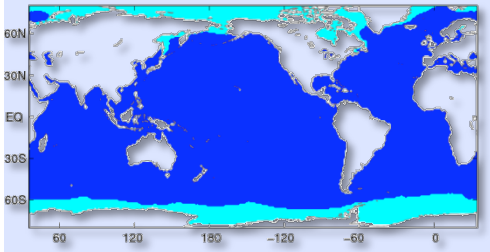
OAFlux = Objectively Analyzed air-sea variables + bulk flux parameterization (COARE3.0)

OAFlux Research Products

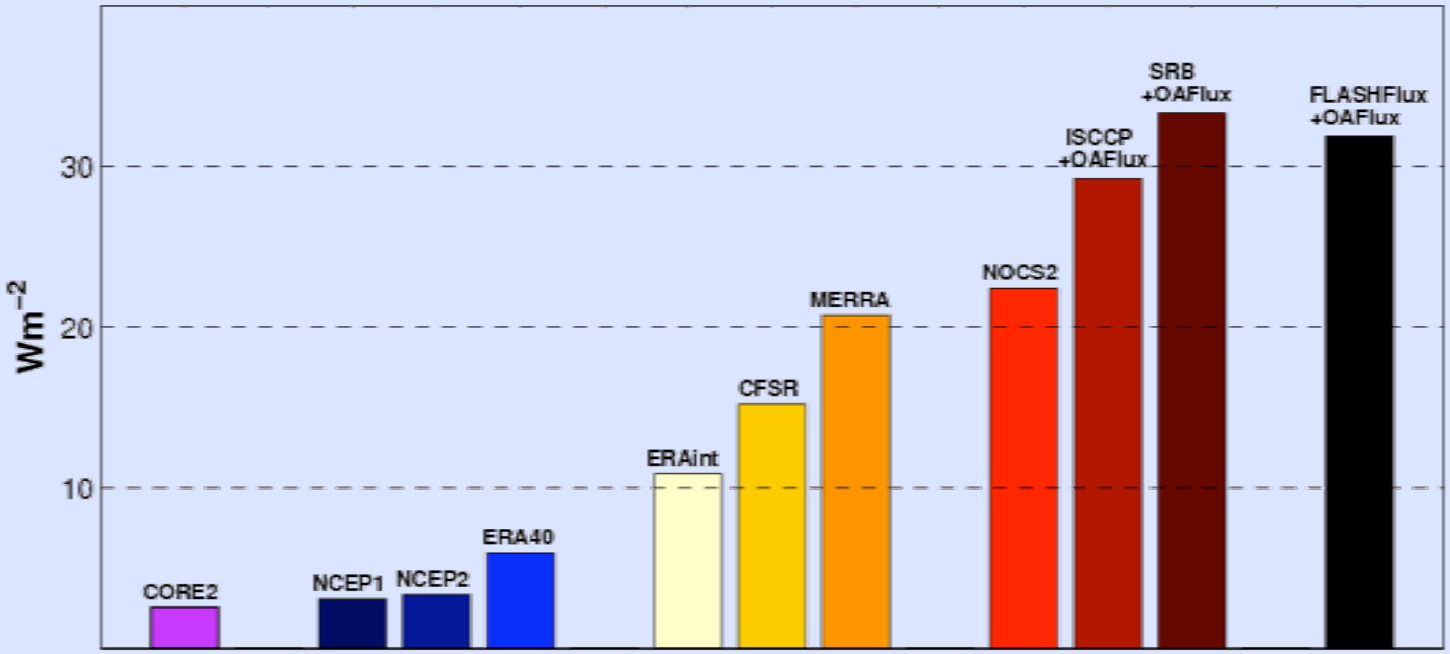
Project website: http://oaflux.whoi.edu

• **Evaporation** • **Latent and Sensible heat fluxes** 	• 1958-present, 1°, daily, monthly • 1999-present, 0.25°, daily • Objective synthesis of satellite products (wind speed, SST, qair and Tair) and selected atmospheric reanalysis fields from NCEP, ERA40, and ERA-interim.	**Freshwater flux (E-P)** OAFlux evaporation GPCP precipitation 1979 to present (>30 yrs)
Wind and Wind Stress 	• 1987-present, daily, 0.25° • 1° analysis is from a spatial average of 0.25° • Objective synthesis of 11 satellite sensors (SSMI, SSMIS, AMSRE, QuikSCAT, and ASCAT).	**Momentum flux** OAFlux wind stress 1987 – present (>24 yrs)
Net Heat flux 	Work in progress • 1983-present, 1°, daily • Synthesis of satellite products and selected reanalysis fields	**Net heat flux** Explore a combined use of OAFlux latent/sensible heat fluxes FLASHFlux/SRB/ISCCP surface radiation from 1983 – present

Ice-free ocean area

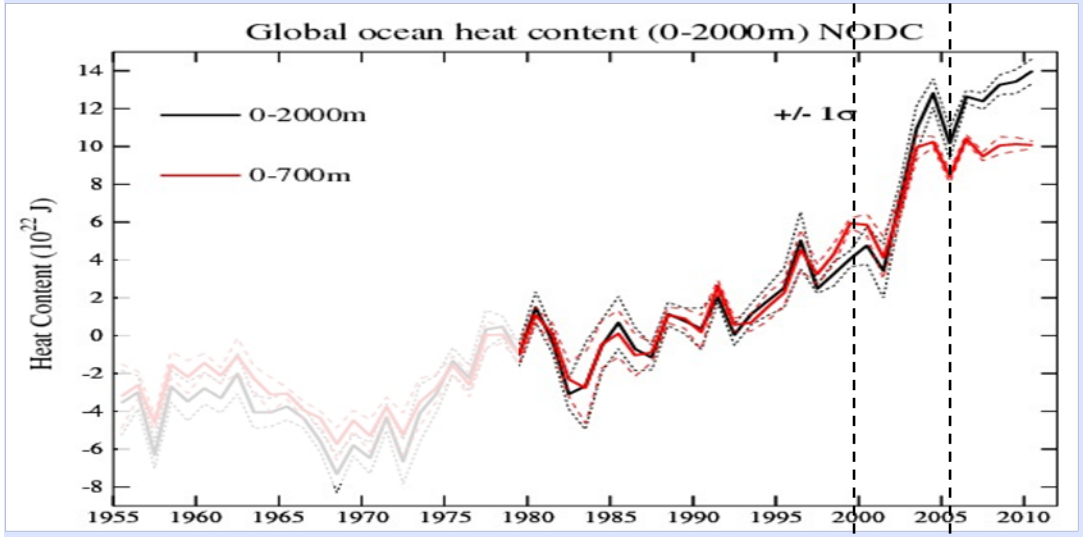


The net heat budget over the global ice-free oceans from 11 products



- How much should the heat budget be balanced over the global ice-free oceans?
- Should it be near zero (O(2-3 Wm^{-2}))?

Uncertainties in Qnet affect not only the global mean but also the variability

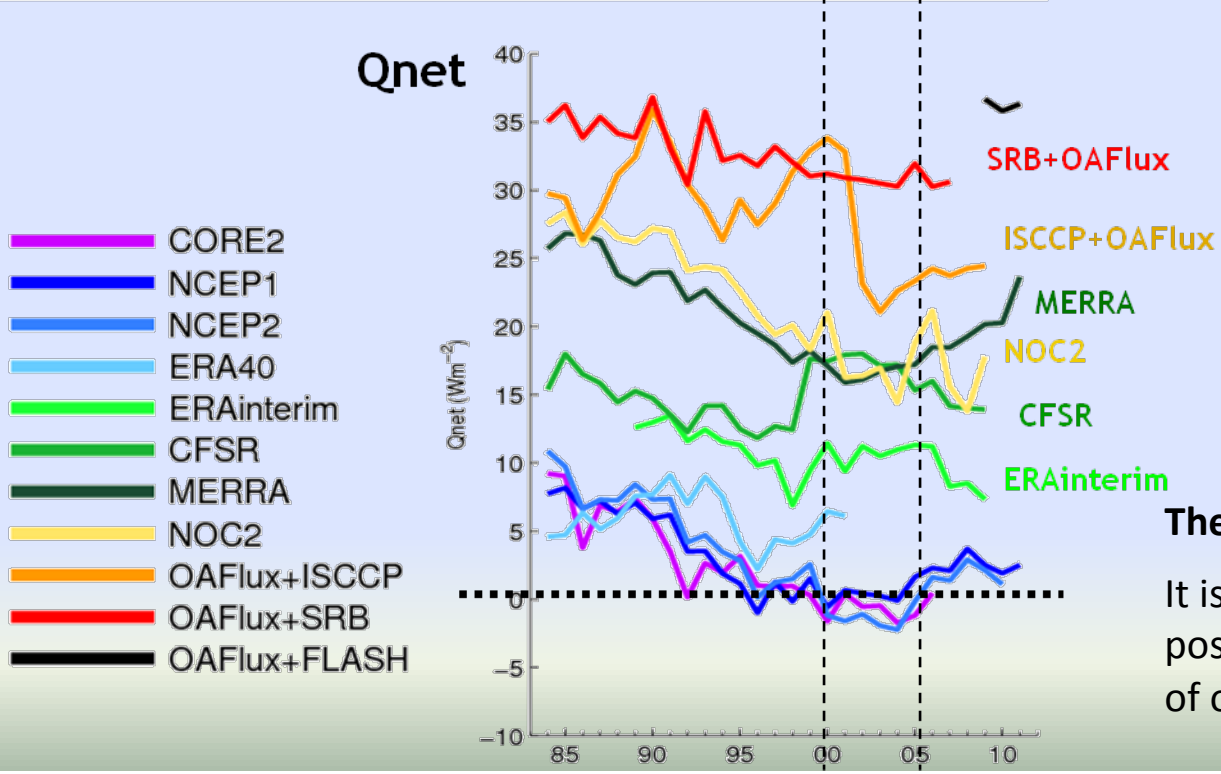


Annual-mean time series
Qnet versus Ocean Heat Content

Loeb et al. 2012, *Nature Geoscience*

"between January 2001 and December 2010, Earth has been steadily accumulating energy at a rate of 0.50±0.43Wm^{-2}"

"energy storage is continuing to increase in the sub-surface".



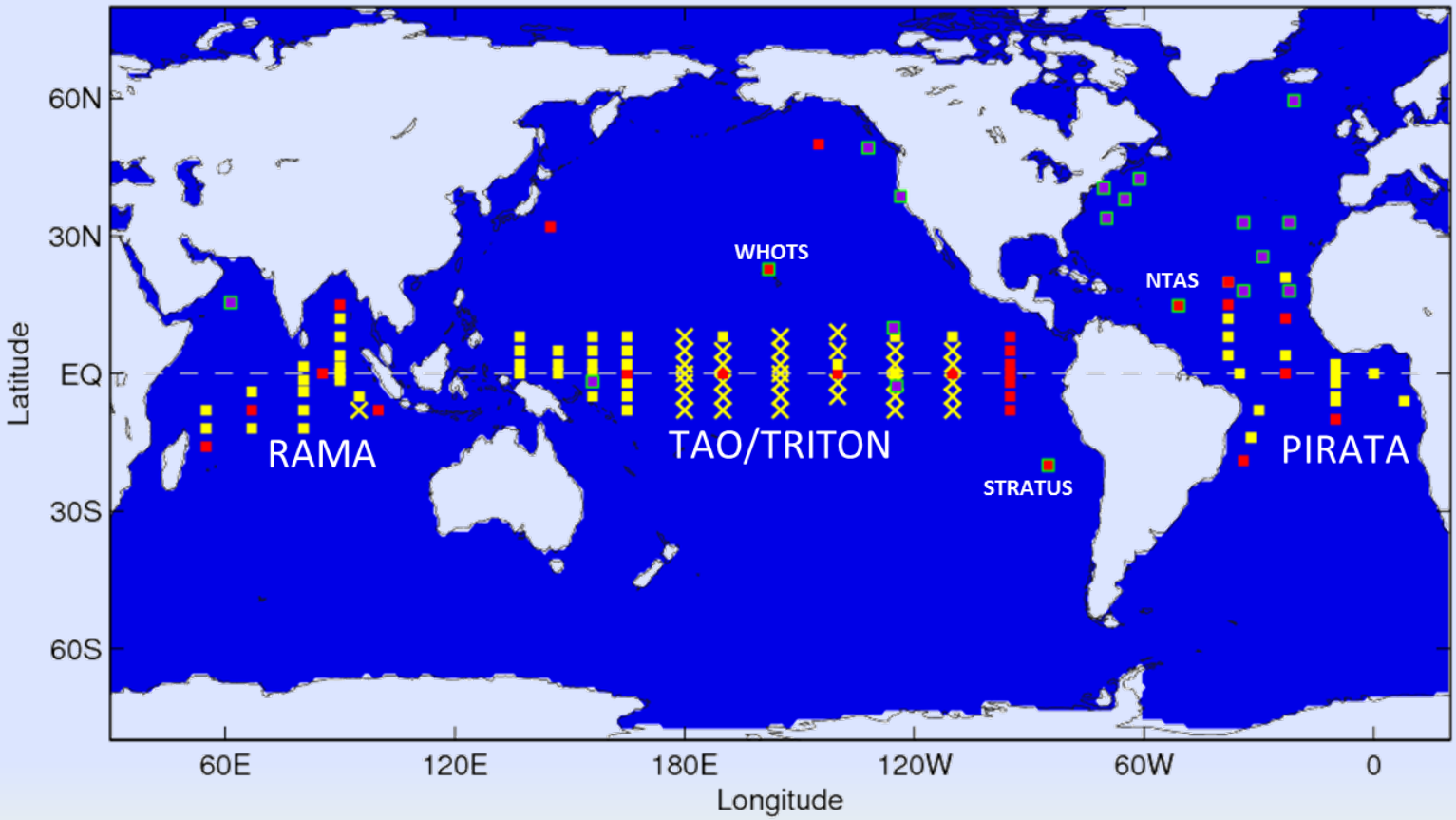
The 11 Qnet products show that

It is not even clear whether Qnet was positive or negative during the increase of ocean HC in recent past.

But Qnet cannot be measured.

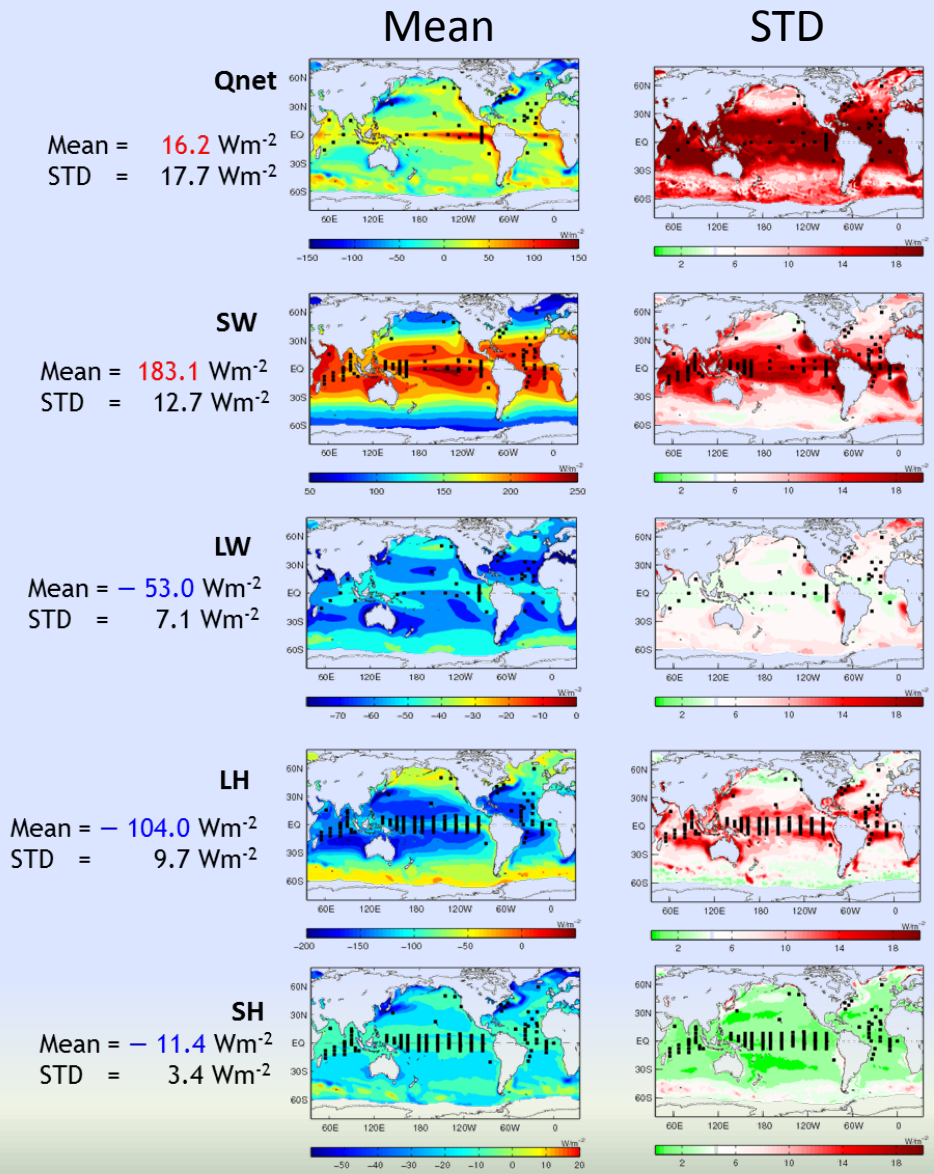
Even the measurements of individual heat flux component are available only at limited locations.

Moored surface flux buoy sites (Active and Archived)



- All components
- No Q_{LW}
- No Q_{LW} and Q_{SW}
- WHOI buoy, active
- WHOI buoy, archive

Mean and STD of existing products



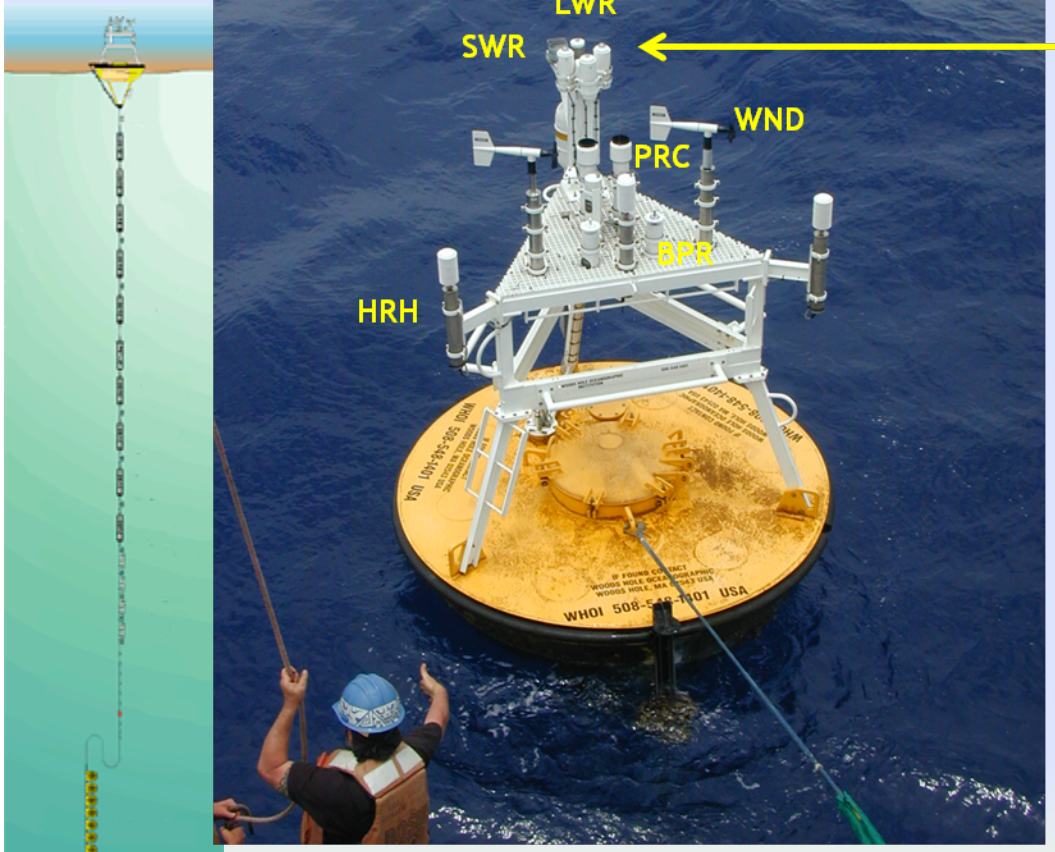
Main topic of this talk:

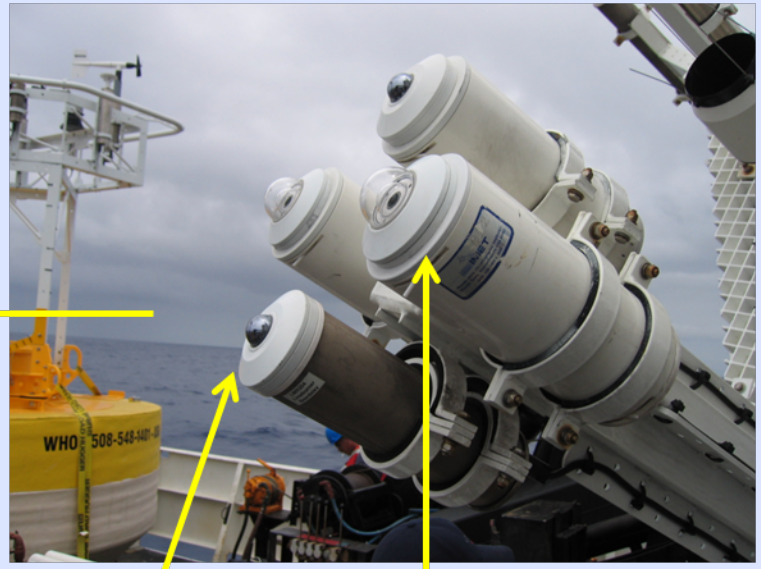
- Evaluating the existing air-sea flux products using buoy measurements, with particular focus on satellite SW and LW products.

What can we learn from buoy measurements?

- bias in each flux component?
- bias in the representation of regional processes/temporal variability?
- sources of warm bias that cause the global budget imbalance?

WHOI Moored Flux Buoy





IR Flux - Pyrgeometer

Solar Flux - Pyranometer

from Bob Weller

Flux Buoy Measurements

What are measured by the WHOI flux buoys?

- Incoming shortwave radiation (SW↓)
- Incoming longwave radiation (LW↓)
- Air and sea temperatures (Ta and Ts)
- Relative humidity (rh)
- Barometric pressure (BPr)
- Wind speed and direction (U, dir)
- Precipitation (P)

Measurements are recorded every minute

How are buoy fluxes computed?

- **Net shortwave radiation:**

  $Q_{SW} = SW\downarrow - \alpha\,(SW\downarrow)$

  α: the surface albedo based on the Payne (1972) formulation

- **Net longwave radiation:**

  $Q_{LW} = (\varepsilon\,\sigma\,T_s^4 - (1-\varepsilon)\,LW\downarrow) - LW\downarrow$

  σ: the Stefan – Boltzmann constant; ε: emissivity

- **Latent and sensible fluxes:**

  $Q_{LH} = \rho\,L_e\,c_e\,U\,(q_s - q_a(rh))$

  $Q_{SH} = \rho\,c_p\,c_h\,U\,(T_s - T_a)$

  The COARE bulk flux algorithm 3.0 (Fairall et al. 2003) is used.

Accuracy of Buoy Measurements

(Colbo and Weller, 2009)

Accuracy = the inherent "noise level" of the instruments

Error sources:

- inherent measurement precision (e.g. the longwave thermopile),
- laboratory calibration uncertainty,
- uncorrectable calibration drift,
- other environmental factors (e.g. low wind errors, solar leakage through the longwave dome, humidity hysteresis near saturation, etc.).

Rooftop radiative flux sensor calibration facility NOAA/ESRL/GMD Boulder, CO (From Chris Fairall)

Estimated errors in annual mean values of buoy fluxes:

	Net longwave	Net shortwave	Sensible heat	Latent heat	Momentum	Total net
Percent error	10	2.5	15	5	10	20
Typical error	3.9 W m^{-2}	5 W m^{-2}	1.5 W m^{-2}	5 W m^{-2}	0.007 N m^{-2}	8 W m^{-2}

WHOI rooftop facility (from Bob Weller)

Errors in Downward Longwave Radiation:

Precision	Lab calibration	Drift	Field errors	Total
Dome temperature: 0.1°C Case temperature: 0.1°C Thermopile: 10 μV	Coef: 1.5 W m^{-2} Noise: 0.5 W m^{-2}	2 W m^{-2}	Tilt: <2 W m^{-2} Temperature gradients: 4 W m^{-2} Salt spray: <1 W m^{-2} Solar: <1% SW↓	Instant: 7.5 W m^{-2} Daily: 4 W m^{-2} Annual: 4 W m^{-2}

Errors in Downward Shortwave Radiation:

Precision	Lab calibration	Drift	Field errors	Total
0.1 W m^{-2}	2 W m^{-2}	<2 W m^{-2}	Tilt: <2% Temperature gradients: 1–2 W m^{-2} Salt spray: <1 W m^{-2}	Instant: 20 W m^{-2} (more in broken cloud) Daily: 6 W m^{-2} Annual: 5 W m^{-2}

Comparison approach

Buoy me:asures SWD and LWD

Net shortwave radiation:

$Q_{SW} = SW\downarrow - \alpha\,(SW\downarrow)$, α: the surface albedo

Net longwave radiation:

$Q_{LW} = (\varepsilon\,\sigma\,T_s^4 - (1-\varepsilon)\,LW\downarrow) - LW\downarrow$

σ: the Stefan – Boltzmann constant; ε: emissivity

(1) Define positive downward, negative upward

Net SW = SWD + SWU

Net LW = LWD + LWU

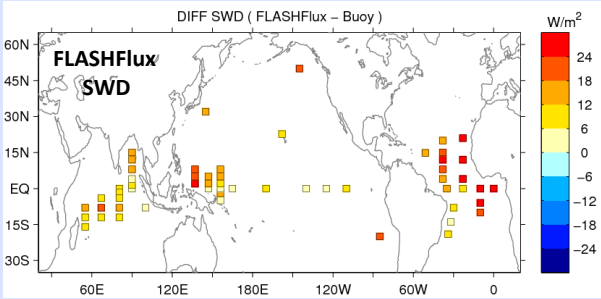
(2) Evaluate SWD, LWD and also net SW, net LW.

(3) Upward components (SWU and LWU) are not compared

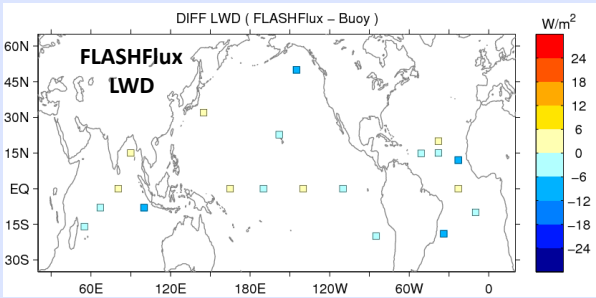
Downward Components: SWD and LWD

(2009-2011)

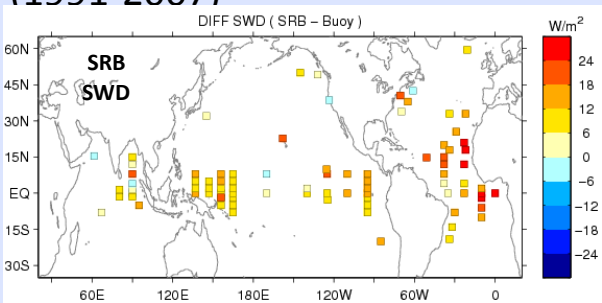
SWD

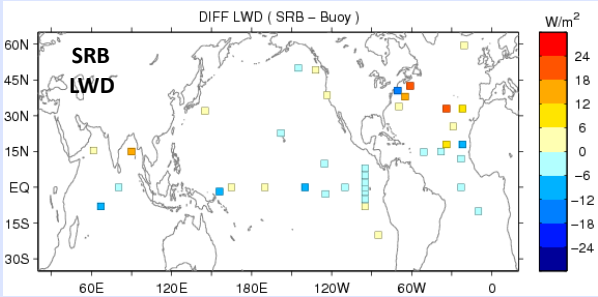


LWD



(1991-2007)





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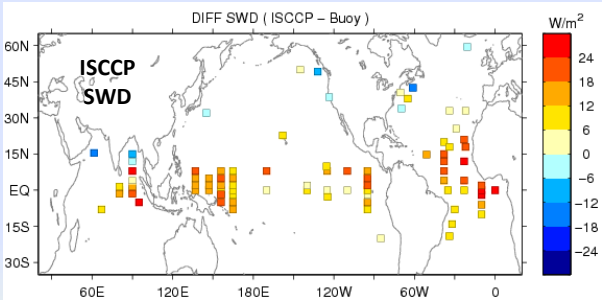
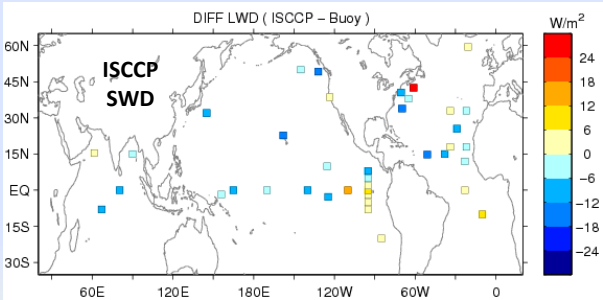


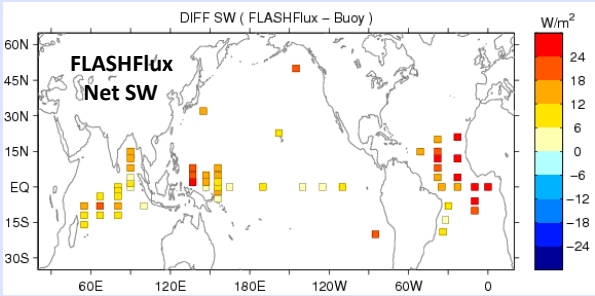


- SWD: overestimated (warm bias)
- LWD: underestimated (cold bias)

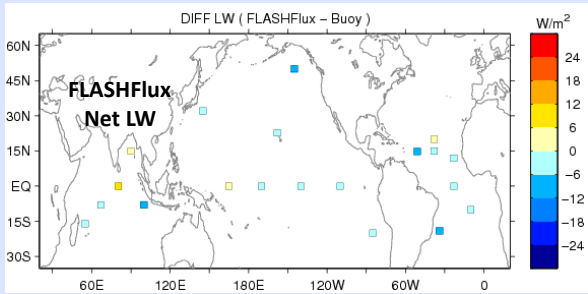
Paul Stackhouse:
Possible aerosol effect

Mean difference between satellite and buoy at each buoy site

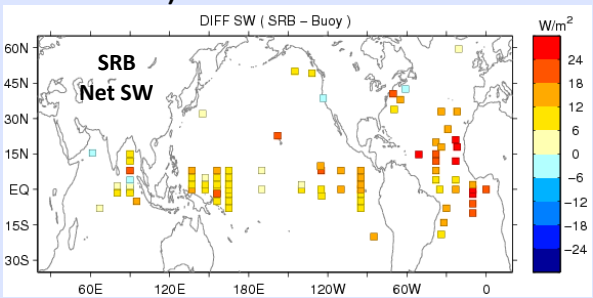
(2009-2011) **Net SW**

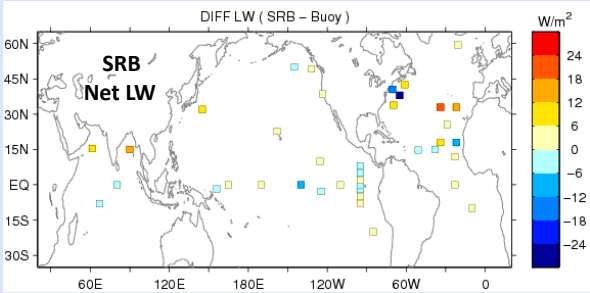


Net LW

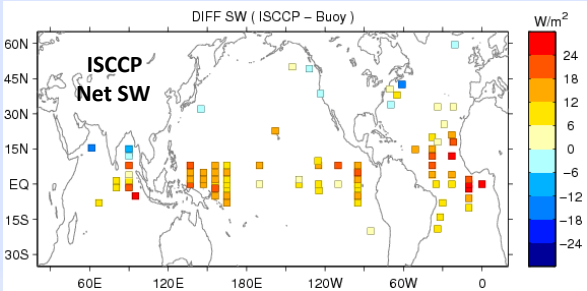


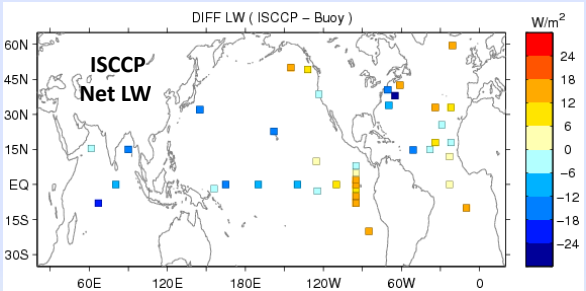
(1991-2007)





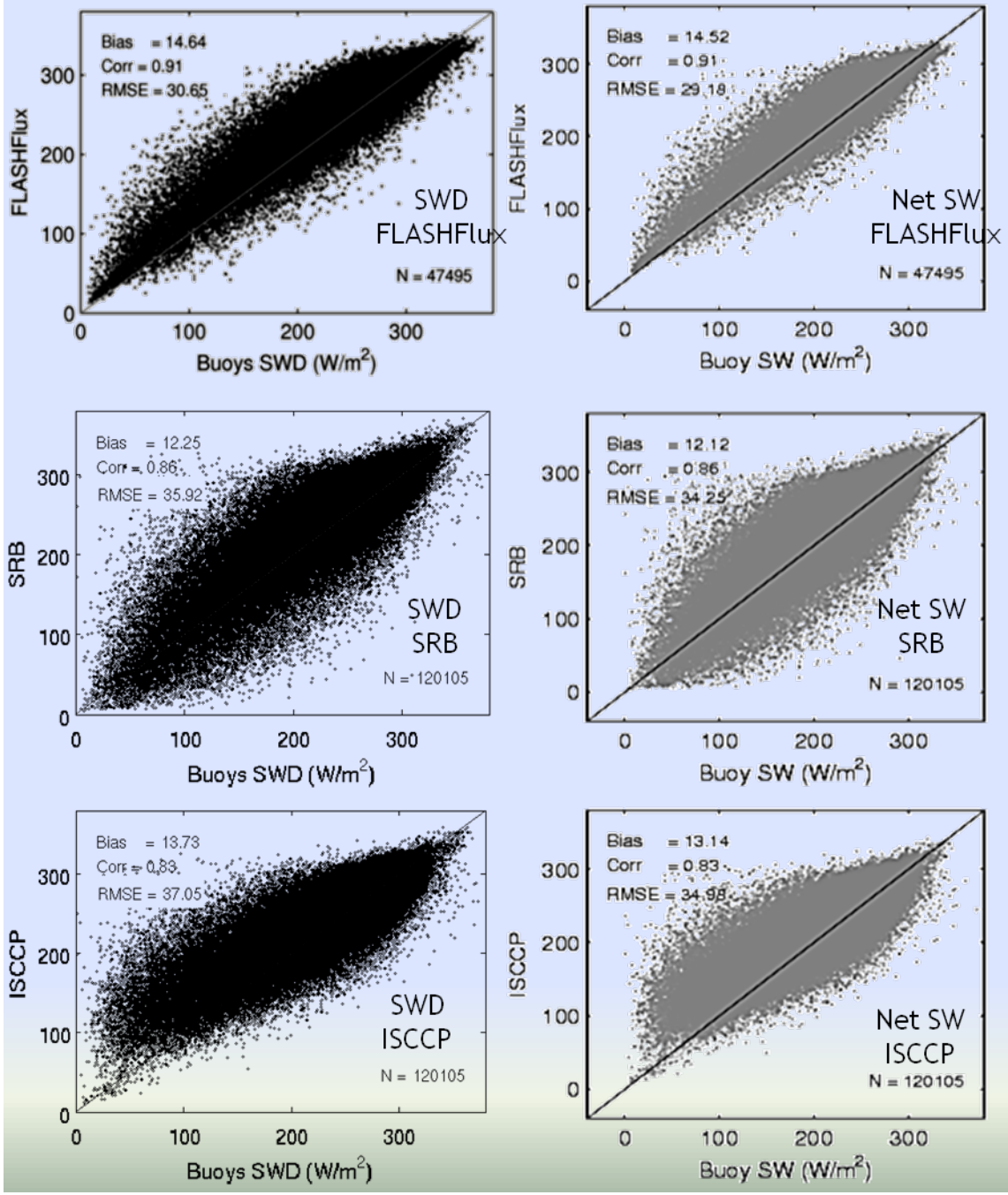
(1991-2007)





- Net SW: positive: net input to the ocean overestimated (warm bias)
- Net LW: negative: net loss from the ocean overestimated (cold bias)

Scatter plot for daily-mean SWD and net SW



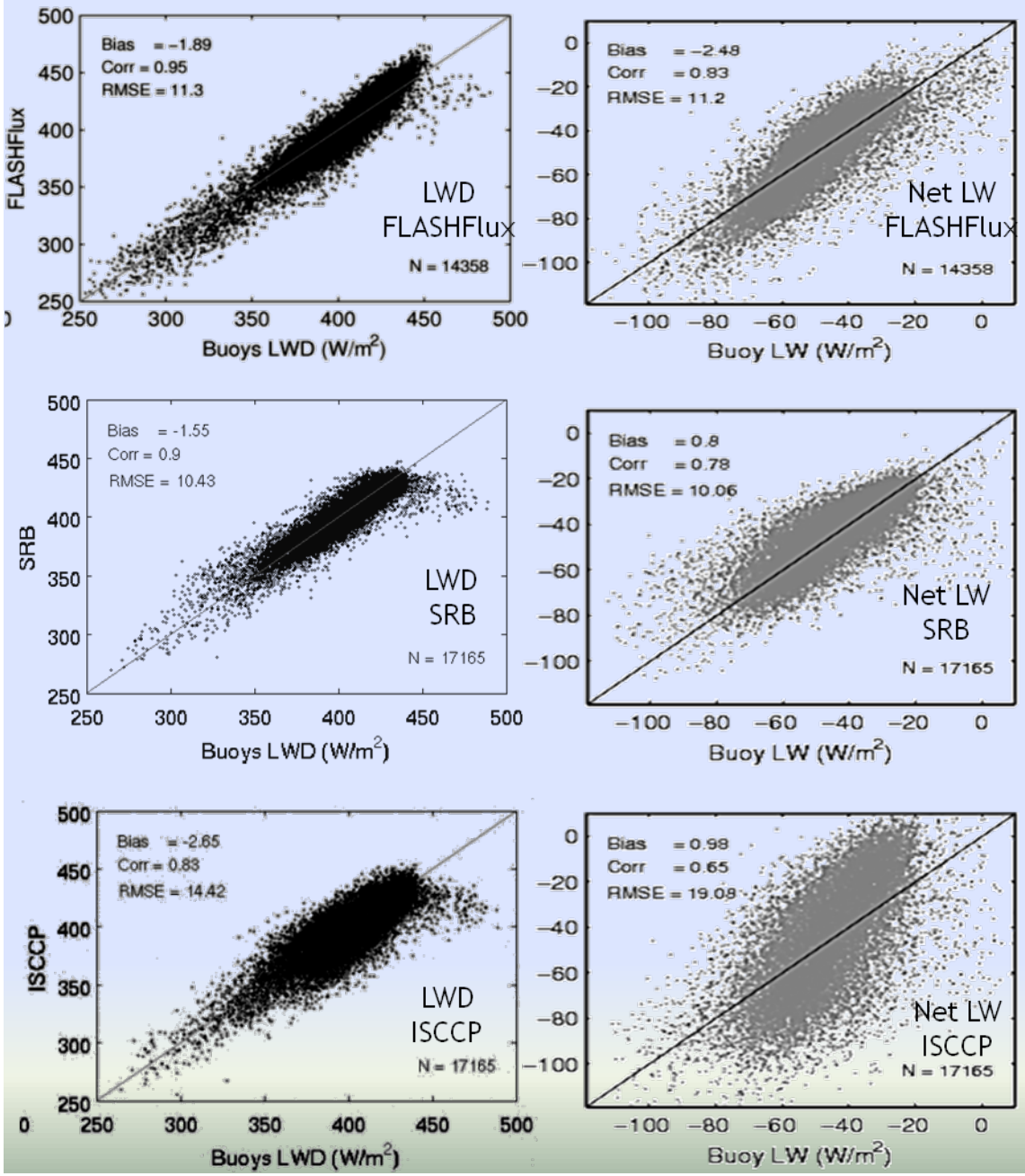
Statistics SWD/SW

Buoy accuracy: 5 Wm^{-2}

	Bias Wm^{-2}	Corr	RMSE Wm^{-2}	N
FLASHFlux				
SWD	14.6	0.91	30.7	47,495
Net SW	**14.5**	**0.91**	**29.1**	
SRB				
SWD	12.3	0.86	35.9	120,105
Net SW	**12.1**	**0.86**	**34.2**	
ISCCP				
SWD	13.8	0.83	37.5	120,105
Net SW	**13.1**	**0.83**	**35.0**	

- Bias between SWD and net SW is linear.
- FlashFlux correlates highly with buoy.

Scatter plots for daily-mean LWD and Net LW



Statistics LWD/LW

Buoy accuracy: 4 Wm^{-2}

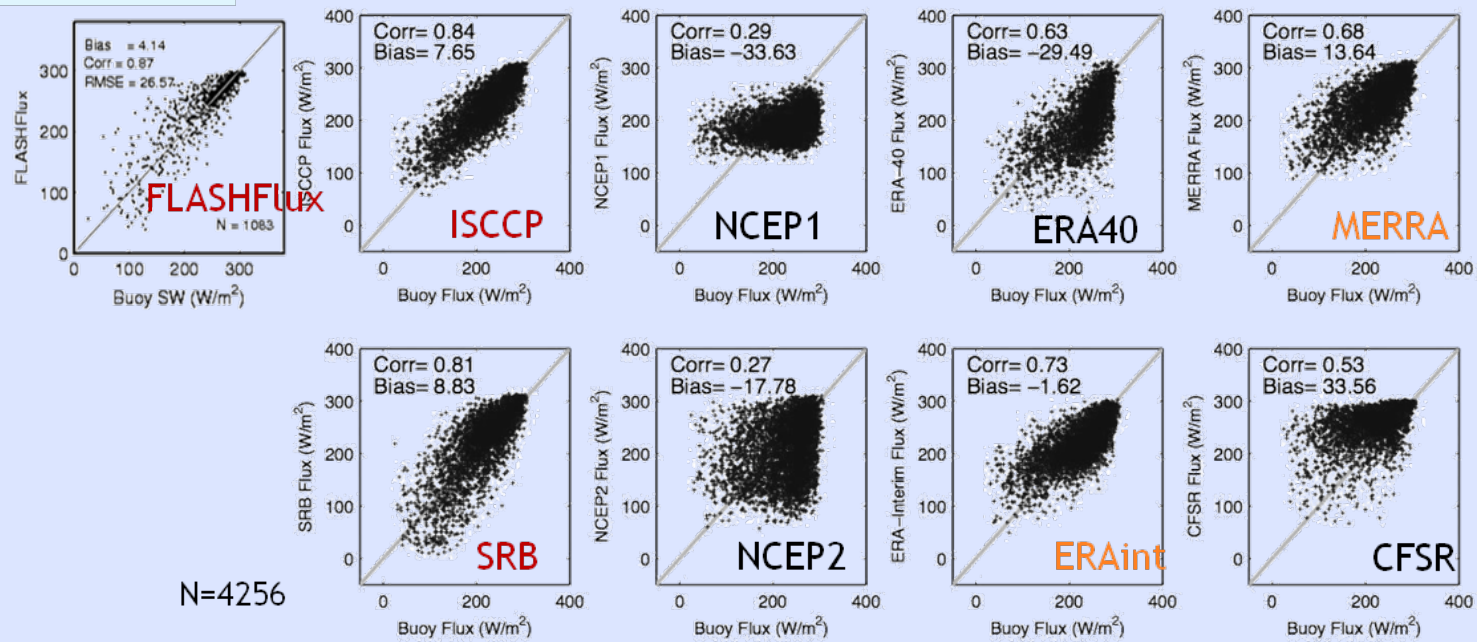
LWD	Bias Wm^{-2}	Corr	RMSE Wm^{-2}	N
FLASHFlux				
LWD	-1.9	0.95	11.3	14,358
Net LW	**-2.45**	**0.83**	**11.2**	
SRB				
LWD	-1.6	0.90	10.1	17,165
Net LW	**0.8**	**0.78**	**10.1**	
ISCCP				
LWD	-2.7	0.83	14.4	17,165
Net LW	**1.0**	**0.65**	**19.1**	

- bias is small but the sign can be changed.
- Correlation deteriorated from LWD to LW.

Satellite products are much better than NWP reanalyses: Net SW

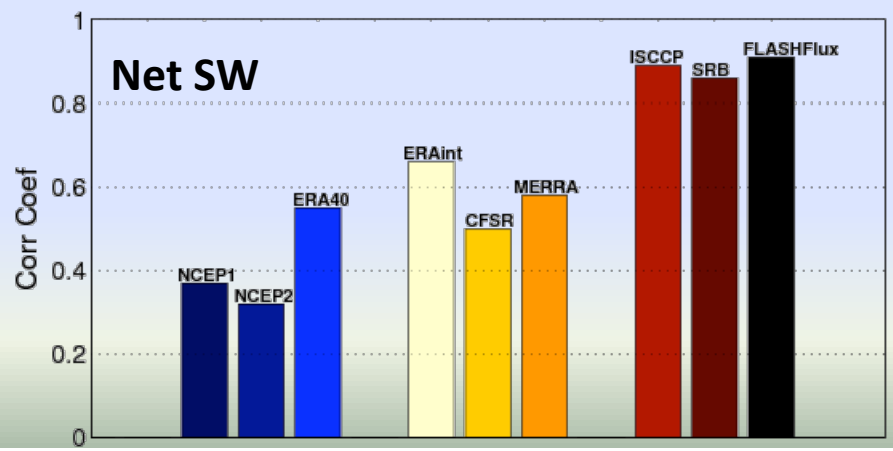
One buoy site:

(a) TAO SW (0°N, 165 °E)



N=4256

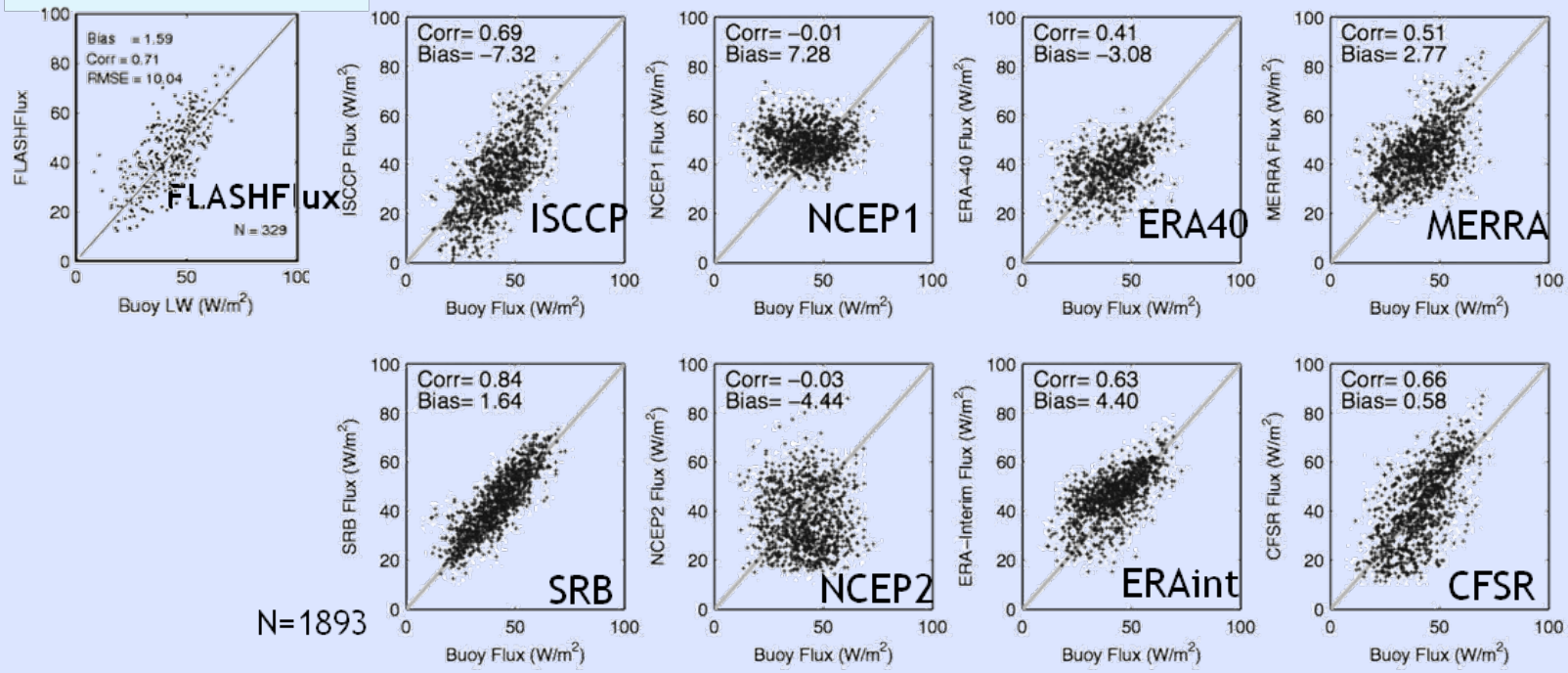
Correlation at all buoy sites



(From Sachiko Yoshida)

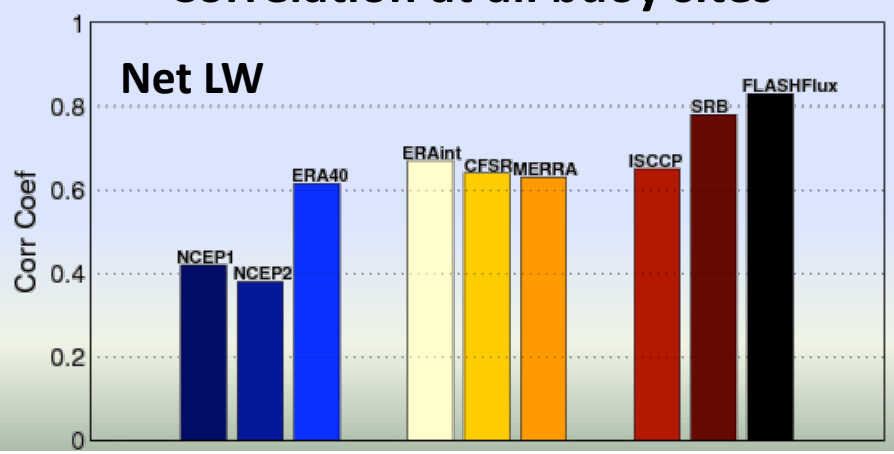
Satellite products are much better than NWP reanalyses: Net LW

One buoy site: TAO LW (2°S, 265 °E)



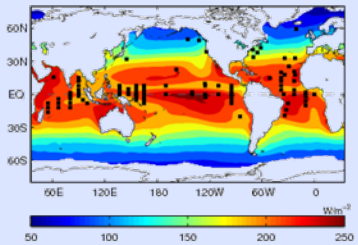
N=1893

Correlation at all buoy sites

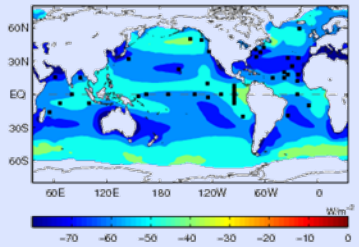


(From Sachiko Yoshida)

Comparison summary: all buoy sites

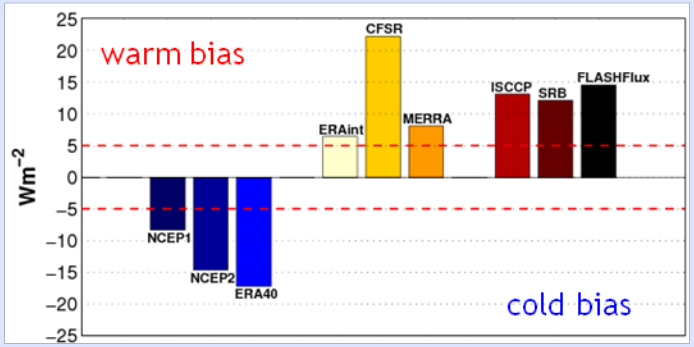


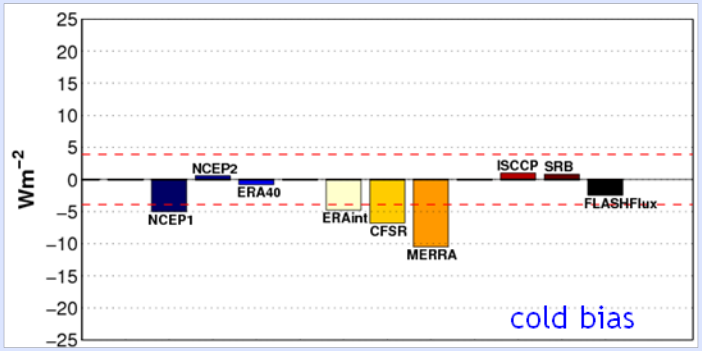
Net SW



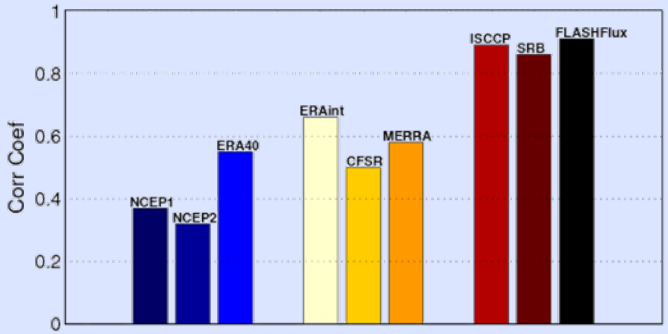
Net LW

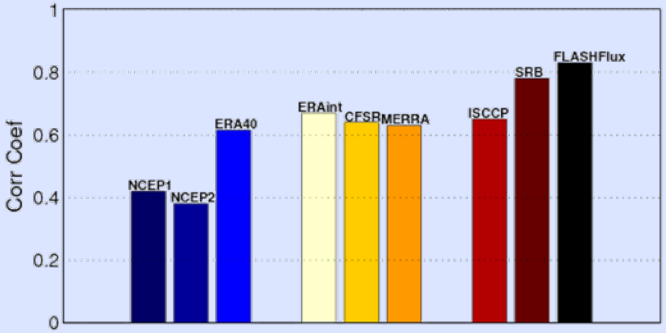
Mean difference (Product - Buoy)





Correlation <product, buoy.



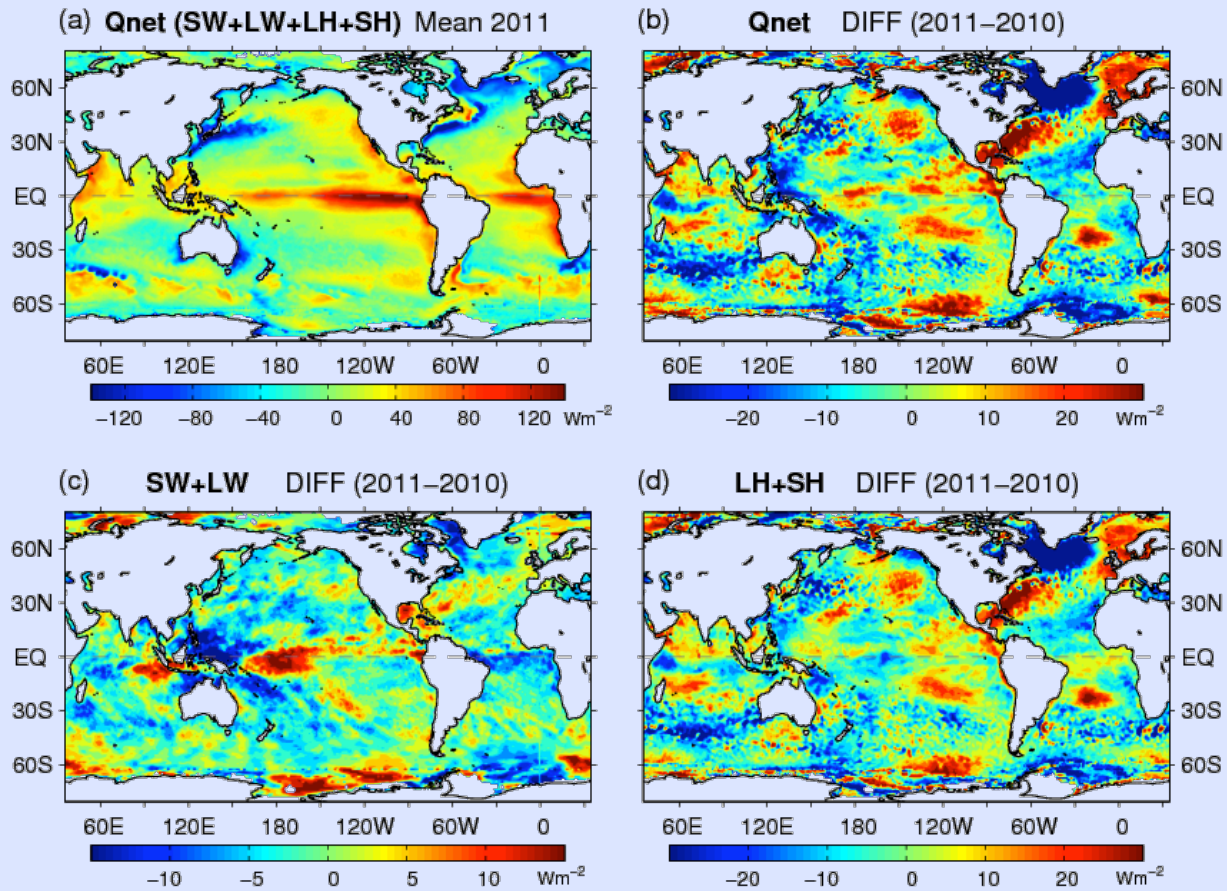


- **Overall, satellite products are compared more favorably with buoy.**
- Satellite SW products: mean is biased warm, correlation with buoy is high (>0.83)
- Satellite LW products: mean is unbiased wrt buoy accuracy, but correlation is lower (<0.83)

Global co-variability between surface radiative and turbulent heat fluxes

State of Climate 2011
(Yu, Stackhouse, & Weller)

Qnet = FLASHFlux + OAFlux



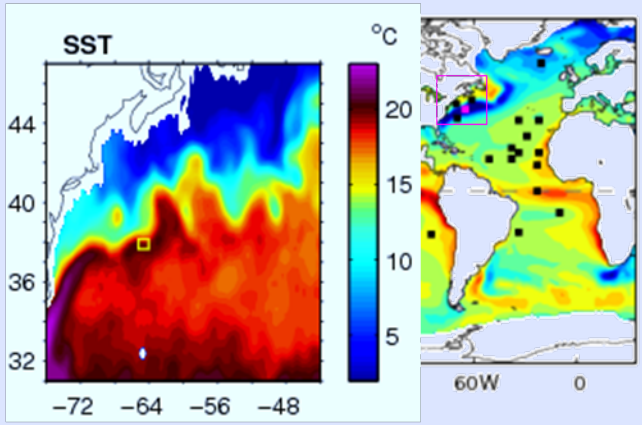
Case analysis:

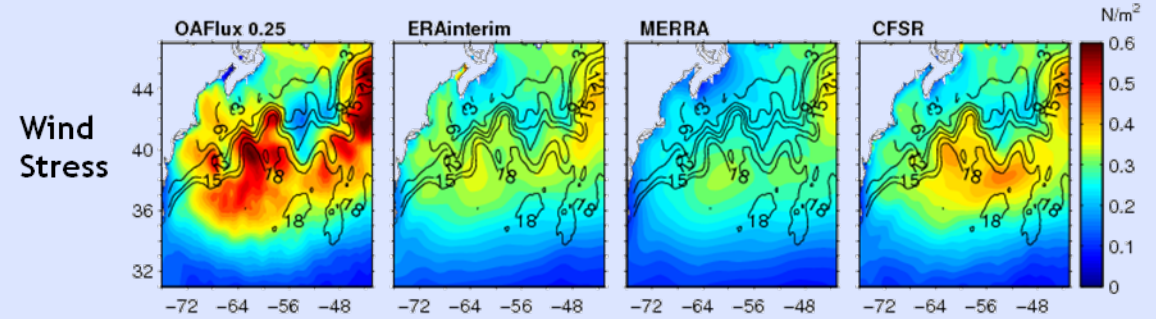
Air-sea fluxes (i) over ocean fronts and eddies (the western boundary current regions), (ii) the eastern Pacific cold tongue, and (iii) tropical Atlantic Ocean.

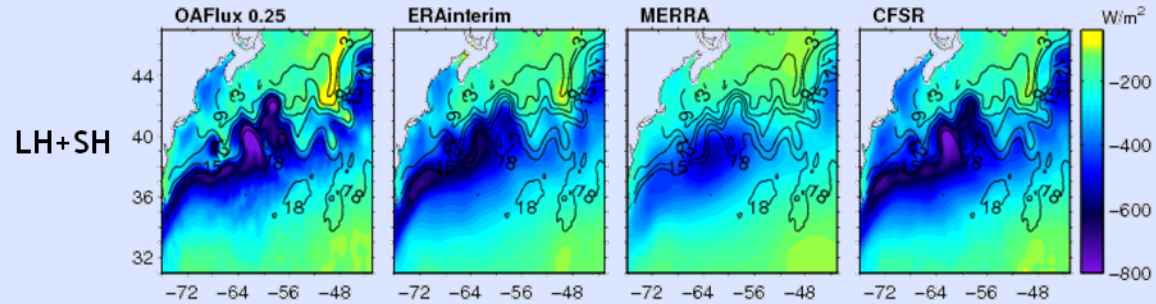
Air-sea fluxes in the Southern Ocean – What can we learn from ship flux observations?

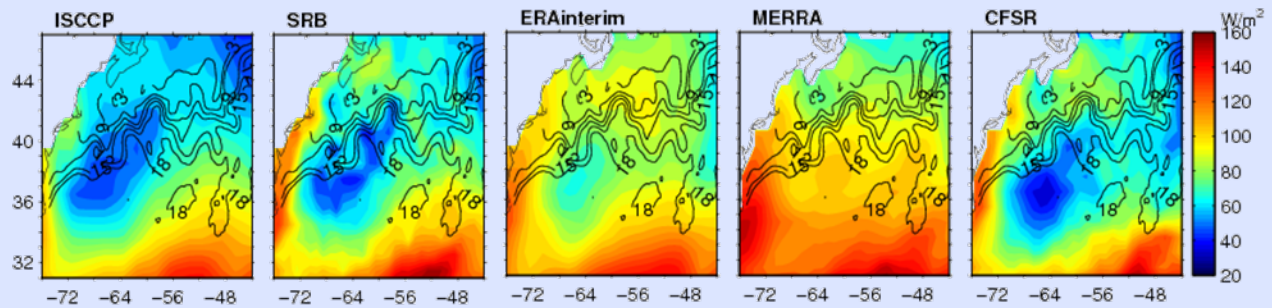
(i) Coupling between SST, wind, and surface fluxes over the Gulf Stream

A cold air outbreak event during February 1-14, 2007

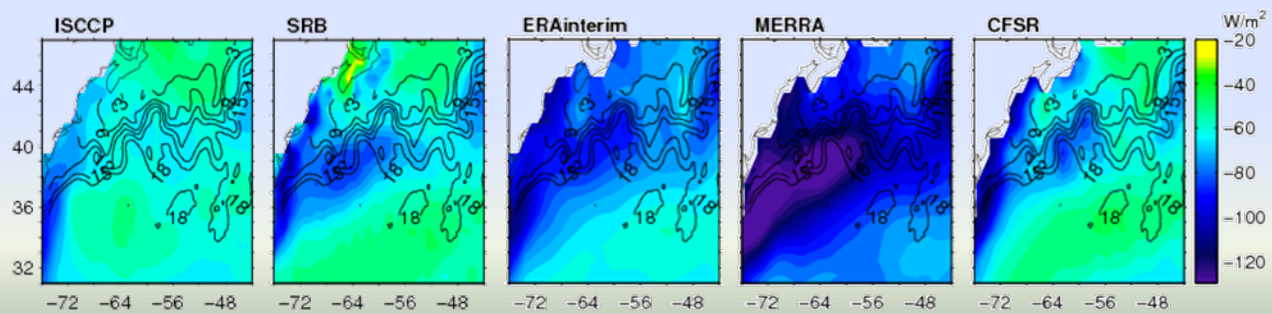




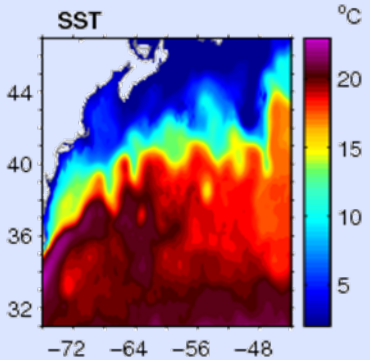




Can LW see the ocean front?

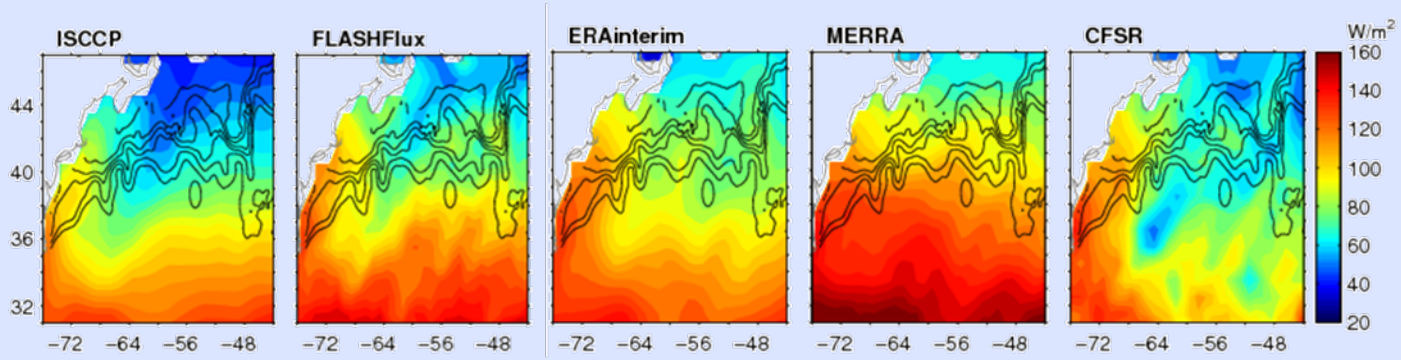


Coupling between SST and surface fluxes over the Gulf Stream

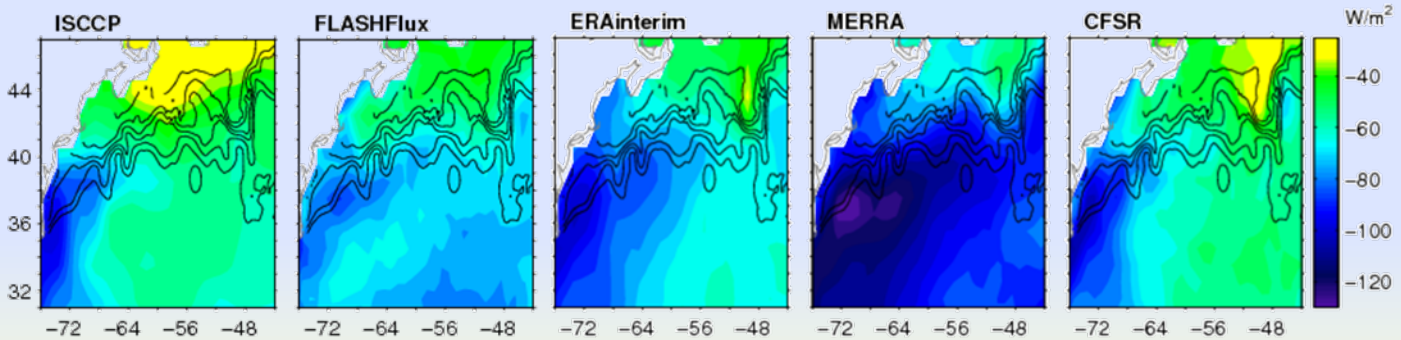


Another case, February 2009

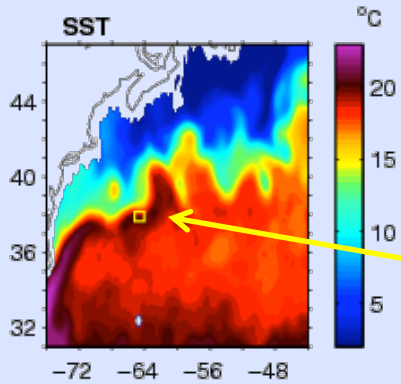
Net SW



Net LW



FLASHFlux shows the ocean's influence.



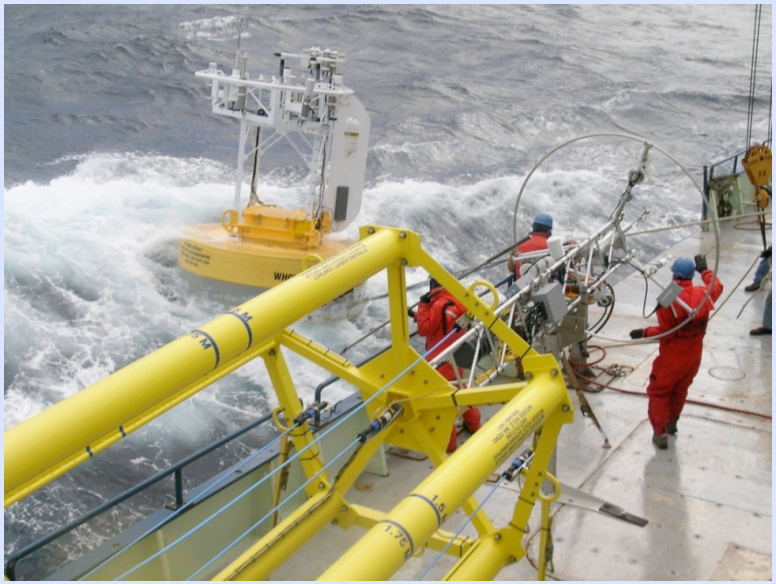
WHOI CLIMODE buoy 11/10/2005 – 2/1/2007)

PI: Bob Weller

It can check SRB and ISCCP

CLIMODE CLIVAR Mode Water Dynamic Experiment .
The buoy broke free on February 1, 2007. Recovery of the buoy took place on February 9, 2007.

Recovering the CLIMODE surface flux buoy



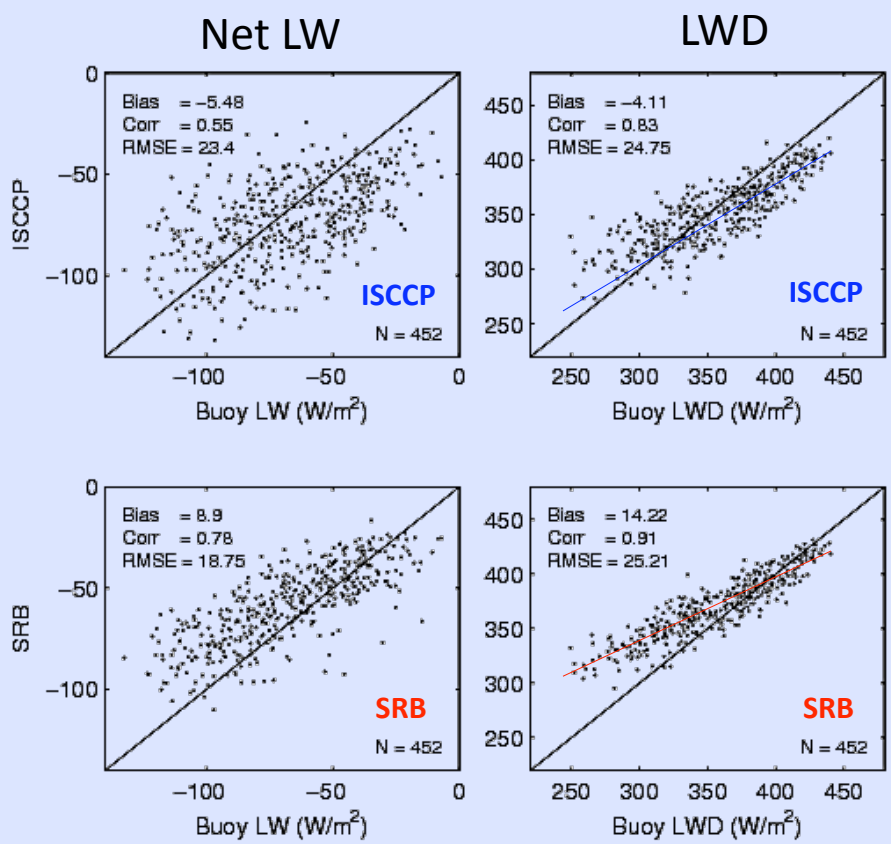
(from Terry Joyce, WHOI)

During the recovery of the buoy (above) and its instrumentation on 9 February 2007, the Knorr experienced rain, sleet, hail, snow, and a visit by a waterspout (right): something one might expect to see in the tropics during the summer rather than amidst sea smoke in the winter N. Atlantic.

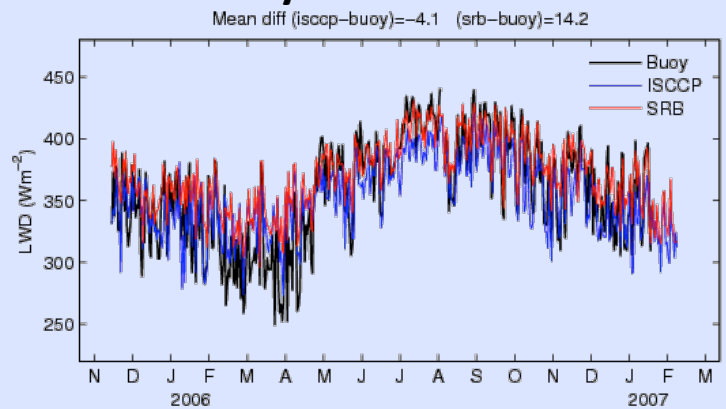
(photo by Al Plueddemann, WHOI)

Satellite LW over the Gulf Stream: comparison with the CLIMODE buoy

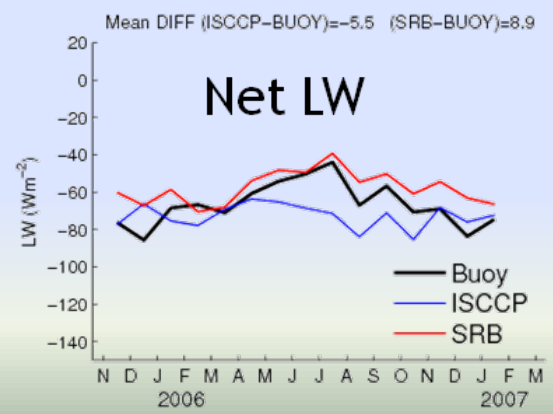
(11/10/2005 – 2/1/2007)

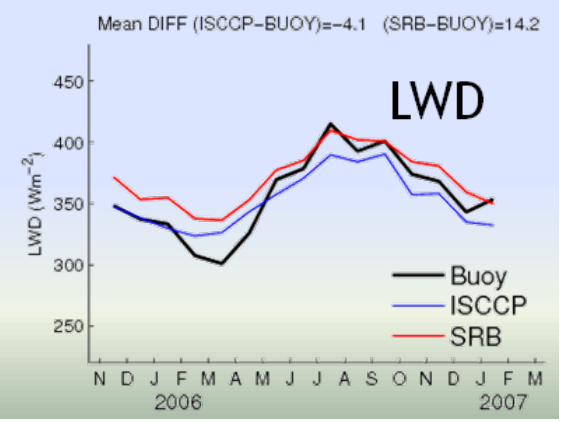


Daily Mean LWD



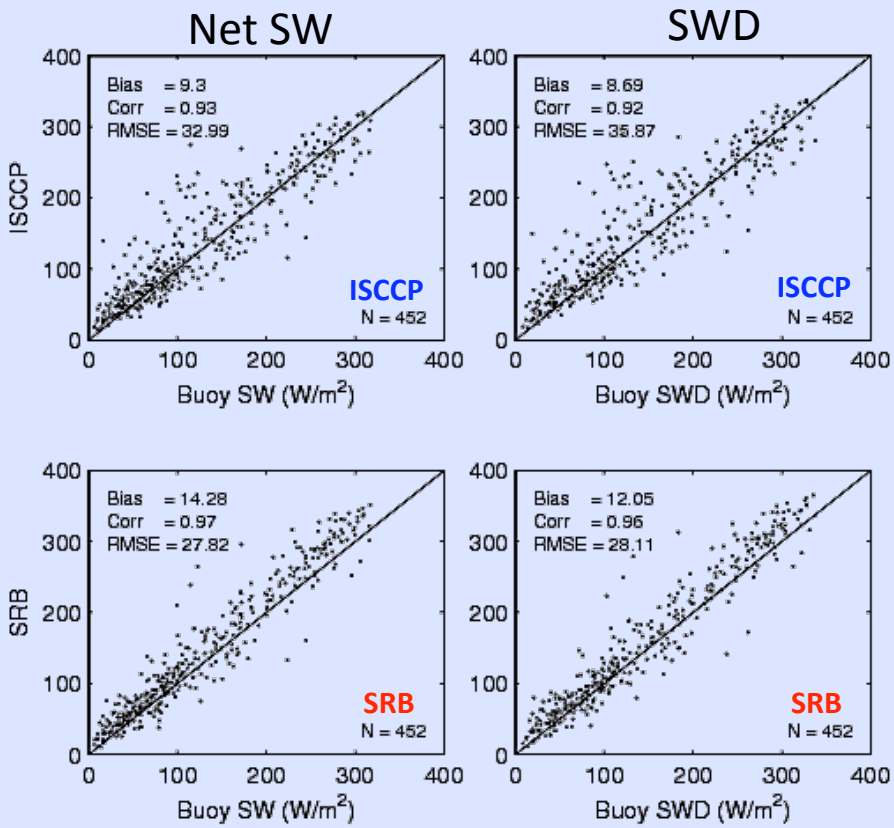
Monthly Mean

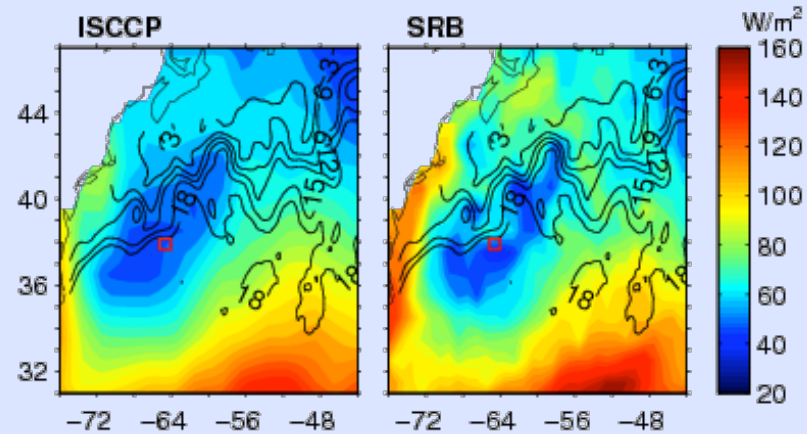




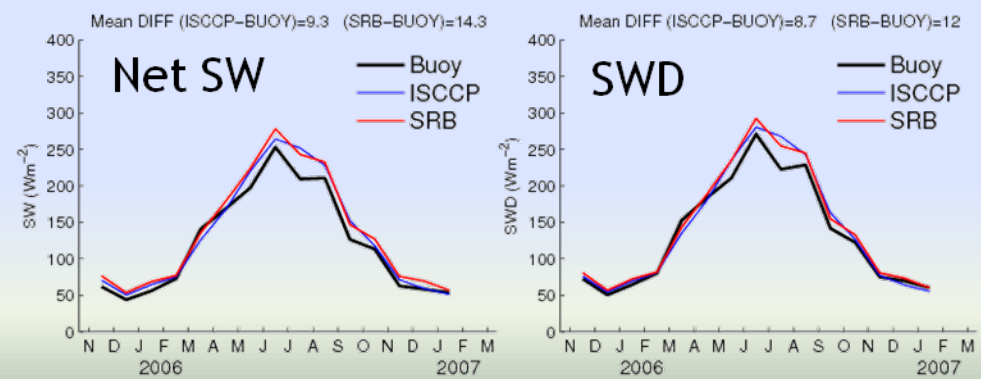
- The bias changes sign with season
- Correlation deteriorated from LWD to LW

Satellite SW over the Gulf Stream



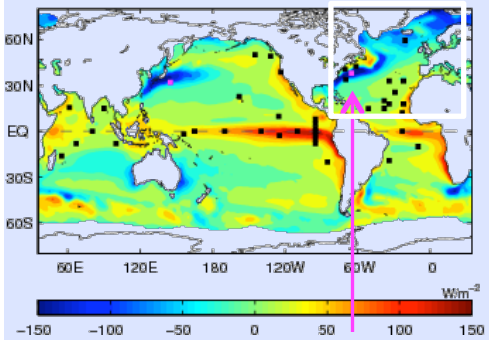


Monthly Mean (14 months)

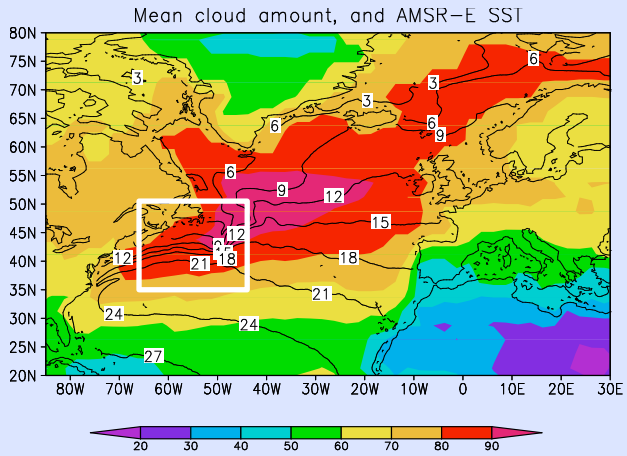


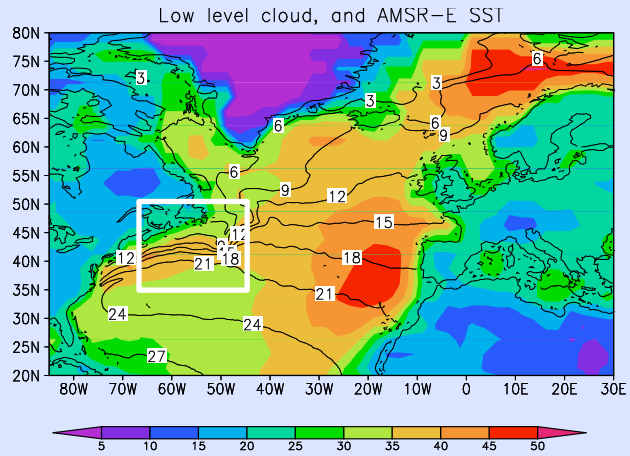
- SWD overestimated.
- Overestimation is larger during summer (JUN-JUL-AUG).

ISCCP cloud annual climatology



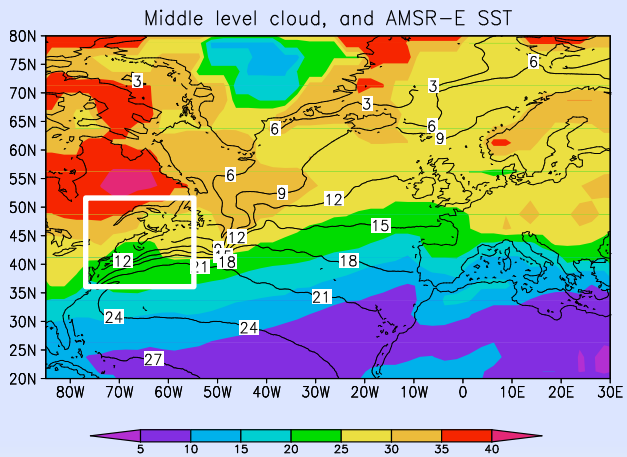
CLIMODE (Gulf Stream)

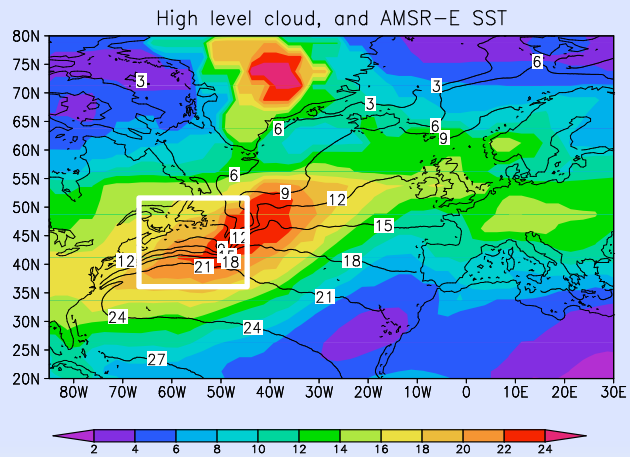




ISCCP annual climatology suggests that there is a maximum of low level and high level clouds closely associated with the Gulf Stream extension.

(there is no obvious effect on medium level cloud).



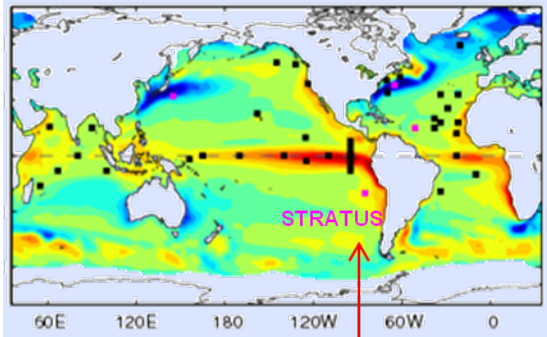


ISCCP climatology of cloud amount and cloud classification

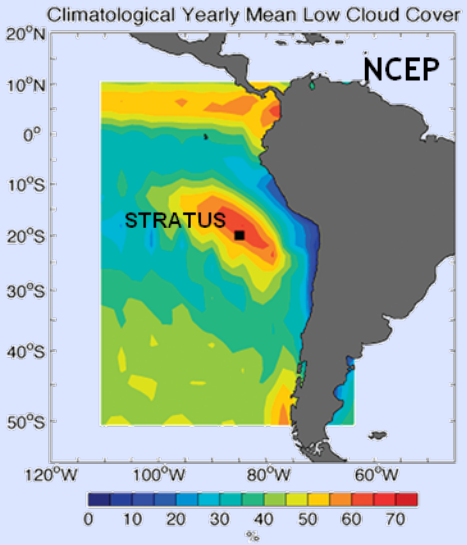
low is 680 to 1000mb, middle is 440 to 680mb, high is 440mb to 50mb. Cloud amounts in percentage.

(from Justin Small)

Satellite LWD and net LW at STRATUS



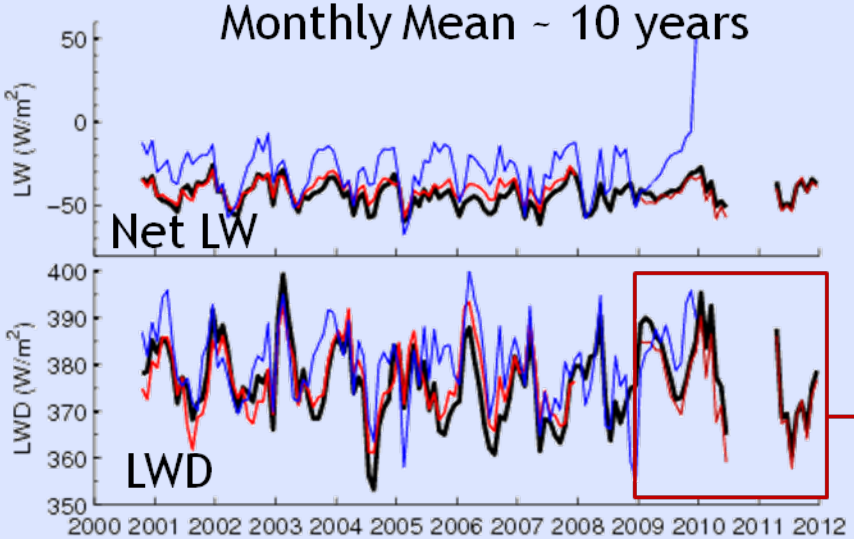
STRATUS 10/7/2000 - present
PI: Bob Weller



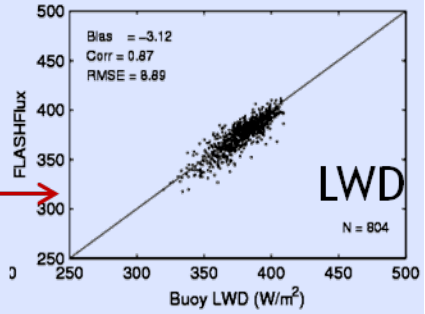
(Colber and Weller 2007)

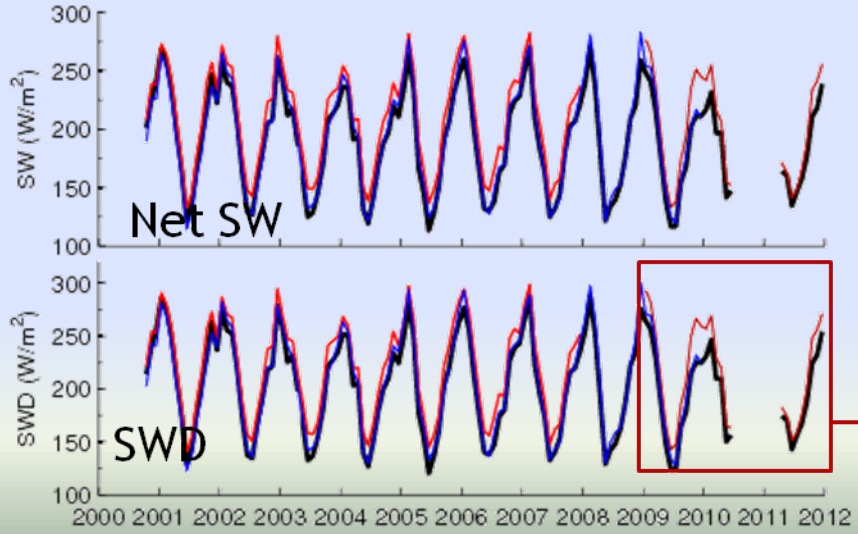
ISCCP SRB Buoy FLASHFlux

Monthly Mean ~ 10 years

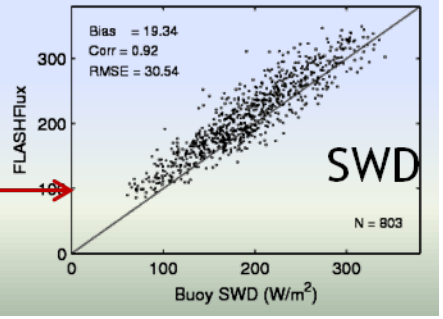


FLASHFlux
2009 - 2011

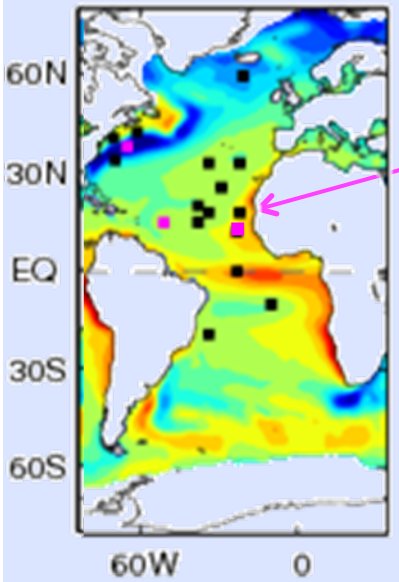




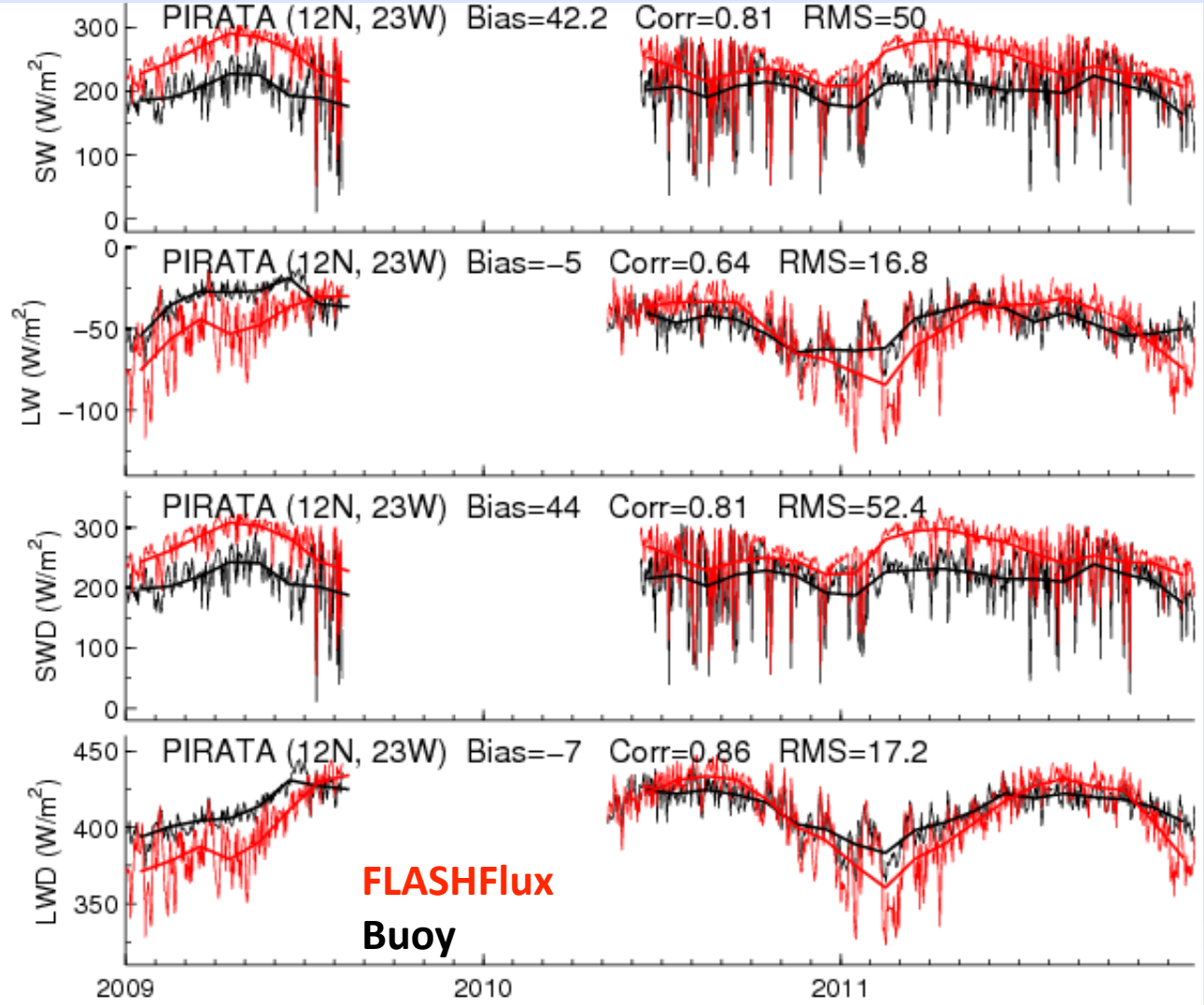
FLASHFlux
2009 - 2011



FLASHFlux SWD and LWD at **PIRATA (12N, 23W)**



Daily and monthly



- SWD is overestimated by 44 Wm^{-2}

- Bias in LWD changes sign with season

Satellite SW and LW:
Comparison with buoy time series

Satellite SW and SWD

- All SWD/SW are overestimated (warm bias for the ocean).
- Biases in SWD and net SW are linear.
- Correlation is high between satellite and buoy.

Satellite LW and LWD:

- Bias changes sign with season (e.g. ocean fronts)
- Correlation is deteriorated from LWD and net LW
- ISCCP net LW has poor linear correlation with buoy, although LWD is reasonable. FLASHFlux LWD/LW shows improvement.
- algorithm?

Buoy net shortwave radiation:

$Q_{SW} = SW\downarrow - \alpha\,(SW\downarrow)$

α: the surface albedo based on the Payne (1972) formulation

Buoy net longwave radiation:

$Q_{LW} = (\varepsilon\,\sigma\,T_s^4 - (1-\varepsilon)\,LW\downarrow) - LW\downarrow$

σ: the Stefan – Boltzmann constant; ε: emissivity

(ii) What are Surface Air-sea Fluxes in the Southern Ocean?

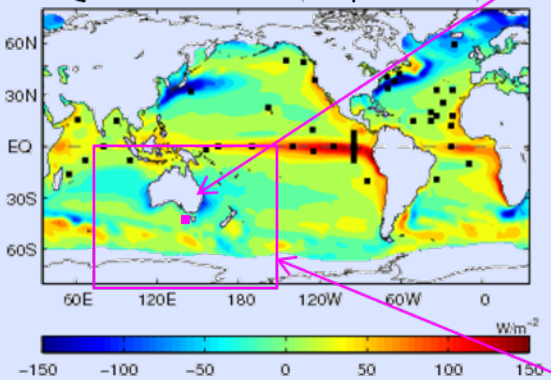
Collaborators:
Simon Josey (NOC, UK)
Eric Schultz (BoM, Australia)

SOFS Mooring (46.75S, 142E)
South Ocean Flux Station

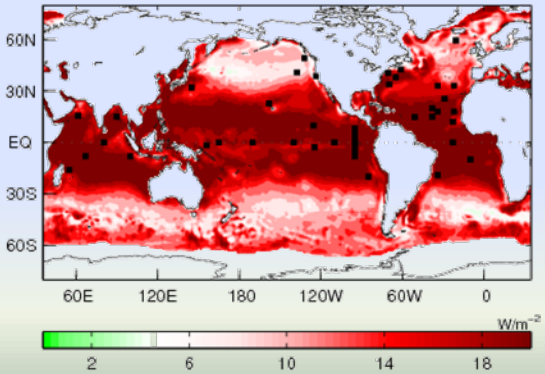
SOF1: Mar 2010 - Mar 2011
SOF2: underway, Nov 2011 - Jul 2012

From Eric Schultz

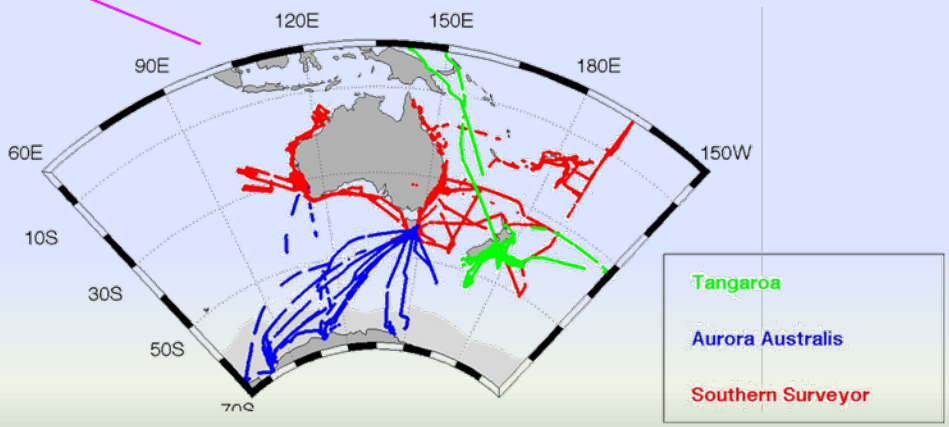
Qnet Mean (11 products)



Qnet STD (11 products)



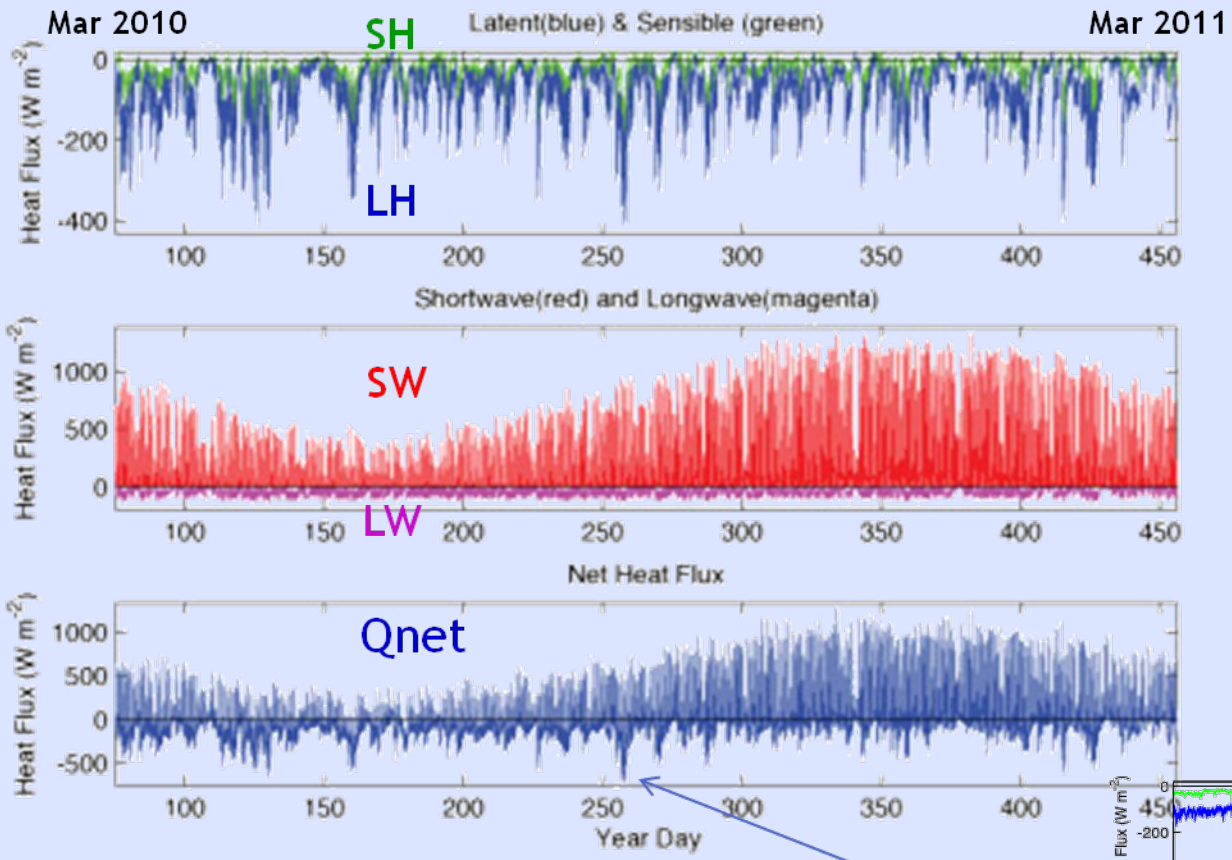
Research Ships



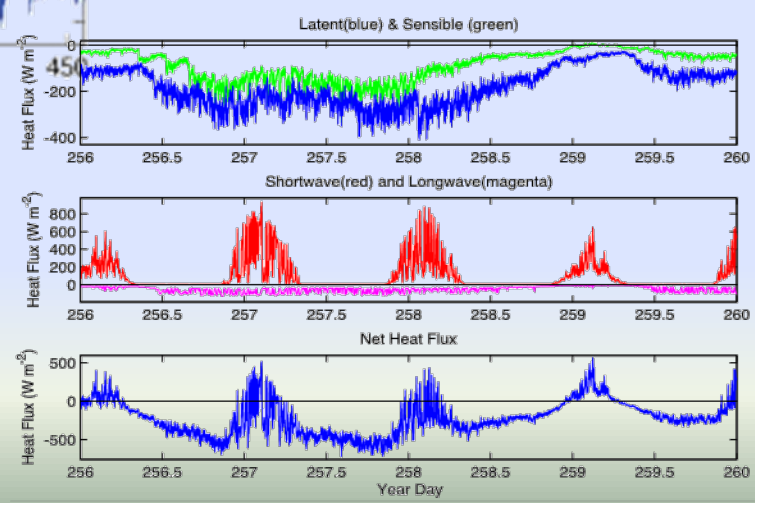
SOFS time series

(From Simon Josey/Eric Schultz)

Time series of 1 minute means over full period

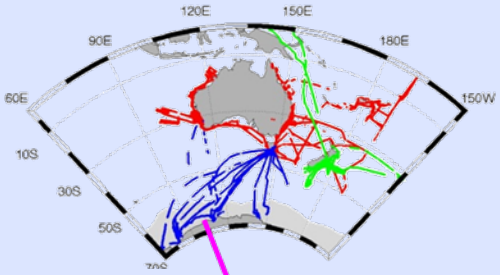


- Cold, dry air episode with enhanced wind speed from Sep 14-16 2010...
- Extreme latent and sensible heat loss of order -250 (-150) Wm^{-2} maintained over 2 day period.
- Resulted in Qnet heat loss as low as -600 Wm^{-2} modulated by daily shortwave cycle.

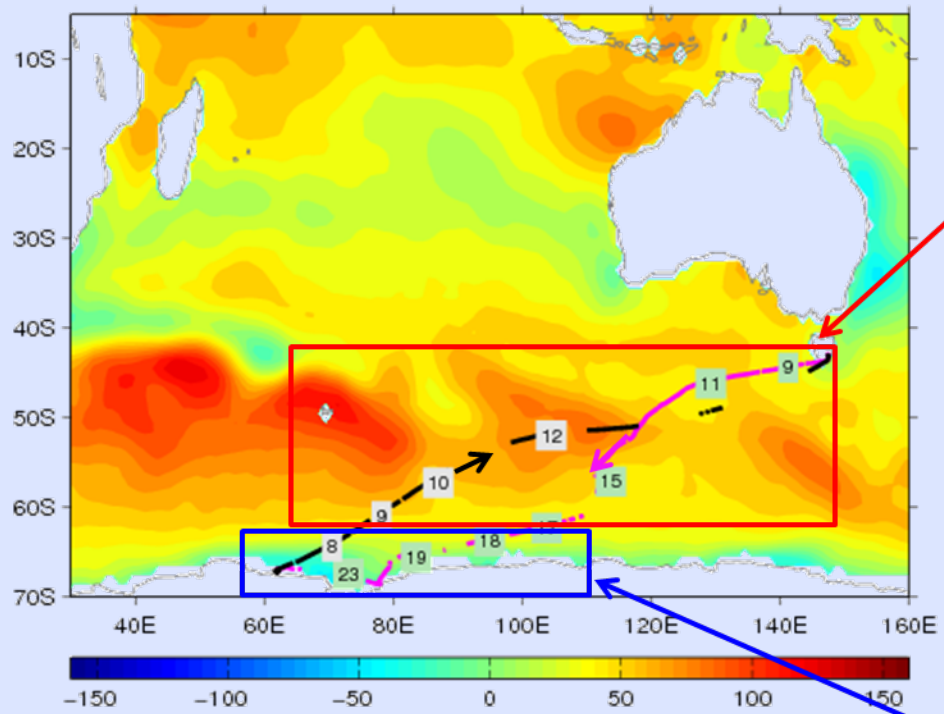


Flux observations from research ships

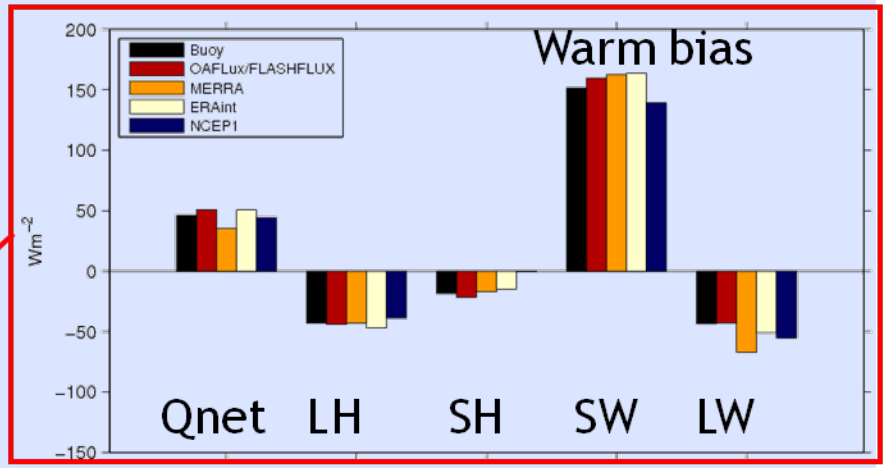
One example: Feb 8 2011 - Mar 17 2011

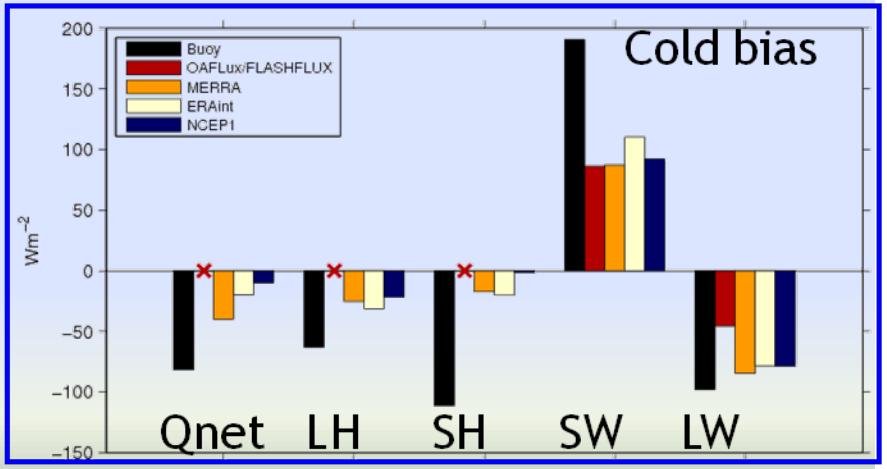


Mean Feb-Mar Qnet (11 products)



Mean





Summary (i)

- SWD (net SW) is biased warm (overestimated) at all buoy locations.
  The only place where cold bias in SW is identified is along the ship track near the ice edge in the southern ocean.

- The mean LWD bias is small, mostly within the buoy accuracy. But the bias changes with season/location and can be large (e.g. western boundary currents, the tropical Atlantic).

- Near the ice edge the FlashFlux net LW loss has a warm bias of ~ 50Wm^{-2}. and net SW input has a cold bias of ~ — 100 Wm-2. There is error compensation.

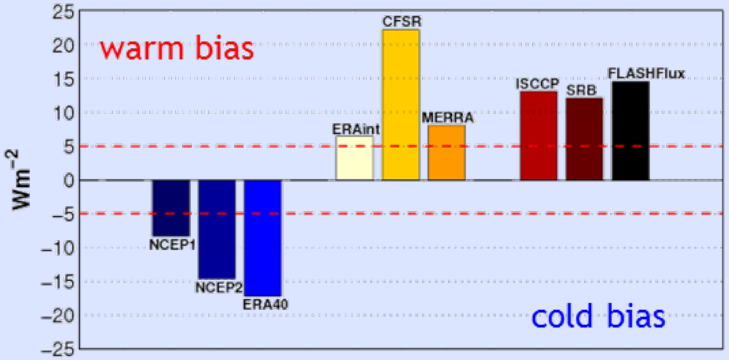
- SWD (net SW) correlates highly with buoy (>0.83 for all satellite products). LW is generally lower (<0.83) and the correlation deteriorated from LWD to net LW.

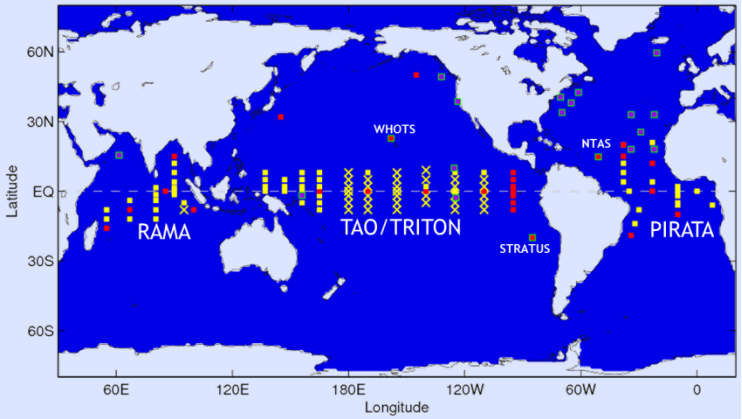
- FLASHFlux shows better comparison with buoy than SRB and ISCCP.

Summary (ii)

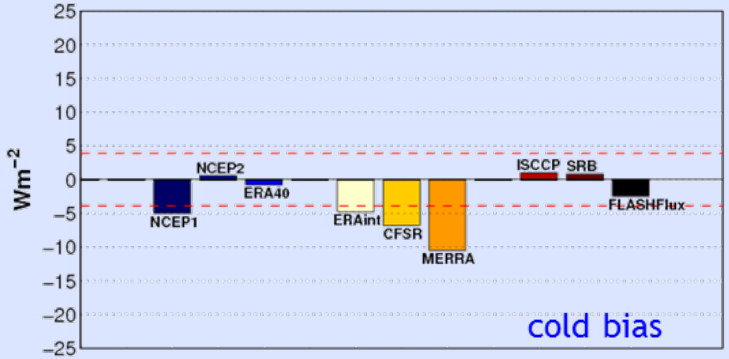
Mean Diff (Product-Buoy)

Net SW



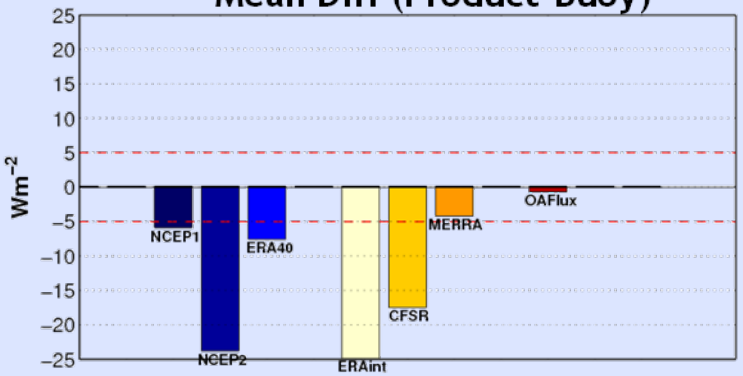


Net LW

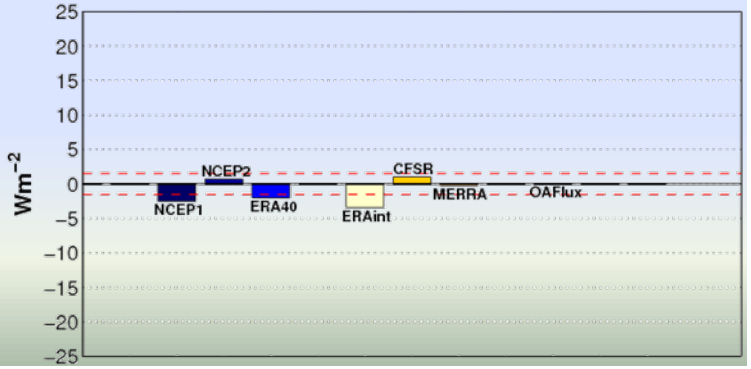


Mean Diff (Product-Buoy)

LH



SH



- Buoy validation shows that satellite SW is a source of warm bias ~ O(10-15Wm^{-2})

- the global heat imbalance of satellite+OAFlux is ~ O(30Wm^{-2}), what are other sources of warm bias?

Summary (iii)

Limitations:

- Buoys are heavily tropical, and high-latitude measurements are needed
- Number of LW sensors is too limited.

Future study:

- regional heat budget analysis that connects to ocean temperature observations