Inverse modelling for the Earth's Energy and Water budgets.

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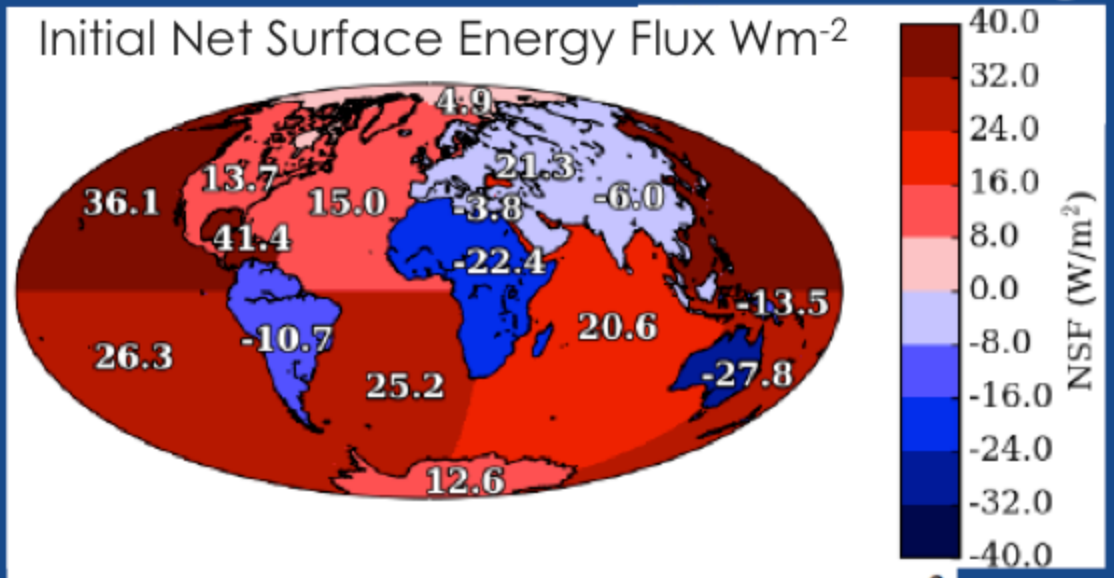
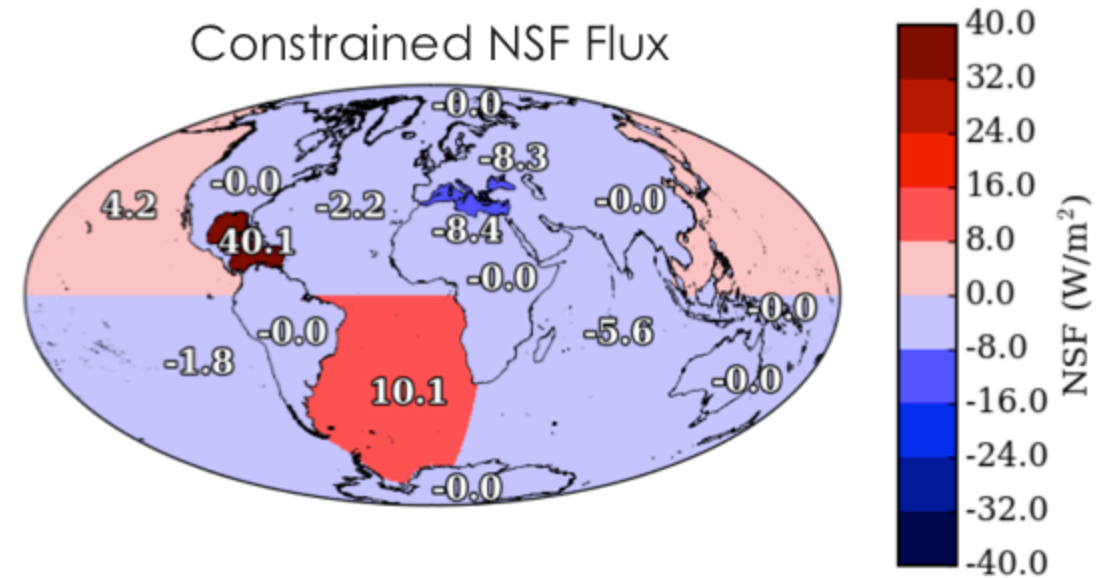
NASA NEWS (Remote Sensing)

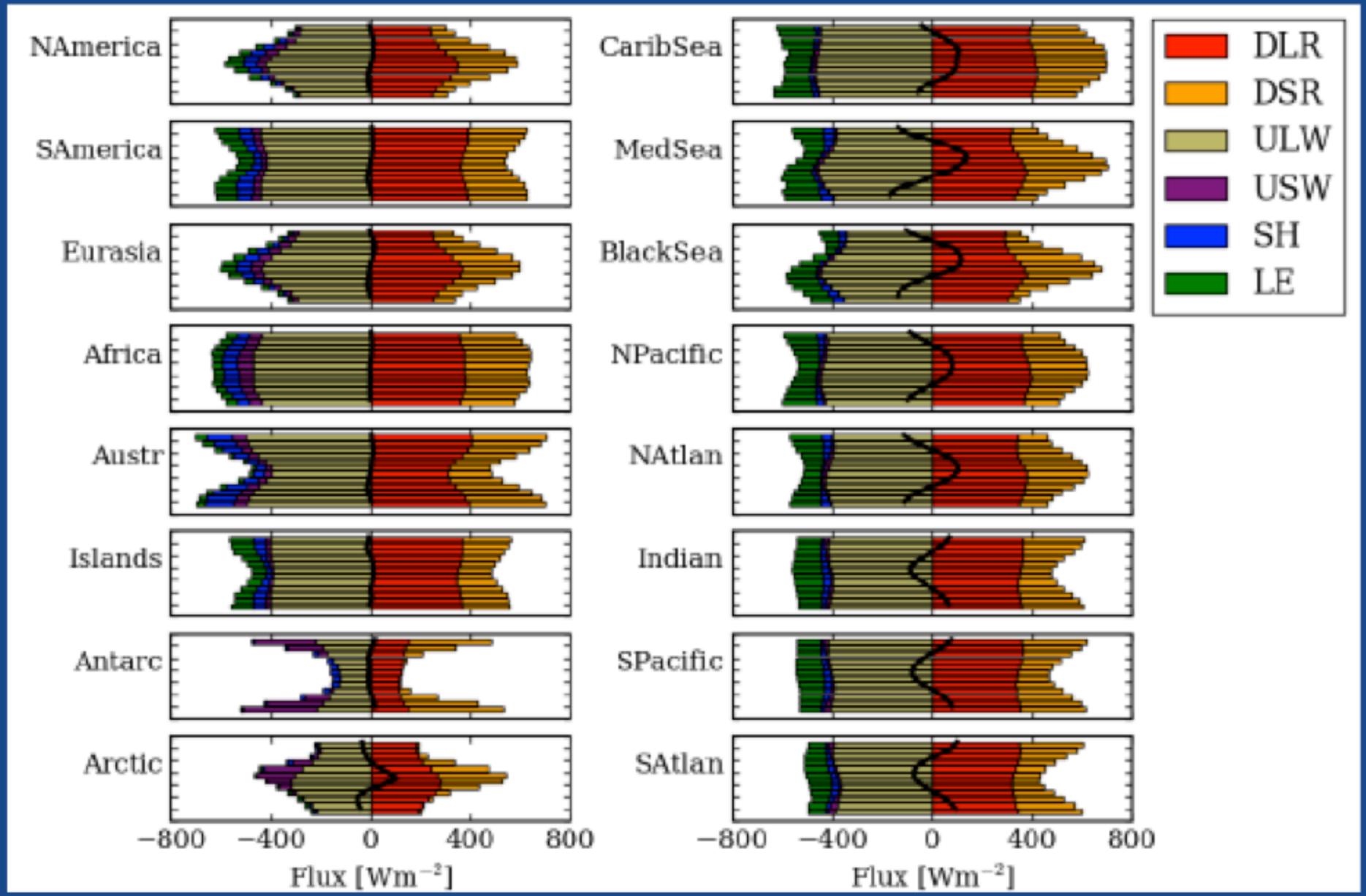
- L'Ecuyer et al. , Rodell et al. (2015)
  - 16 regions: 7 Land, 9 Ocean
  - 11 fluxes $\mathbf{F_{obs}}$ with errors $\mathbf{S_{obs}}$
  - 2000-2010 means
- TOA Energy fluxes: ISW, OLR OSW
- Surface Energy and Water Fluxes
  - DSW, DLW, USW, ULW, Latent, Sens. Precip.
- Horizontal water convergence
  - Runoff or Merra Atm.
- Constrained surface energy flux $\boldsymbol{R_{obs}}$
  - Regional Land, Global Ocean
- **Coupled Energy and Water cycle**



$$J = (\mathbf{F} - \mathbf{F}_{\text{obs}})^{\mathrm{T}} \mathbf{S}_{\text{obs}}^{-1} (\mathbf{F} - \mathbf{F}_{\text{obs}}) + \frac{(R - R_{\text{obs}})^2}{\sigma_R^2}$$



Seasonal cycle at surface



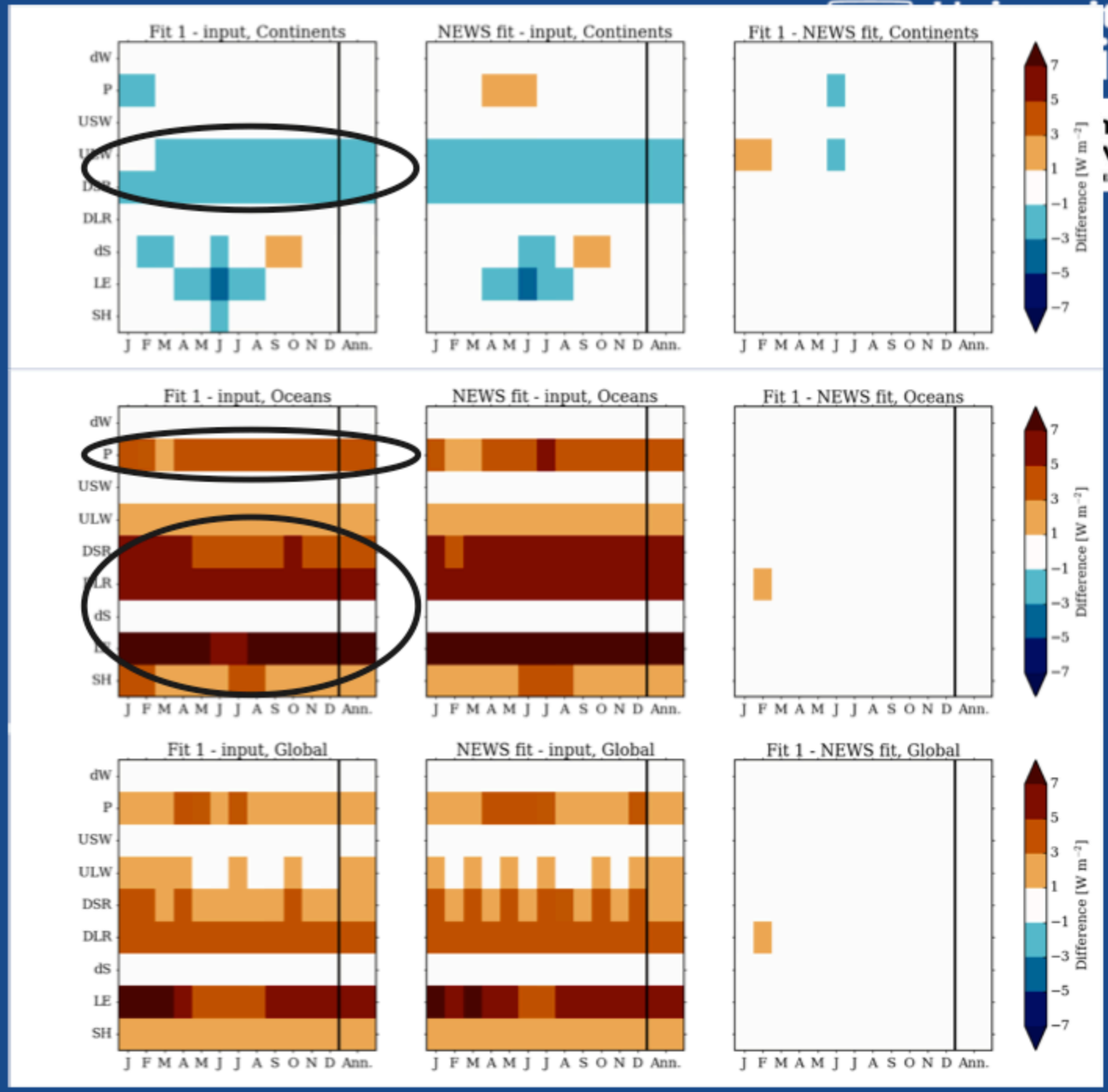
Seasonal cycle:

Upward flux adjustments

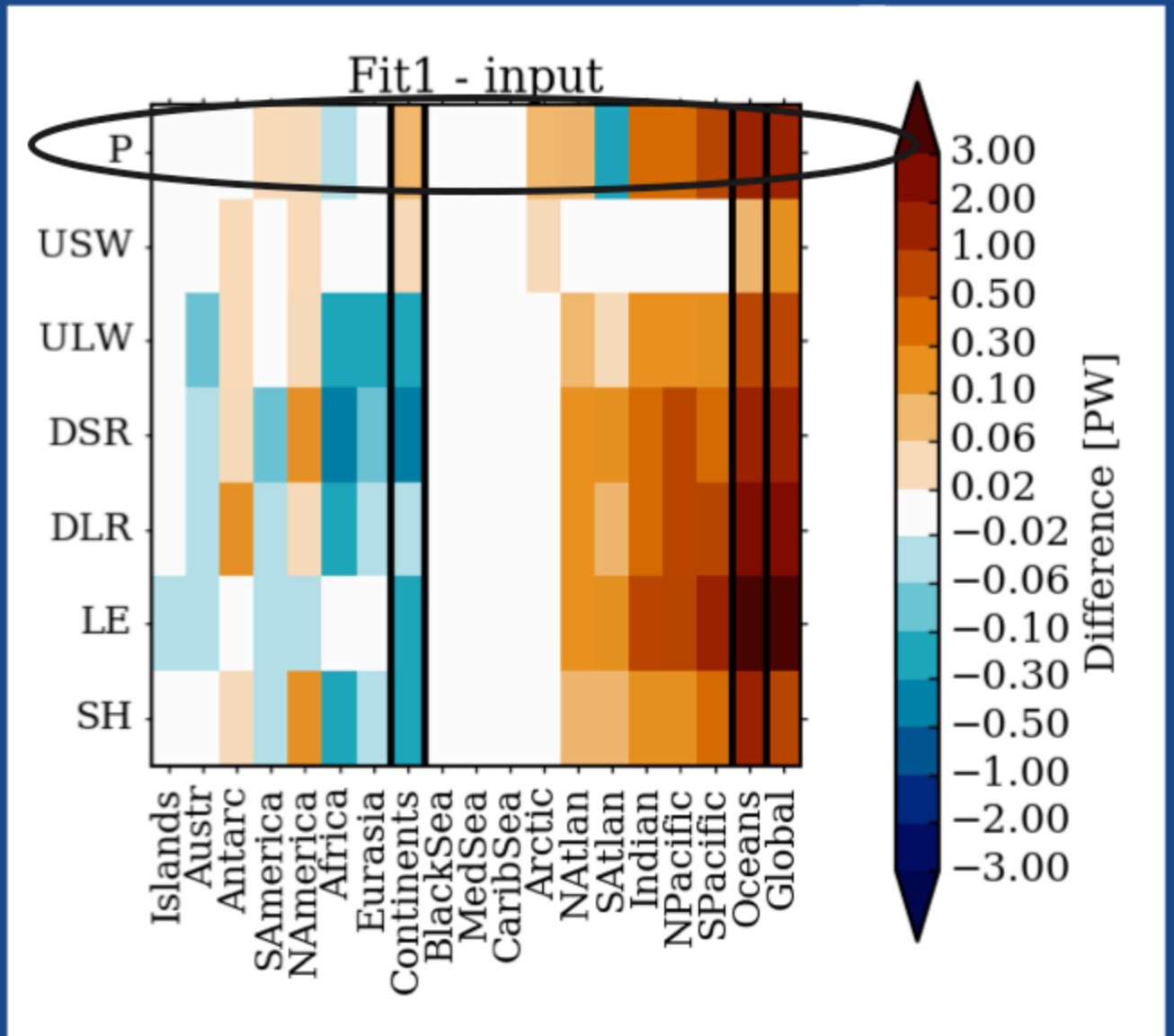
Subtle differences

Solving Annual fit then fitting monthly fluxes to annual averages

Solving for Global ocean then partitioning ocean basins to fit global ocean values



Regional adjustments (upward ht. fluxes) PW



Consider Original N Atlantic solution?

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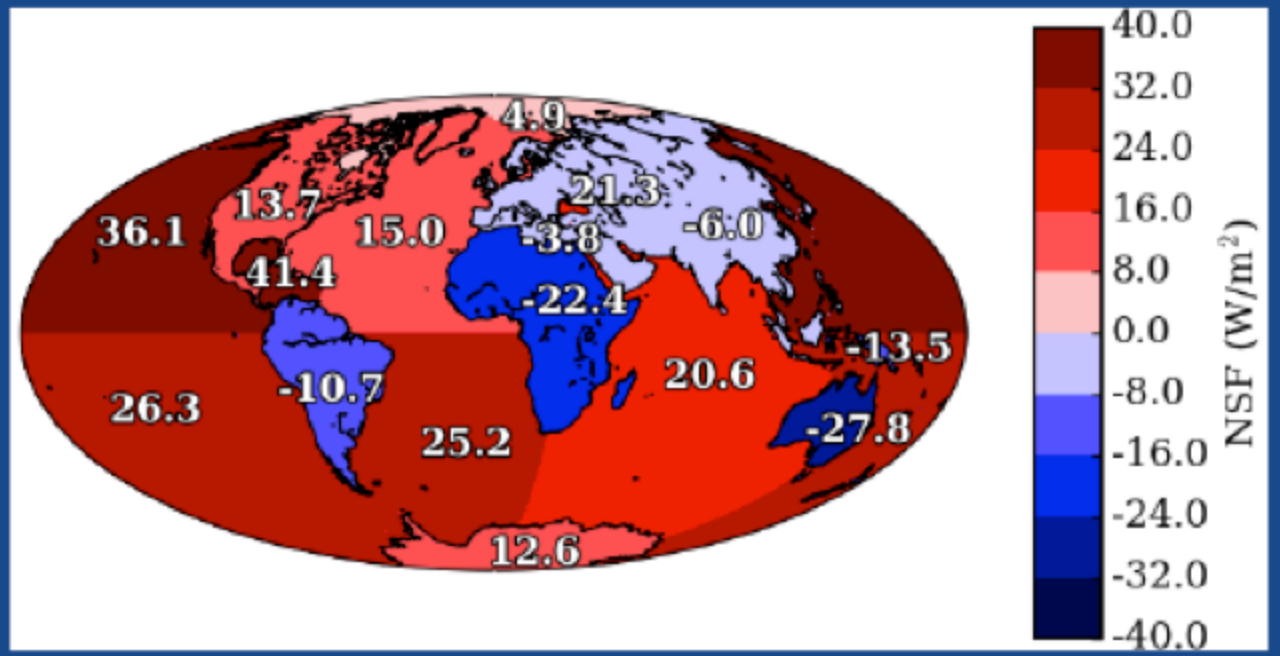
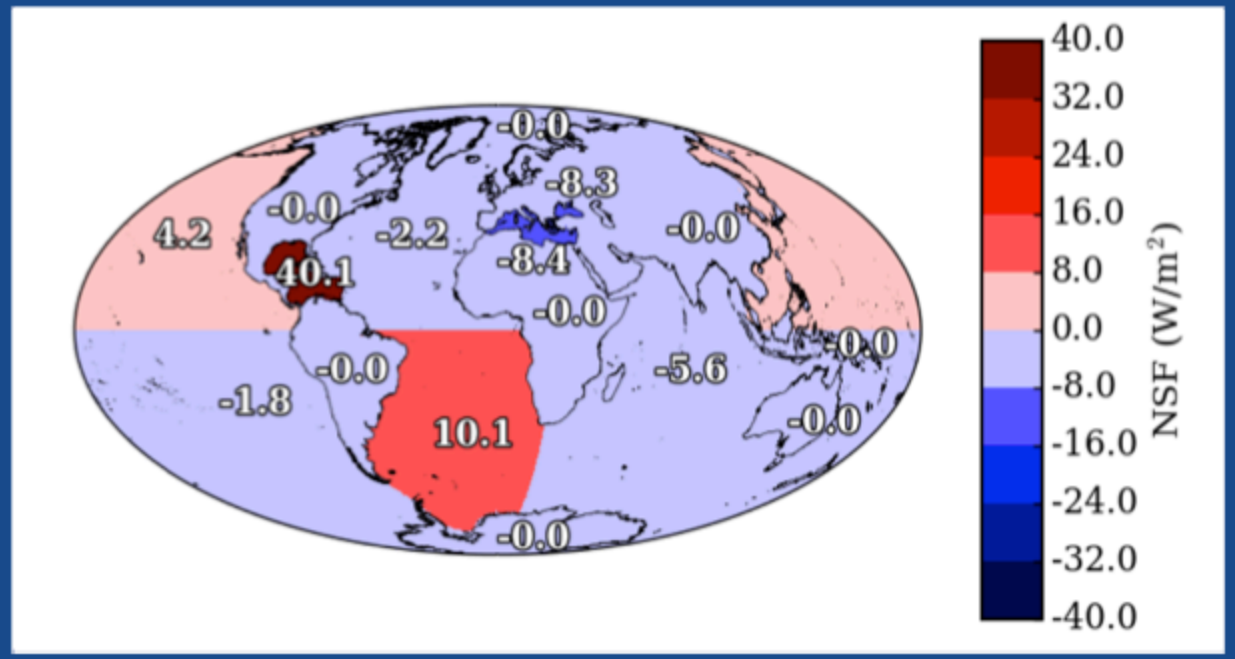
Unconstrained NSF



NEWS-constrained NSF



Unconstrained N Atlantic fluxes lower than other basins

Not preserved in constrained solution : Regions too independent!

Error Covariances for Ocean Turbulent fluxes

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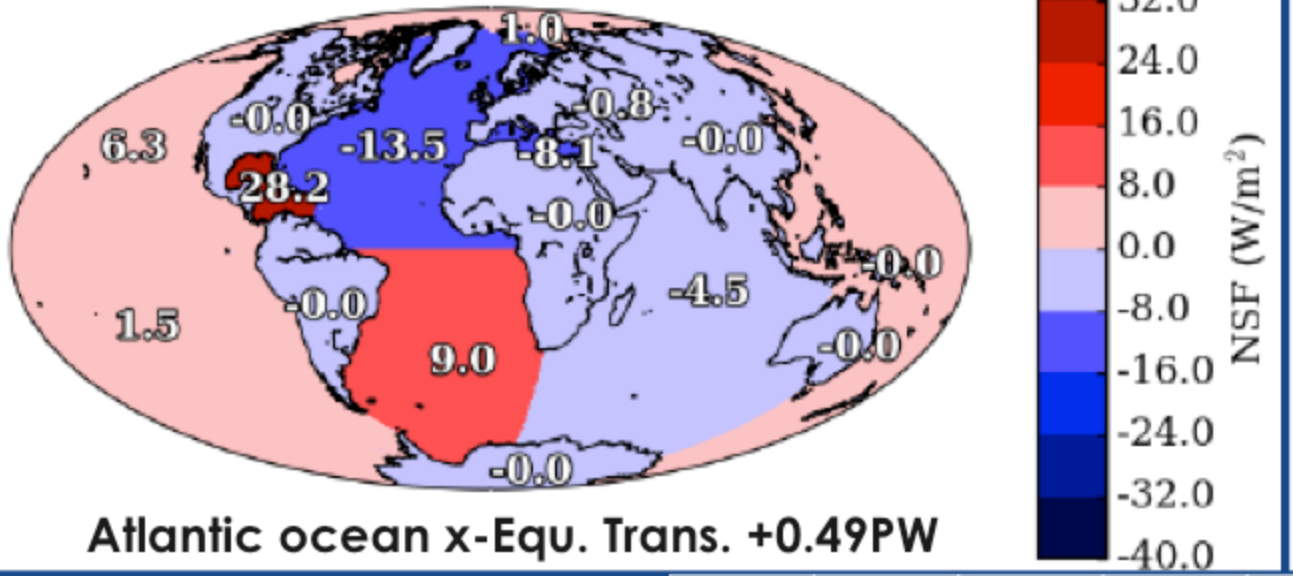
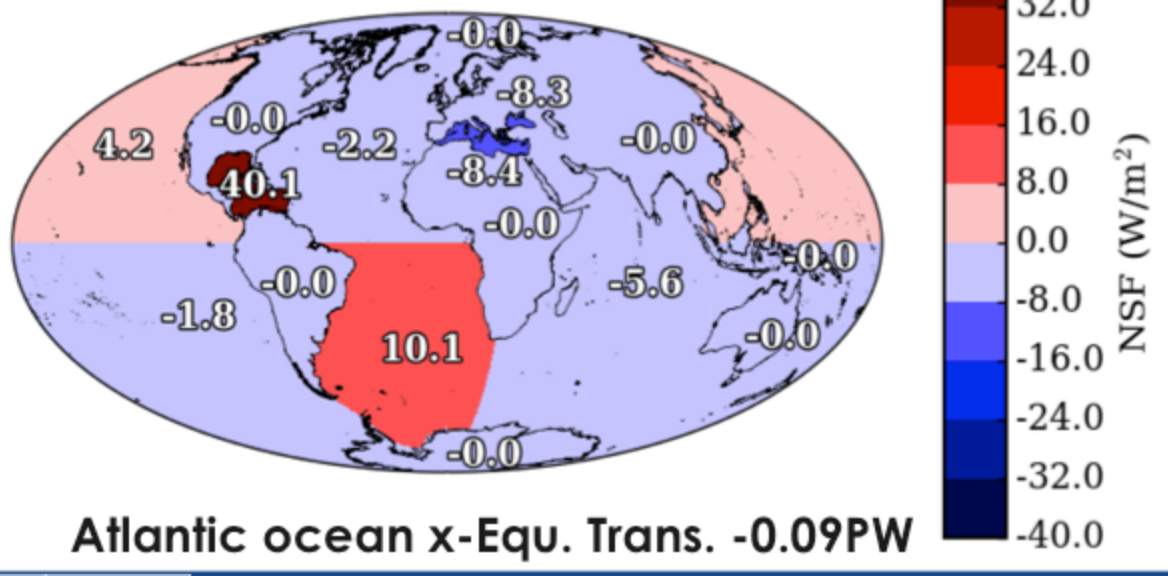
Latent and Sensible error covariances



Atlantic ocean x-Equ. Trans. +0.49PW

NEWS-constrained NSF



Atlantic ocean x-Equ. Trans. -0.09PW

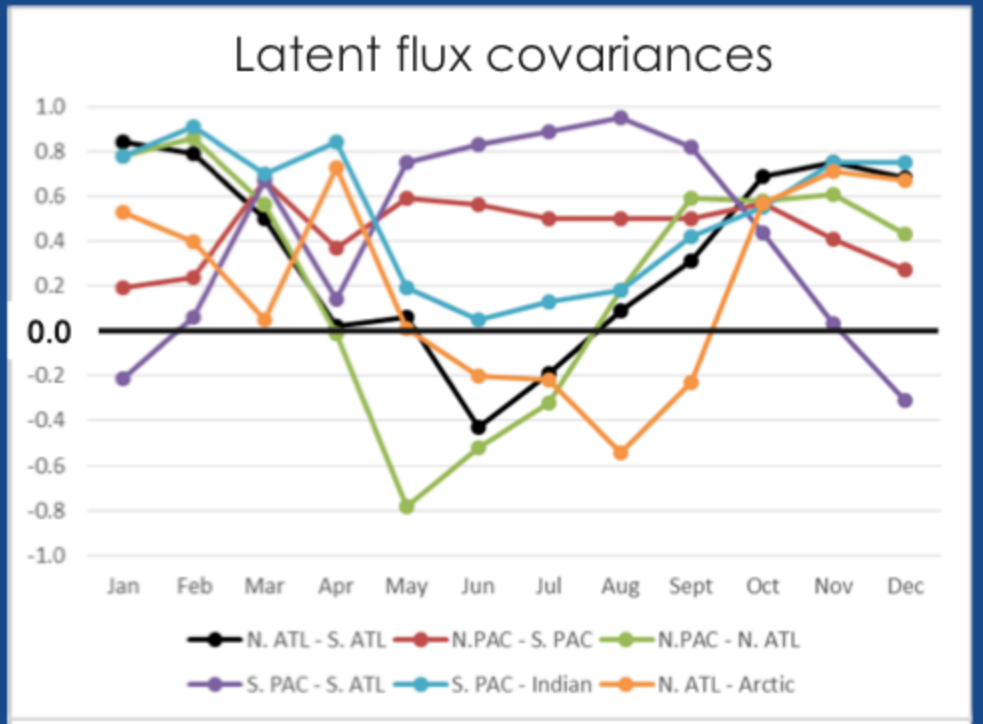
5 EO Flux products 2000-07
SeaFlux-v1
HOAPS-v3
Ifremer-v4
J-Ofuro3
OAFlux-v3

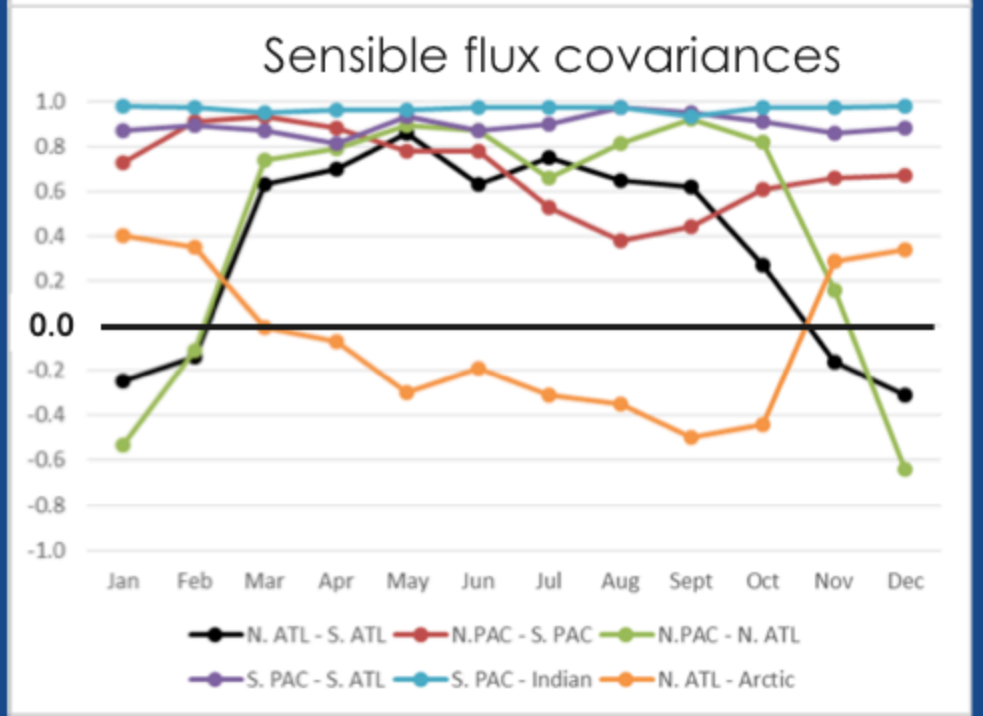
Latent Ht Corr.	N. Atl.	S. Atl.	N. Pac.	S. Pac.	Indian
N. Atl.	1.0	0.93	0.65	0.86	0.93
S. Atl.		1.0	0.67	0.94	0.94
N. Pac.			1.0	0.87	0.87
S. Pac.				1.0	0.98
Indian					1.0

Correlation matrix

Improved
N. Atlantic Ht. Flux

Seasonal correlations between different EO turbulent flux products over Ocean basins





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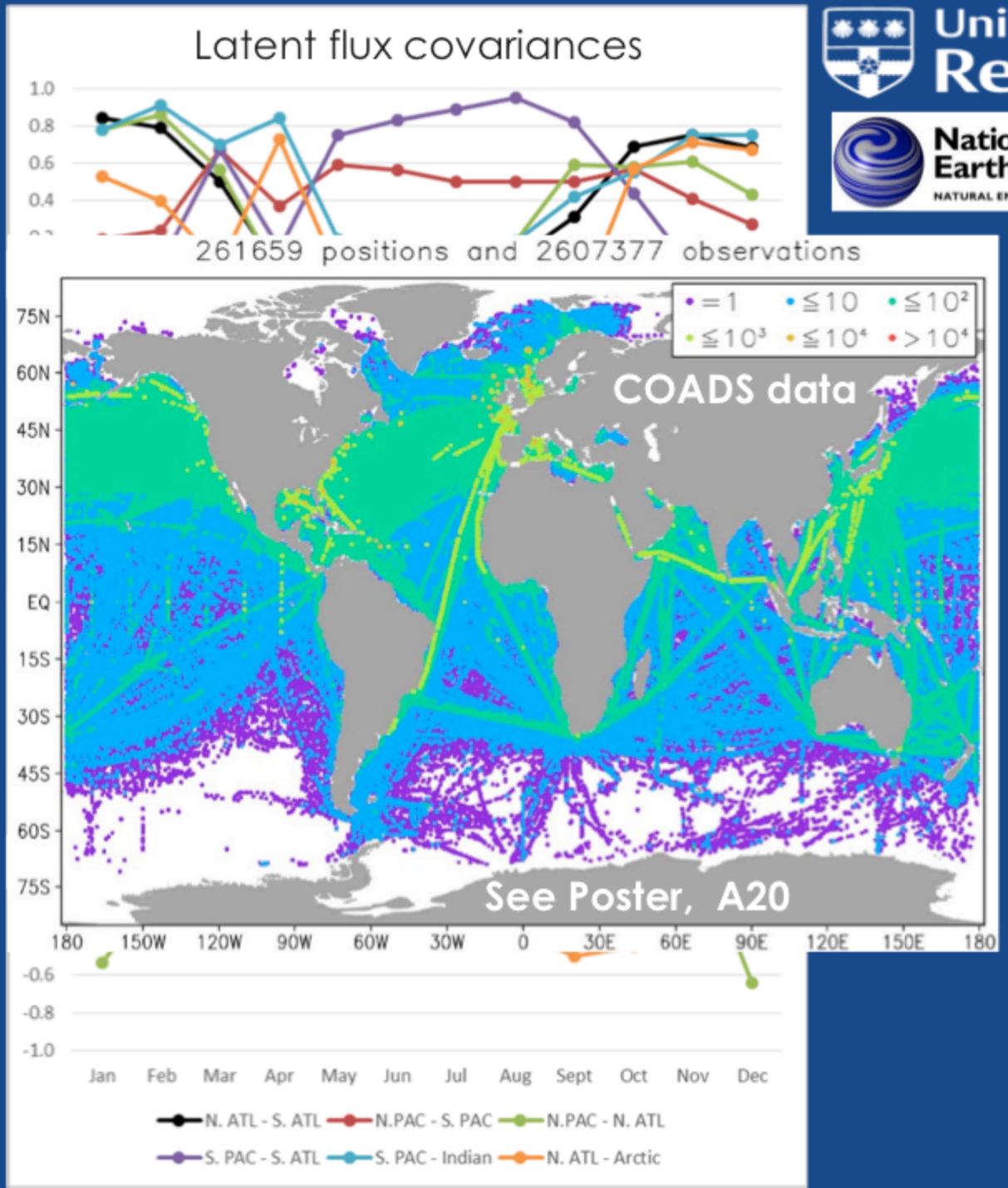

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ERAInterim Ht+Water Flux Convergences (Oceans only)

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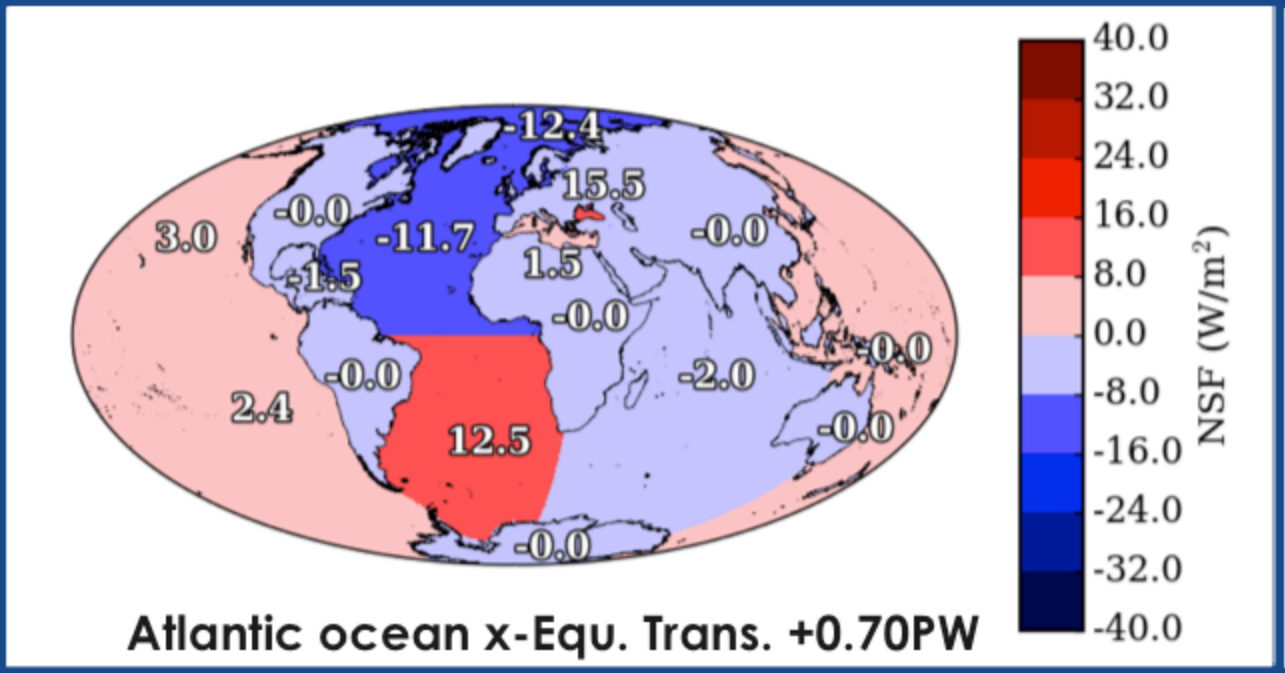
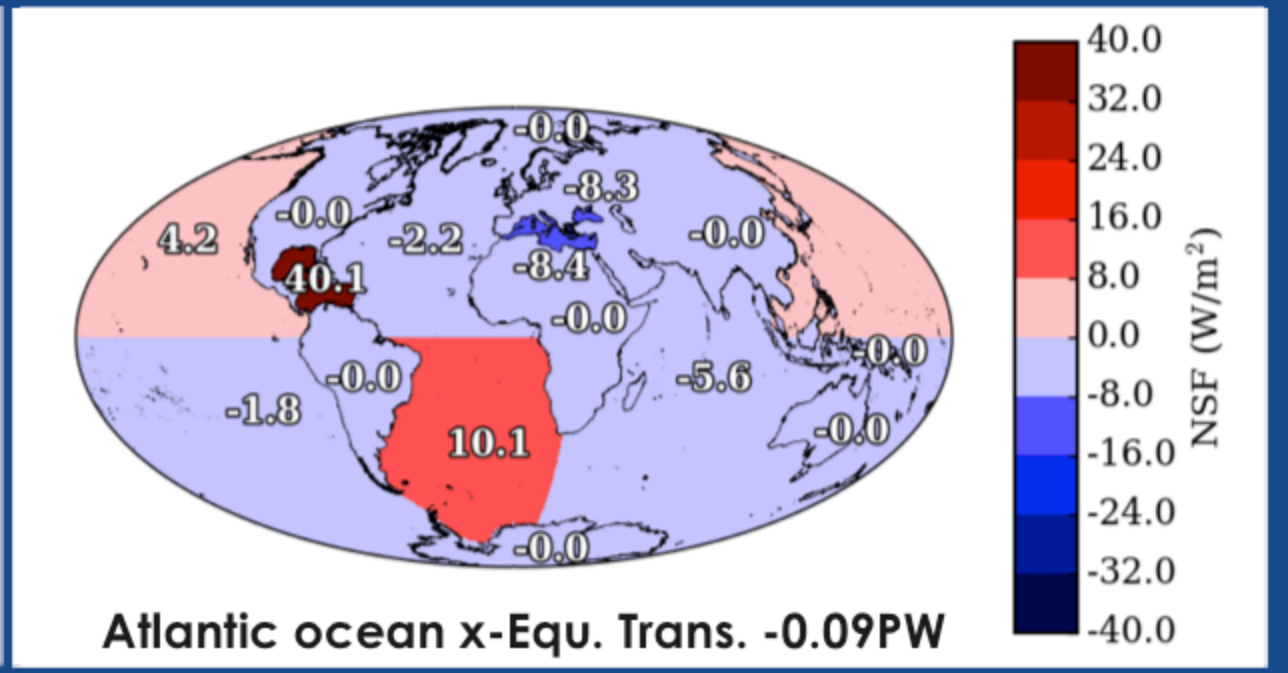
Net surface flux : NEWS + ERAInterim



Atlantic ocean x-Equ. Trans. +0.70PW

NEWS-constrained NSF



Atlantic ocean x-Equ. Trans. -0.09PW

Convergence errors from spread of 5 reanalyses

Med + Black sea errors (small area issue)

Heat loss over Arctic too large

ERAInterim Ht+Water Flux Convergences (Oceans only)

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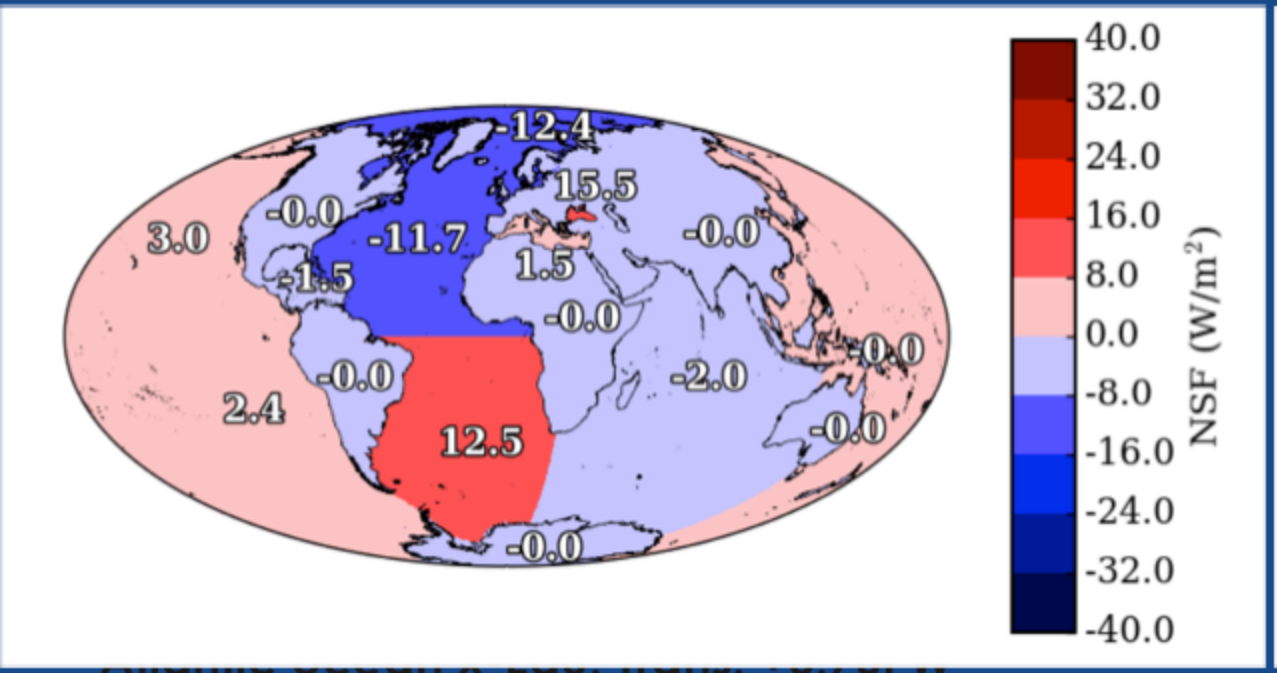
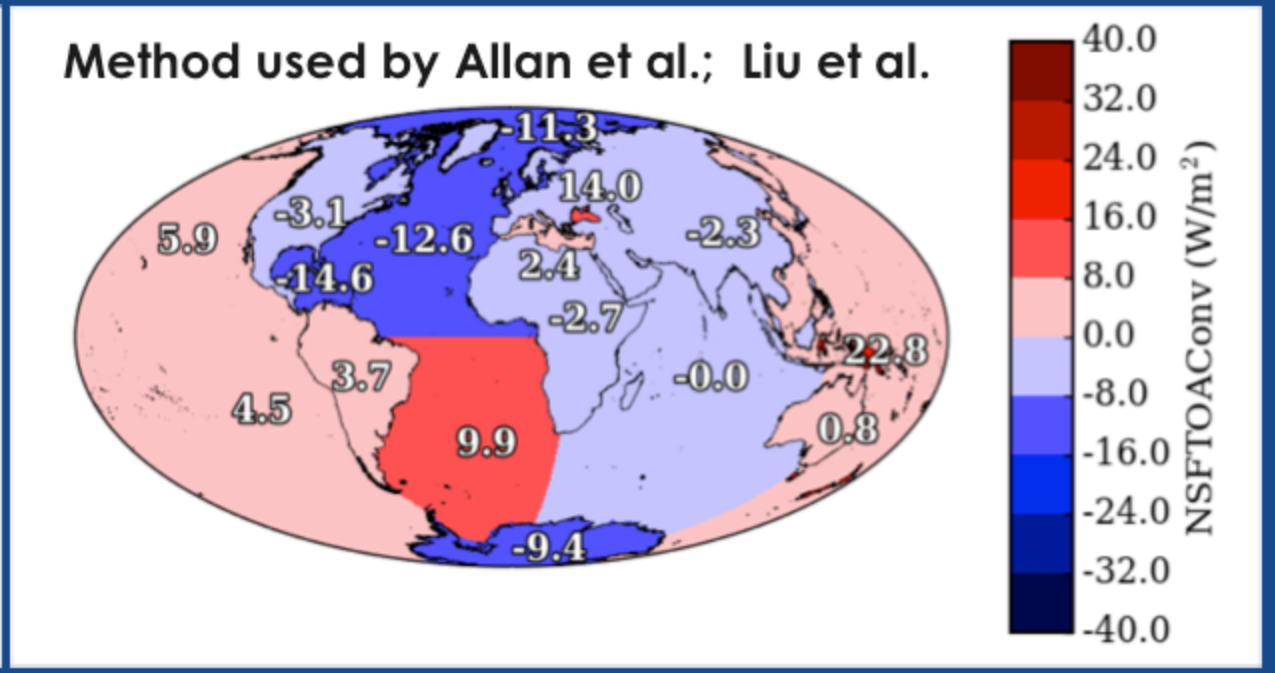
NEWS+ERAInterim



TOA + ERAInterim



Convergence errors from spread of 5 reanalyses

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Heat loss over Arctic too large

Ocean Reanalysis Heat + Freshwater Flux Convergences

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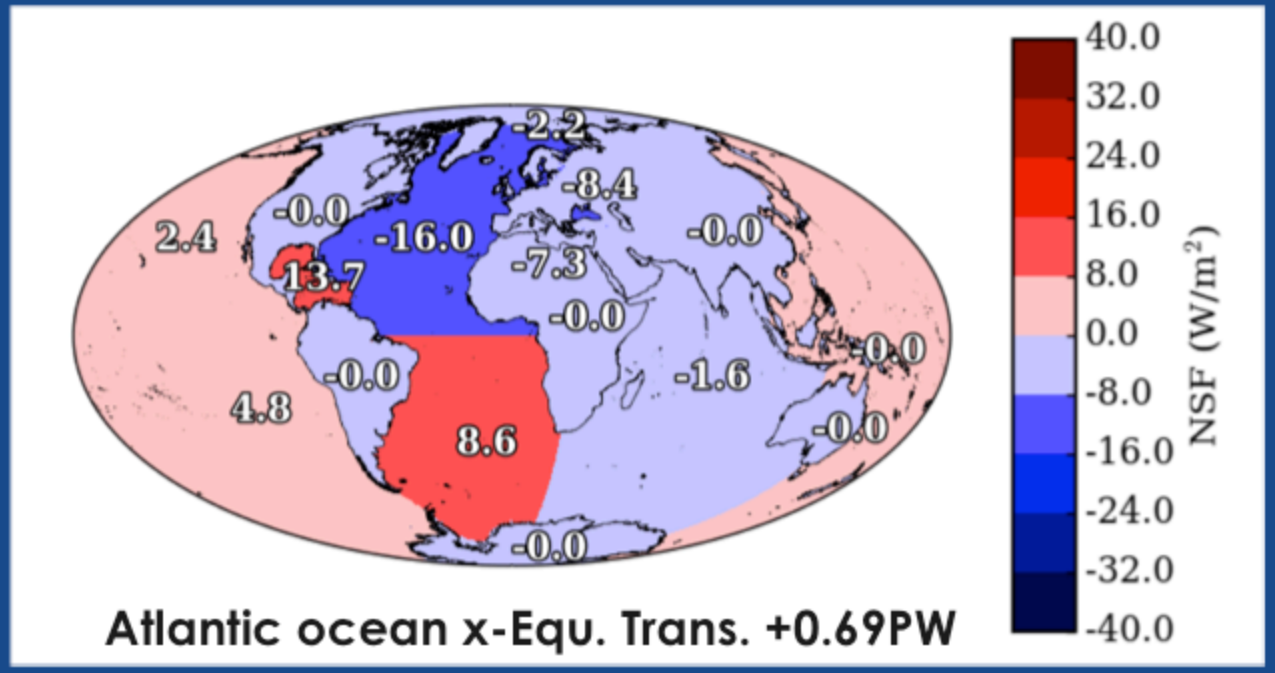
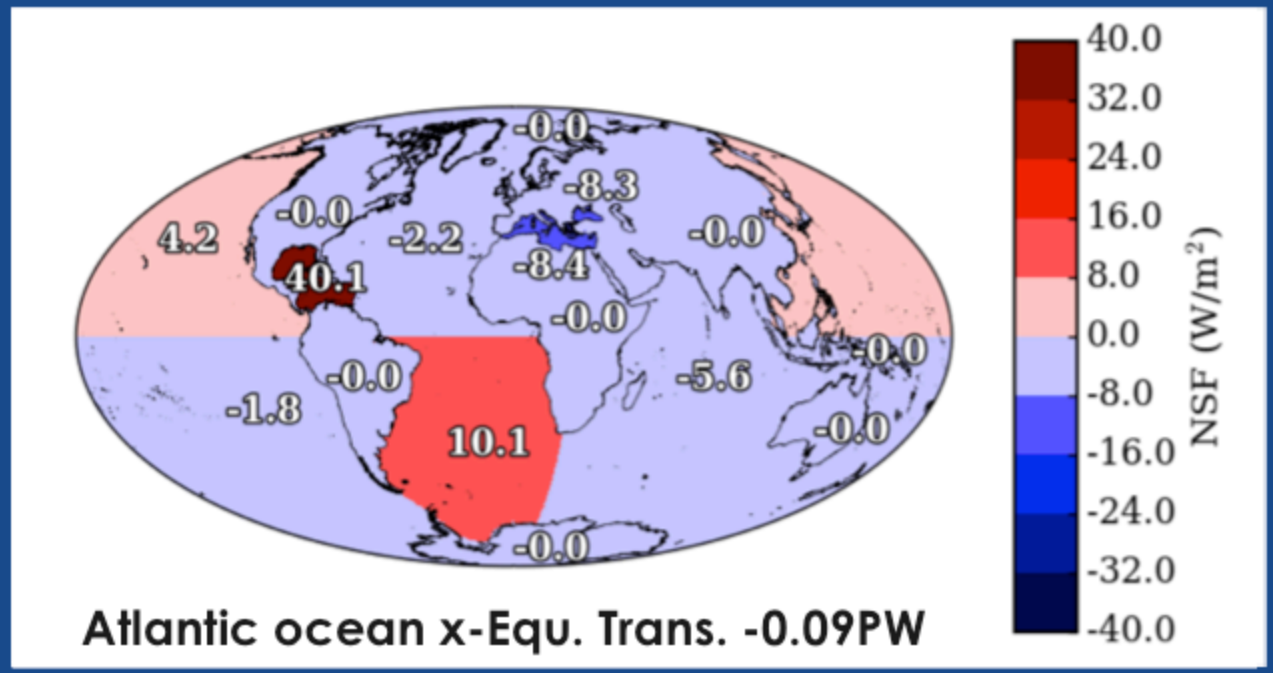
NEWS + Ocean Reanalysis Mean



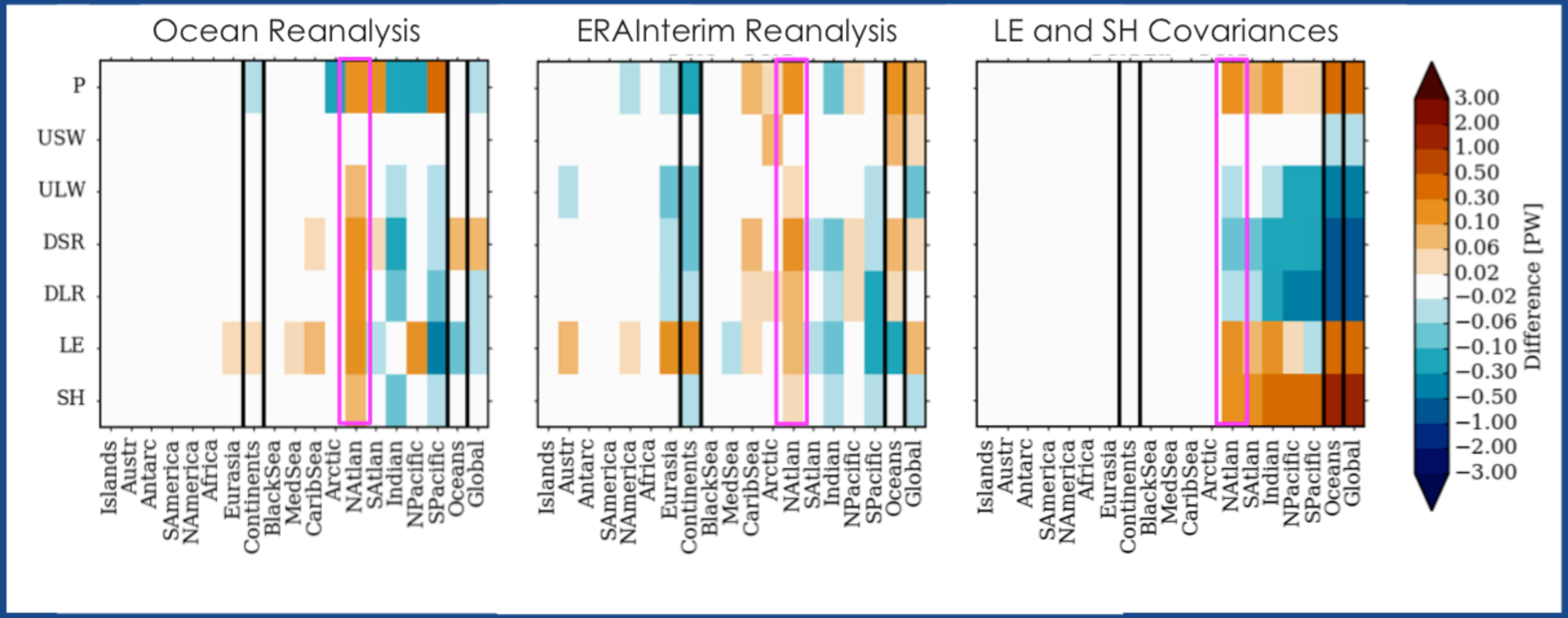
NEWS-constrained NSF



Convergence errors from spread of 4 ocean reanalyses

Med + Black sea fluxes better
Arctic heat loss much more realistic

Signature regional changes relative to NEWS/Fit1 (PW)



Arctic Energy Budget

Surface Energy Fluxes

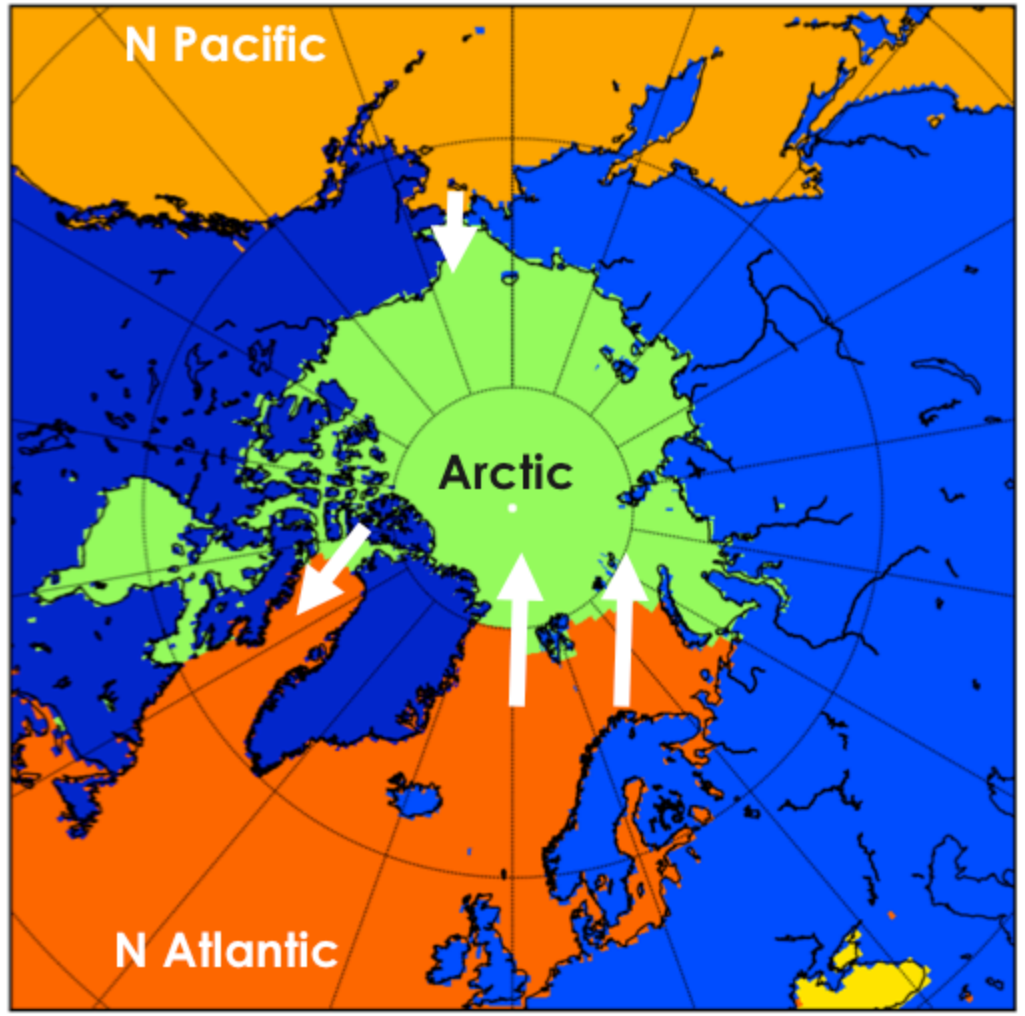
NEWS Initial Conditions +40TW
NEWS Solution +0TW ±130TW

TOA + ERAI. transports -130TW

NEWS with ERAI. transports -140TW ±40TW

NEWS with Ocean transports -24TW± 8TW

ERAInterim transporting too little heat into Arctic?



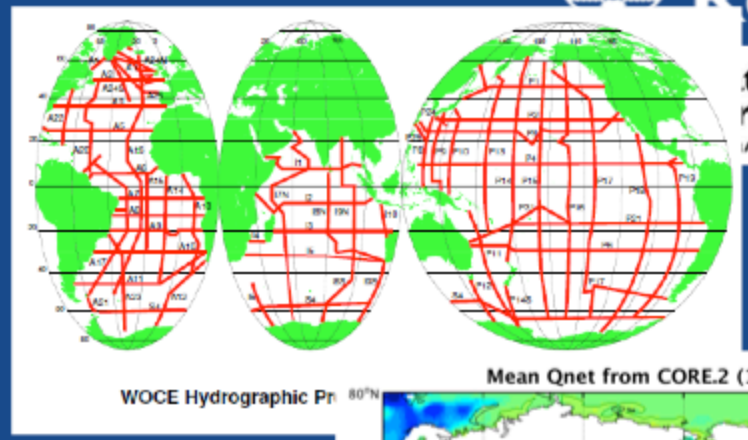
Future directions

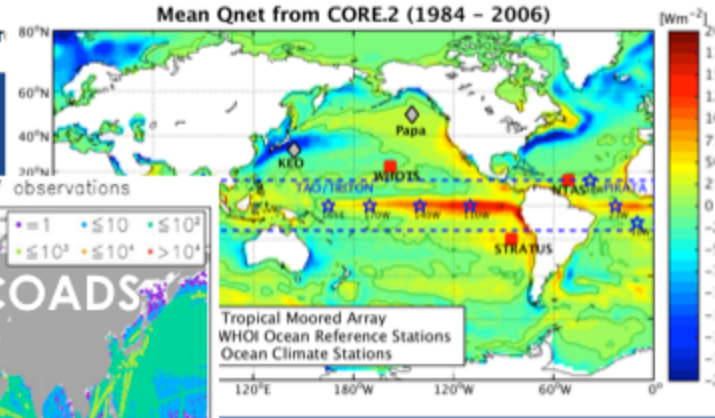
1. Reanalysis Transports
   - Higher space-time resolution products
   - Which products?
   - Uncertainties
2. Better use of In situ data

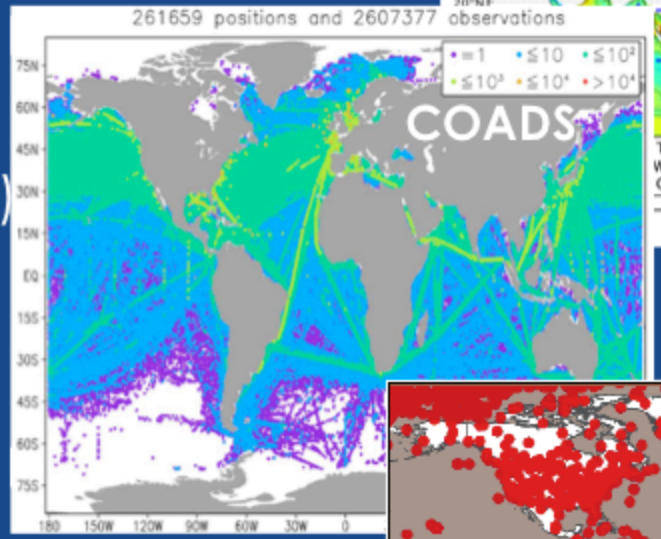
   Ocean hydrography transport constraints
   - eg. Grist and Josey (2003), Isemer et al (1989)
   - RAPID-MOCHA, OSNAP, WOCE…….
   - North Atlantic focus

   EO structural errors and covariances
   - OceanSITES flux buoys, COADS,...
   - Regional OHC distributions, Argo,….
   - Radiation networks: BSRN, GEBA,..

Thank you!







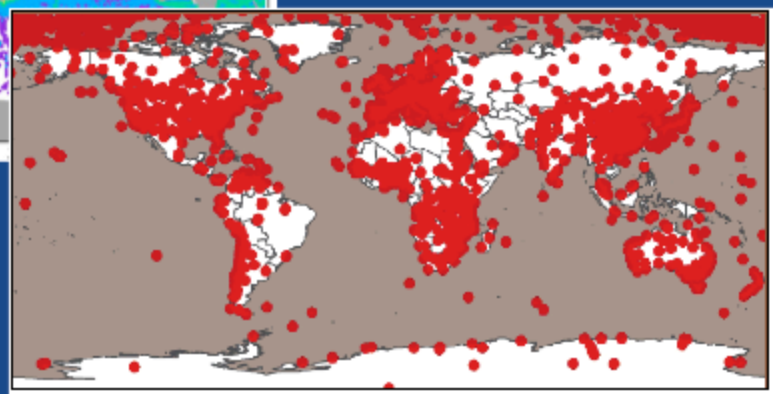


FIGURE 1 Worldwide observation sites in GEBA

a) ERAInterim convergences (Oceans only)
b) Ocean Ens. convergences.

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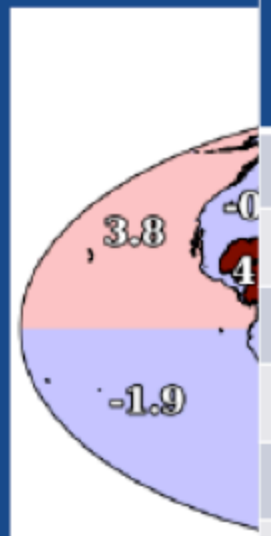
Net

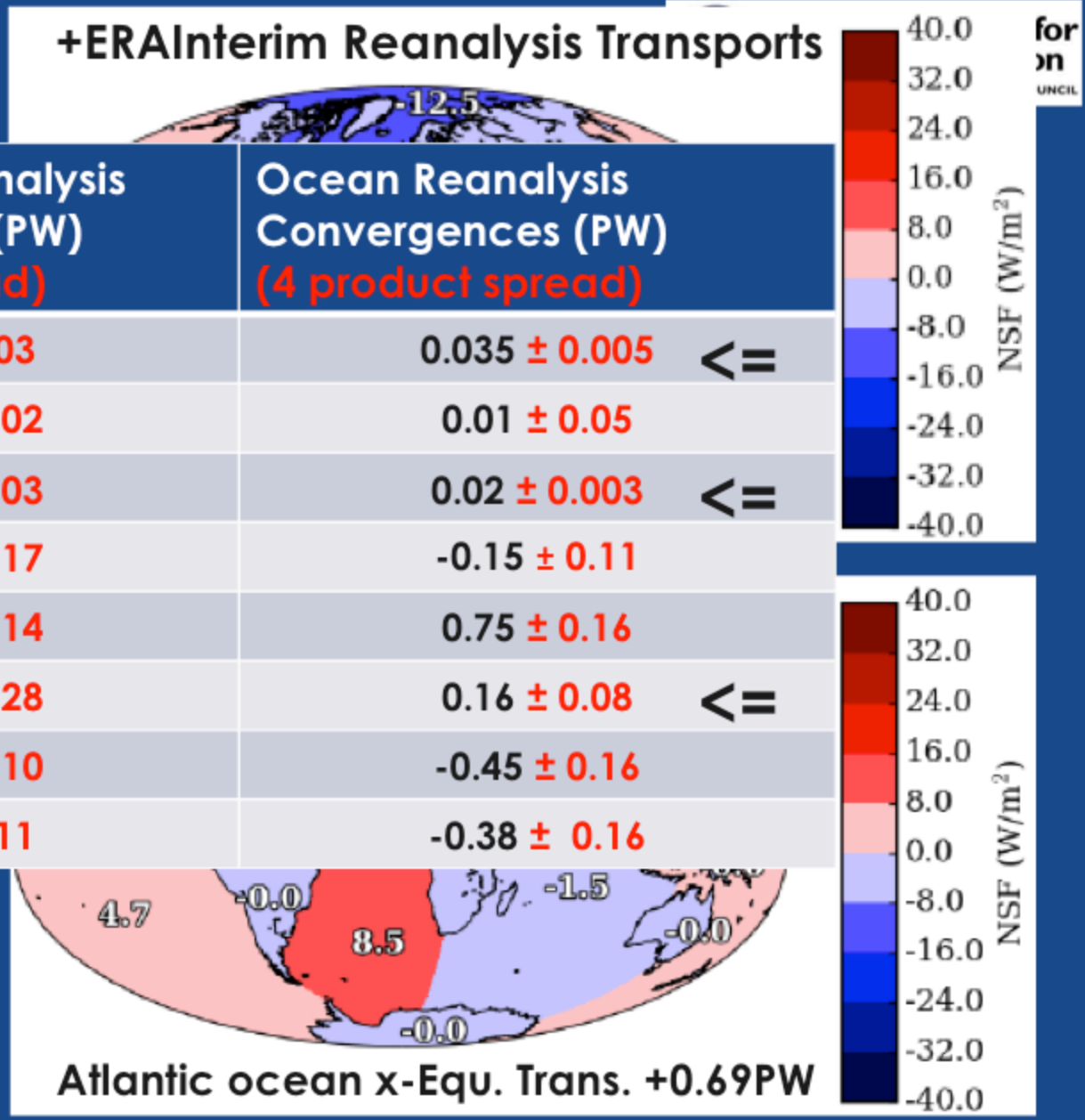
Ocean Region	ERA-Interim Reanalysis Convergences (PW) (5 product spread)	Ocean Reanalysis Convergences (PW) (4 product spread)	
8 (Arctic)	1.10 ± 0.03	0.035 ± 0.005	<=
9 (Caribbean)	-0.27 ± 0.02	0.01 ± 0.05	
10 (Mediterranean Sea)	-0.01 ± 0.03	0.02 ± 0.003	<=
12 (North Pacific)	-1.90 ± 0.17	-0.15 ± 0.11	
13 (North Atlantic)	-0.60 ± 0.14	0.75 ± 0.16	
14 (Indian Ocean)	-0.82 ± 0.28	0.16 ± 0.08	<=
15 (South Pacific)	-0.36 ± 0.10	-0.45 ± 0.16	
16 (South Atlantic)	0.85 ± 0.11	-0.38 ± 0.16	



Atlantic

Both improve N Atlantic and Caribbean

ERAinterim anomalous over small regions
--Mediterranean, Black Sea, Arctic



Atmospheric Reanalysis Surface flux products

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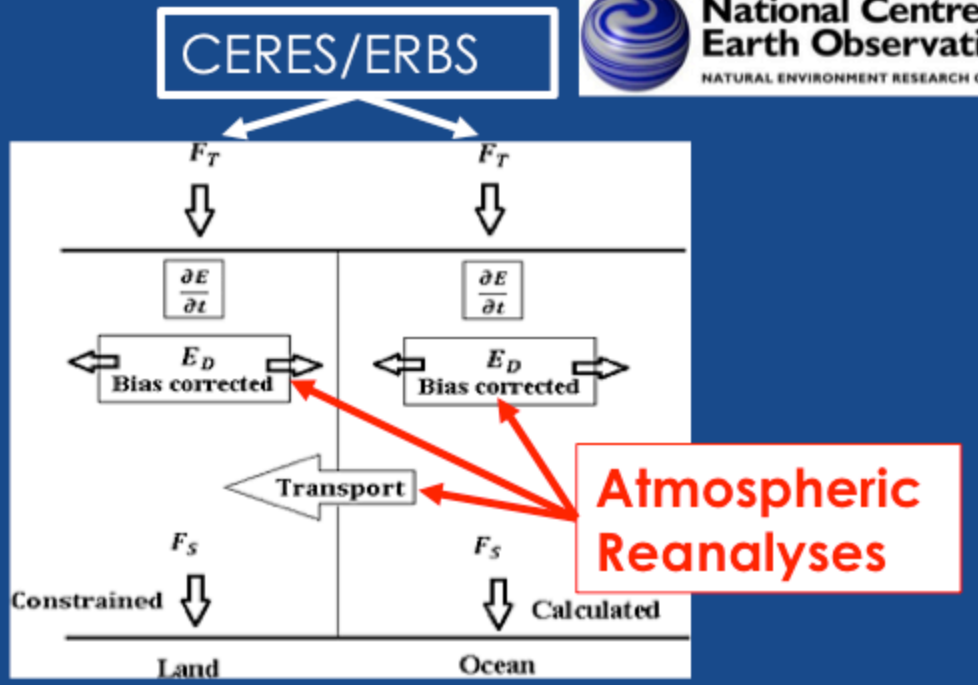
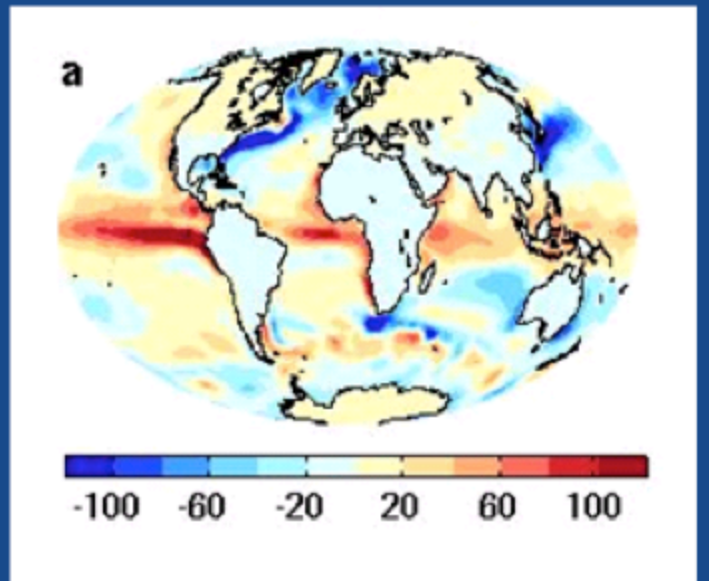
TOA Energy fluxes modified by Atm. Reanalysis Energy transports

- Trenberth and Fasullo (2008)
- Allan et al (2014), Liu et al (2015)





Advantages

- High resolution surface product
- Horizontal dynamical constraints

Disadvantages

- Model dependent? Uncertainties?
- Surface constraints ad-hoc
- No separate water cycle (mass corrections)
- No flux component information, LW, SW etc.

EO datasets from NEWS: (L'Ecuyer et al. 2015)

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TABLE 1. Data sources and associated documentation.

Parameter	Dataset	Relevant satellite inputs	References
Radiative fluxes 4 semi-independent products	SRB	CERES, AVHRR	Gupta et al. (1999)
	ISCCP-FD	AVHRR	Zhang et al. (2004)
	2B-FLXHR-lidar	*CloudSat*, *CALIPSO*	Henderson et al. (2013)
	C3M	MODIS, AMSR-E, CERES, *CloudSat*, *CALIPSO*, MODIS	Kato et al. (2010); Kato et al. (2011)
Ocean turbulent heat fluxes 1 product + errors	SeaFlux	SSM/I	Curry et al. (2004); Clayson et al. (2015, manuscript submitted to *Int. J. Climatol.*)
Land turbulent heat fluxes 3 semi-independent products	Princeton ET	AIRS, CERES, MODIS, AVHRR	Vinukollu et al. (2011)
	MERRA	Numerous	Rienecker et al. (2011); Bosilovich et al. (2011)
	GLDAS	SSM/I, SSMIS, GOES-IR, TOVS, AIRS, TRMM, MODIS, AVHRR	Rodell et al. (2004b)
Atmospheric latent heating 1 product + errors	GPCP v.2.2	SSM/I, SSMIS, GOES-IR, TOVS, AIRS	Adler et al. (2003); Huffman et al. (2009)

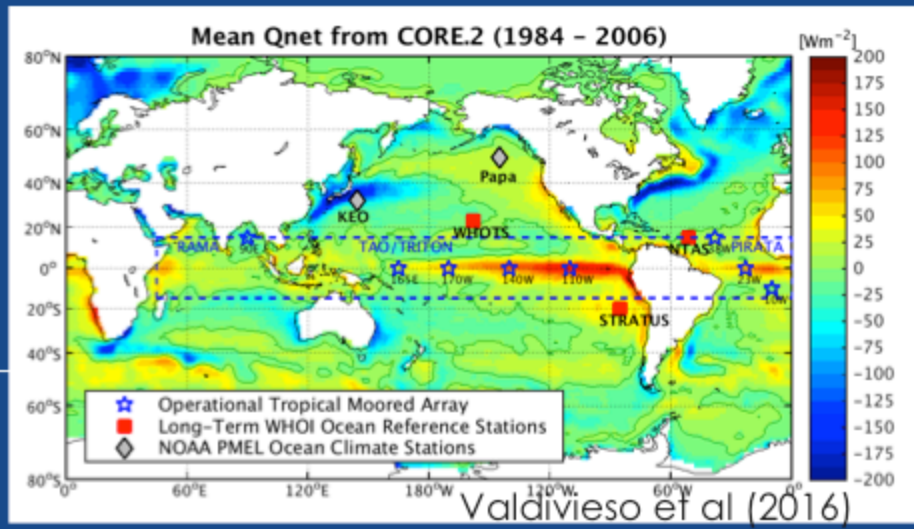
Structural error covariances needed for all flux components

Energy Budget datasets L'Ecuyer et al (2015)

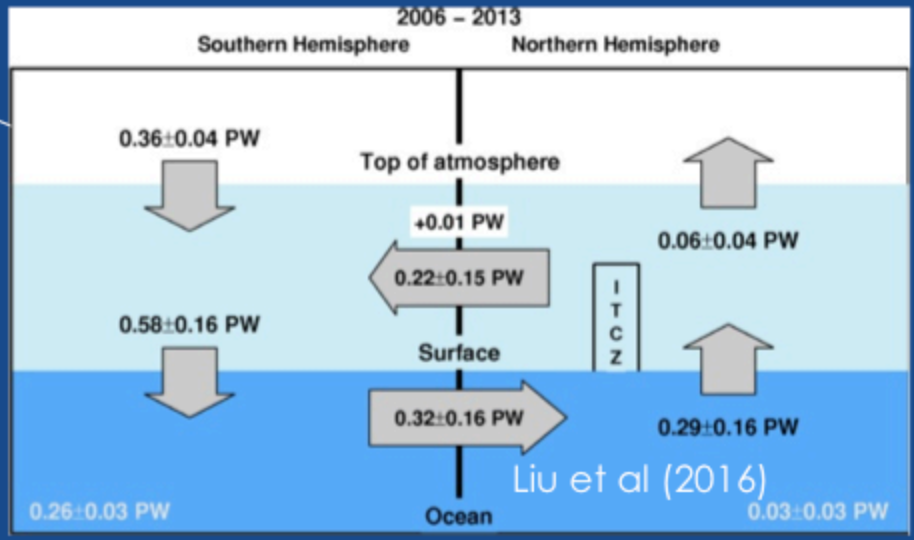
Current work

1. General Developments
   - Seasonal + full inter-annual analysis
     - Storage constraints; Argo, Altimeter, GRACE…..
   - Improved spatial analysis
     - Ocean constraints RAPID-MOCHA, OSNAP, WOCE…….
   - Independent verification (Flux buoys?)
   - Inter-hemispheric fluxes (Coupled A-O solution)
2. Adding Reanalysis Transports
   - Space-Time-scales and Uncertainties?
   - Higher resolution products
3. Calculating structural EO error covariances
   - Surface Radiation and Precipitation
   - Land turbulent fluxes
   - Solve inverse with EOF structural error basis functions

Thank you!



Valdivieso et al (2016)



Liu et al (2016)