Surface Heat Fluxes From Global Ocean Reanalyses

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Context

- This study is part of **the Ocean Reanalysis Intercomparison Project (ORA-IP)** under the GOV and CLIVAR-GSOP programs– which focus is on the comparison of various relevant quantities such as SL, SH, OHC, OSC, MLD, SI, and the net surface heat fluxes *(see Balmaseda et al. 2015 for further details).*
- Results reported in CLIVAR Exchanges M. Valdivieso et al. (2014): **Heat fluxes from ocean and coupled reanalyses.** *CLIVAR Exchanges Issue no. 64, 28-31, February 2014.*
- M. Valdivieso et al. (2015): **An assessment of air-sea heat fluxes from ocean and coupled reanalyses.** *Submitted to Climate Dynamics, Special Issue: Ocean Reanalyses, 15 February 2015.*

Talk

- Global heat budgets and the ocean tranports implied by these ORA-IP heat fluxes
- ORA-IP ensemble consistency of flux variability on seasonal to interannual time scales
- Comparisons with available surface heat flux datasets, including local buoy flux data at a number of OceanSITES

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ORA-IP Datasets

Group	#	ORA-IP Data Sets	Model	Forcing	Assimilation	Period	Reference
Low Resolution	1	BOM PEODAS	MOM2, 2°	ERA40/NCEP-R2	EnKF (T, S, SST)	1980-2012	Yin et al. (2011)
	2	ECMWF ORAS4	NEMO, 1°	ERA40/ERAi Flux Forcing	3DVAR (T, S, SLA)	1960-2009	Balmaseda et al. (2012)
	3	MRI/JMA MOVEG2	MRI.COM, 1°	CORE.2 with CORE Bulk Fluxes	3DVAR (T, S, SST, SLA)	1948-2007	Fujii et al. (2015)
	4	MRI/JMA MOVECORE	MRI.COM, 1°	JRA-25 with Bulk Fluxes	3DVAR (T, S, SST, SLA)	1993-2012	Toyoda et al. (2013)
	5	U. Hamburg GECCO2	MIT, 1°	NCEP-R1 with Bulk Fluxes	4DVAR (T, S, SST, SLA)	1993-2010	Köhl (2014)
	6	JPL ECCOv4	MIT, 1°	ERAi with CORE Bulk Forcing	4DVAR (T, S, SLA)	1993-2010	Wunsch & Heimbach (2013)
	7	NCEP GODAS	MOM3, 1°	NCEP-R2 Flux Forcing	3DVAR (T, SLA)	1980-2011	Behringer (2007)
My Ocean	8	CMCC C-GLORS05v3	NEMO, ½°	ERAi corr + CORE Bulk Forcing	3DVAR (T, S, SST, SLA)	1990-2011	Storto et al. (2014)
	9	U. Reading UR025.3	NEMO, ¼°	ERAi with CORE Bulk Forcing	OI (T, S)	1989-2010	Haines et al. (2012)
	10	U. Reading UR025.4	NEMO, ¼°	ERAi with CORE Bulk Forcing	OI (T, S, SST, SLA, IC)	1989-2010	Valdivieso et al. (2014)
	11	Met Office GloSea5	NEMO, ¼°	ERAi with CORE Bulk Forcing	3DVAR (T, S, SST, SLA)	1993-2010	Waters et al. (2014)
	12	Mercator GLORYS2v1	NEMO, ¼°	ERAi corr + CORE Bulk Forcing	KF (T, S, SST, SLA)	1993-2009	Ferry et al. (2012)
	13	Mercator GLORYS2v3	NEMO, ¼°	ERAi corr + CORE Bulk Forcing	KF (T, S, SST, SLA, IC)	1993-2011	Ferry et al. (2012)
Coupled	14	MRI/JMA MOVE-C	MRI.COM, 1°	Coupled Model Fluxes	3DVAR (T, S, SST, SLA)	1993-2011	Fujii et al. (2009)
	15	NCEP CSFR	CSFRv2/MOM4, ½°	Coupled Model Fluxes	3DVAR (T)	1980-2011	Xue et al. (2011)
	16	GFDL ECDA	CM2.1/MOM4, 1°	Coupled Model Fluxes	EnKF (T, S, SST)	1993-2011	Chang et al. (2013)

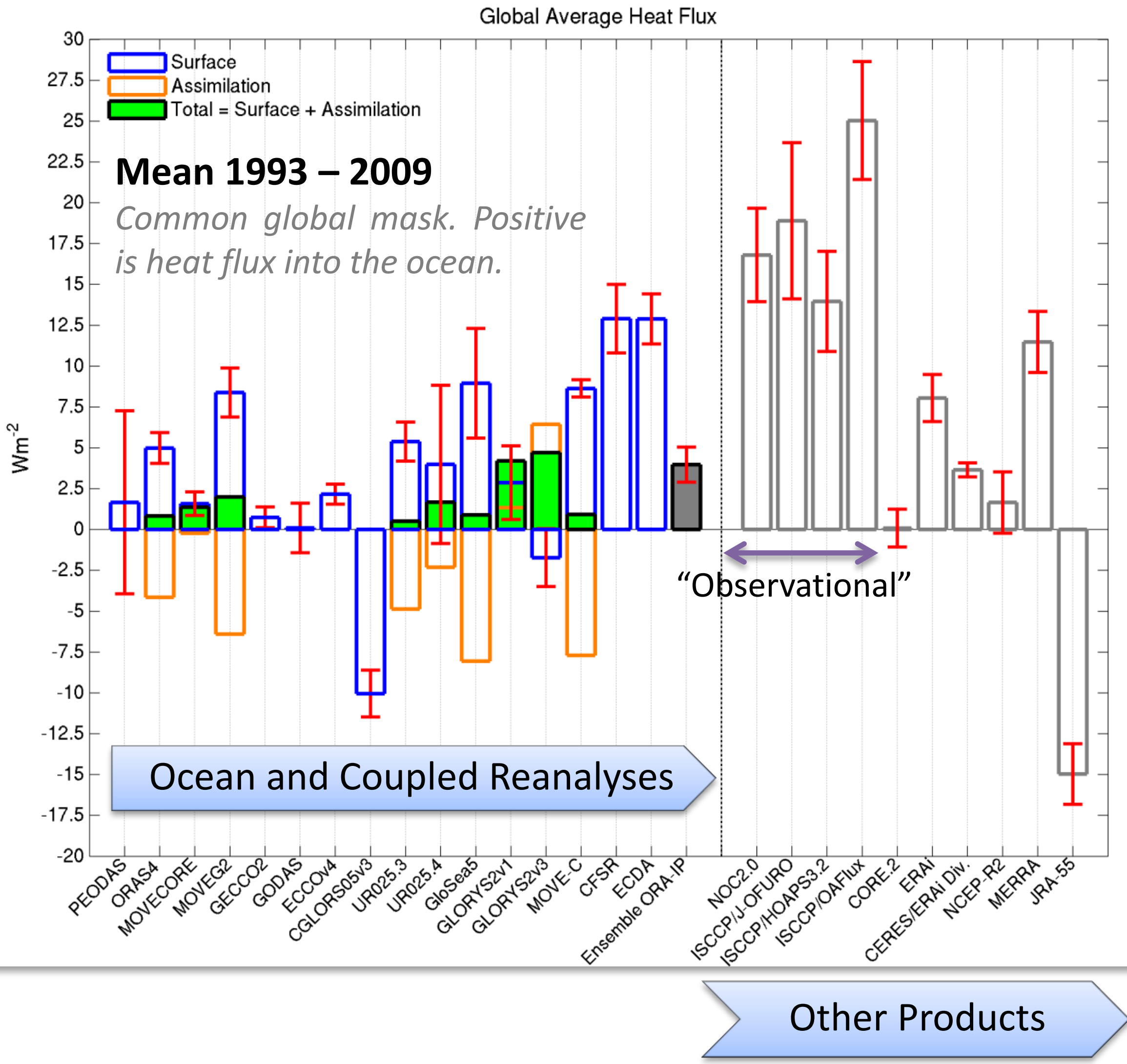
→Most reanalyses are forced with bulk formula using an atmospheric reanalysis product

Other Surface Heat Flux Data

Type	*Data Sets*	*Resolution*	*Period*	*Reference*
Ship-Based	***NOC2.0***	*Monthly, 1°*	*1973-2009*	*Berry and Kent (2009)*
Satellite-Based	***CERES***	*Monthly, 1°*	*2000-*	*Loeb et al. (2009)*
	ISCCP-FD	*3 Hourly, 2.5°*	*1984-2009*	*Zhang et al. (2004)*
	J-OFURO	*Daily, 1°*	*1988-2008*	*Kubota et al. (2002)*
	HOAPS	*Monthly, 0.5°*	*1987-2008*	*Andersson et al. (2010)*
NWP	***ERA-Interim***	*6 Hourly, T255*	*1979-*	*Dee et al. (2011)*
	JRA-55	*Daily, 1.25°*	*1958-*	*Kobayashi et al. (2015)*
	MERRA	*Hourly, 0.5°*	*1979-*	*Rienecker et al. (2011)*
	NCEP-R2	*Hourly, T62*	*1979-*	*Kanamitsu et al. (2005)*
Hybrid	***CORE.2***	*Monthly, 1°*	*1948-2006*	*Large and Yeager (2009)*
	TOA CERES/ERAi Divergence	*Monthly, 1°*	*1984-*	*Liu et al. (2015)*
	OAFlux	*Daily, 1°*	*1983-*	*Yu et al. (2008)*
Buoy	***TAO/TRITON***	*Daily, Tropical Pac.*	*2007-09*	*McPhaden et al. (1998)*
	RAMA	*Daily, 15°N90°E*	*2007*	*McPhaden et al. (2009)*
	PIRATA	*Daily, Tropical Atl.*	*2007-09*	*Servain et al. (1998)*
	WHOI Stratus	*Daily, 20°S85°W*	*2001-09*	*Weller et al. (2015)*

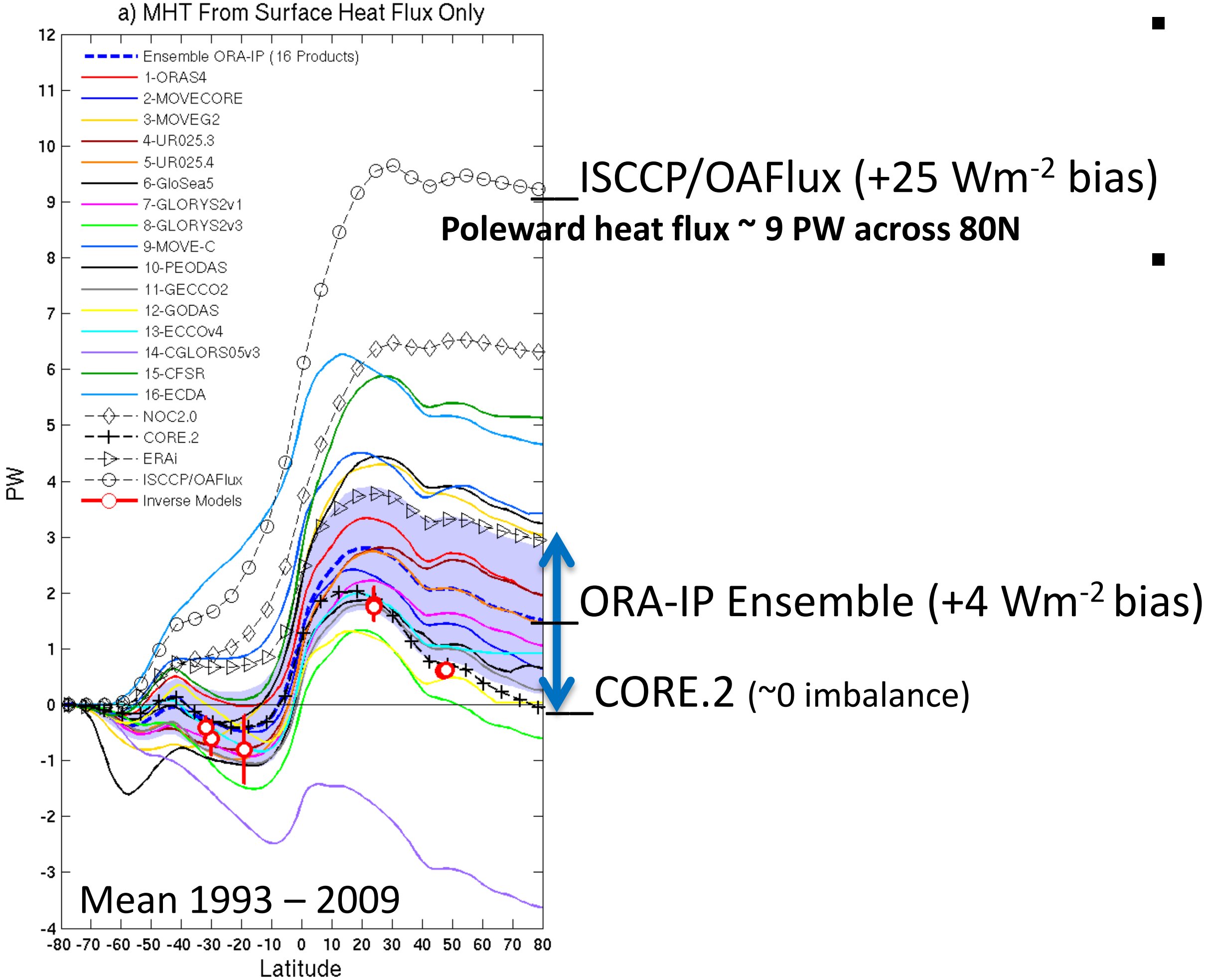
The ORA-IP heat flux products are compared with other global air-sea heat flux data based on **ship observations, satellite data, atmospheric reanalyses, or hybrid products** (a combination of atmospheric reanalysis and remote sensing products), and locally, with **buoy flux data** measured at moorings (limited in both time and space) – *details in Valdivieso et al. (2014, 2015).*

Global Heat Budget



- Most ORA-IP products have positive bias (i.e., net heat flux into the ocean) over 1993-2009 (blue bars). This is usually smaller than for observational products (+15-25 Wm^{-2})
- The 16-member ensemble mean ~ 4 Wm^{-2} (dark grey bar). Variability ~ 1 Wm^{-2} related to ENSO (red error bars)
- Assimilation of ocean observations removes heat from the ocean on a global basis (orange bars)
- Total heat flux applied (i.e., “Surface + Assimilation”) reduced to a small positive imbalances ~1-2 Wm^{-2} (green bars), but still larger than the observed OHC change above 3000 m (~ 0.5 Wm^{-2}) (e.g., Loeb et al. 2012)

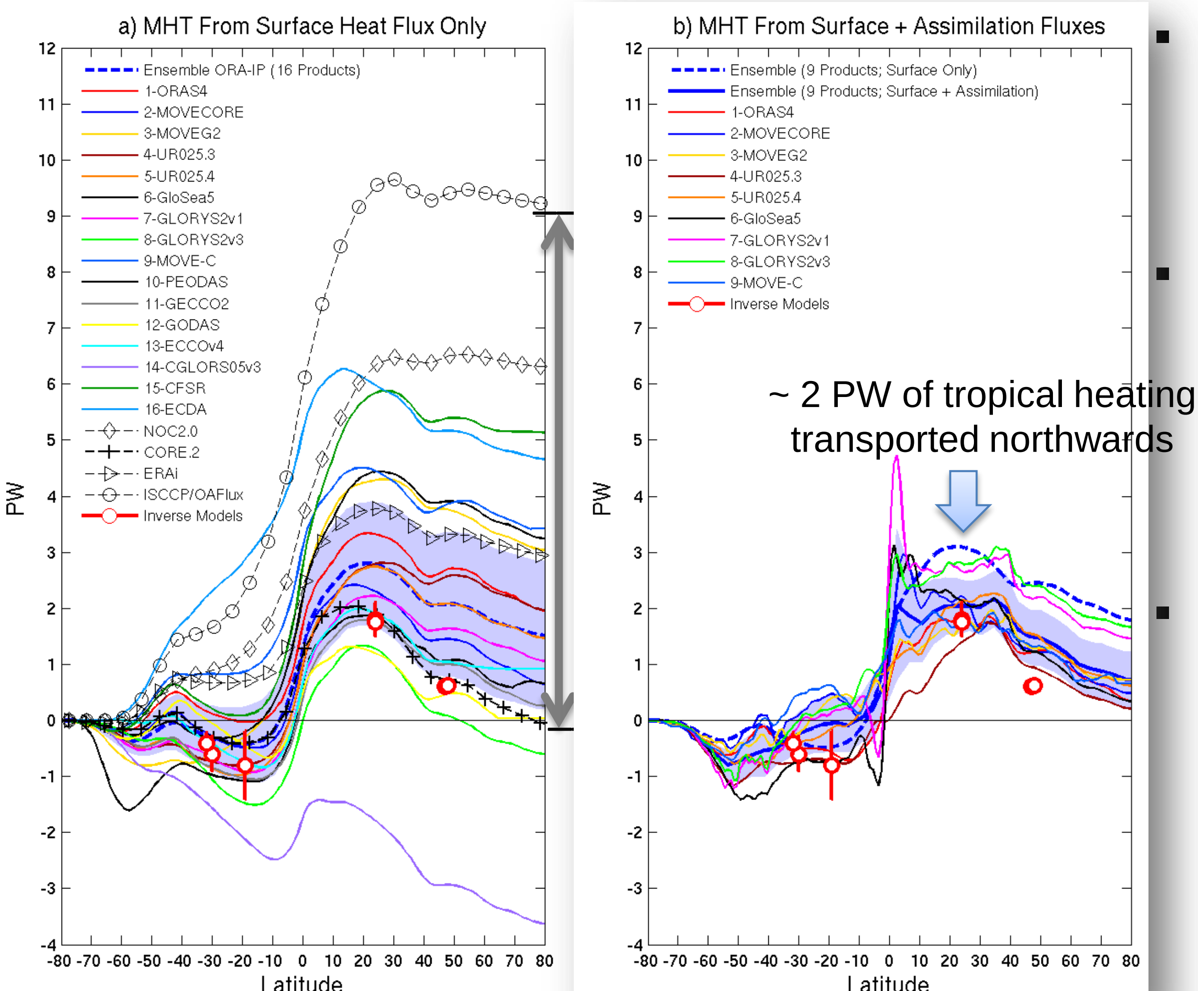
Implied Ocean Heat Transports



Global meridional ocean heat transport inferred from integrated net heat fluxes, starting from the south (i.e., the Antarctic continent) in comparison with WOCE-based inverse model estimates at control sections from Ganachaud and Wunsch (2003) and Lumpkin and Speer (2007).

- Global surface imbalances have large implications for balancing ocean heat transports (discrepancies in the north up to + 9 PW)
- The ensemble spread in ORA-IP (shaded around the mean) grows rapidly in the SO and crossing the tropics → largest uncertainties in net surface heat fluxes occurs in the SO and in the tropics.

Implied Ocean Heat Transports



Global meridional net surface heat transport inferred from integrated heat fluxes, starting in the south (i.e., the Antarctic continent) in comparison with WOCE-based inverse model estimates at control sections from Ganachaud and Wunsch (2003) and Lumpkin and Speer (2007)

- Global surface imbalances have large implications for balancing heat transports (discrepancies in the north up to + 9 PW)
- The ensemble spread in ORA-IP (shaded around the mean) grows rapidly in the SO and crossing the tropics → largest uncertainties in net surface heat fluxes occurs in the SO and in the tropics.
- Better agreement in the implied MHT with obs at various sections by combining **'Surface + Assimilation'** fluxes, but not in the tropics where the bias corrections are not consistent between the ORA-IP products.

Impacts of Using a Prescribed Atmosphere

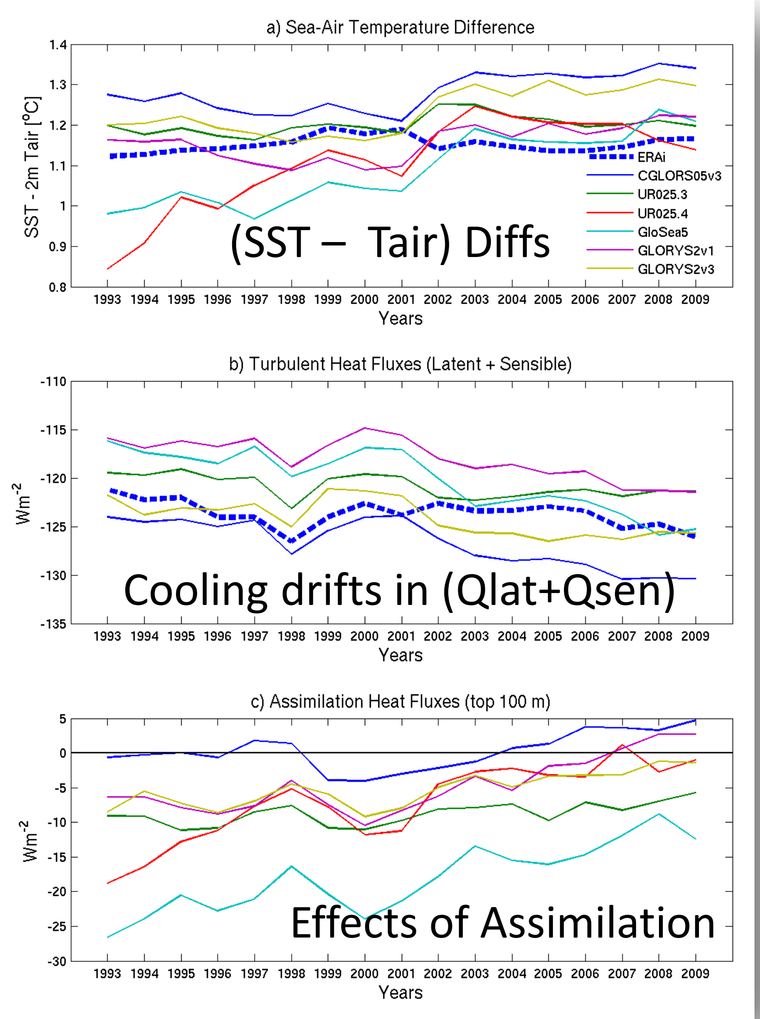
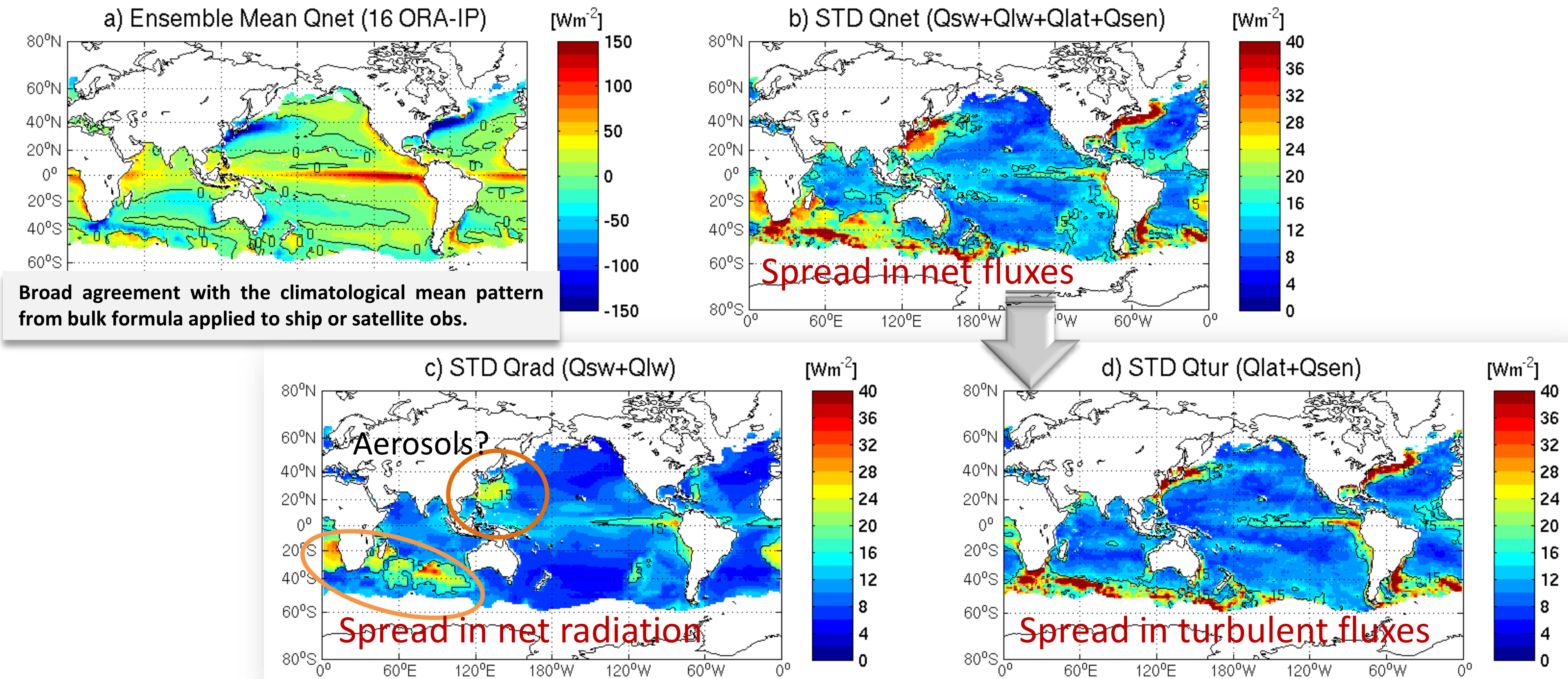


Fig. 3: a) **Year-to-year variability of global (60°S-60°N) averaged sea-air temperature (SST – Tair) from a subset of ORA-IP products forced by CORE Bulk Formula using prescribed ERAi surface fields** in comparison with the ERAi product itself. b) Turbulent (sensible + latent) heat fluxes from the ERAi product and as calculated from the 5 ORA-IP products that provided these fluxes. c) Vertically-integrated assimilation heat fluxes over the top 100 m from the ORA-IP products.

- Some products have (SST – Tair) relatively close to the original ERAi product, whereas others show relatively large differences, e.g., in UR025.4 and GloSea5, reflecting the assimilated OSTIA SSTs (Donlon et al. 2012) .
- Turbulent fluxes (latent plus sensible) are negative (ocean heat loss) and tend to damp SST differences from the prescribed ERAi Tair, with all products showing increased cooling with time relative to ERAi, which shows no trend.
- Assimilation heat fluxes in the mixed layer (top 100 m) show cooling decreasing with time, counteracting the downward trends in turbulent fluxes.
- They can be regarded as a correction for model drifts due to using a prescribed atmosphere.

Ensemble of Flux Estimates

Long-term mean (1993 – 2009) ensemble of Qnet



- The ensemble spread in Qnet is dominated by turbulent heat fluxes (> 40 Wm^{-2} over the major western boundary currents regions), but with contributions from net radiation (up to 25 Wm^{-2}) at certain locations *(e.g., near the west coasts, south of Japan, and Ind sector of the ACC)*
- Flux component errors are correlated between ensemble members, so that net flux errors are smaller than STD Qrad + STD Qtur

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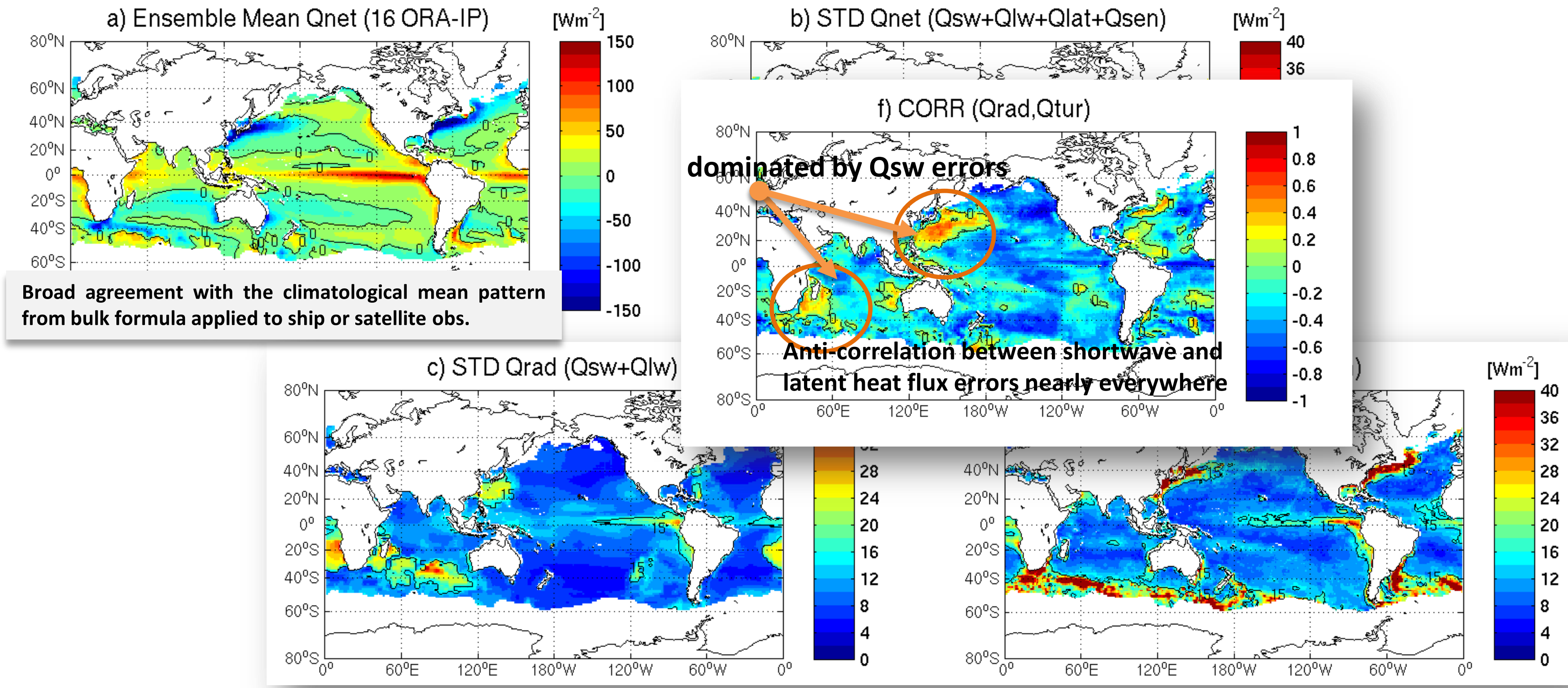

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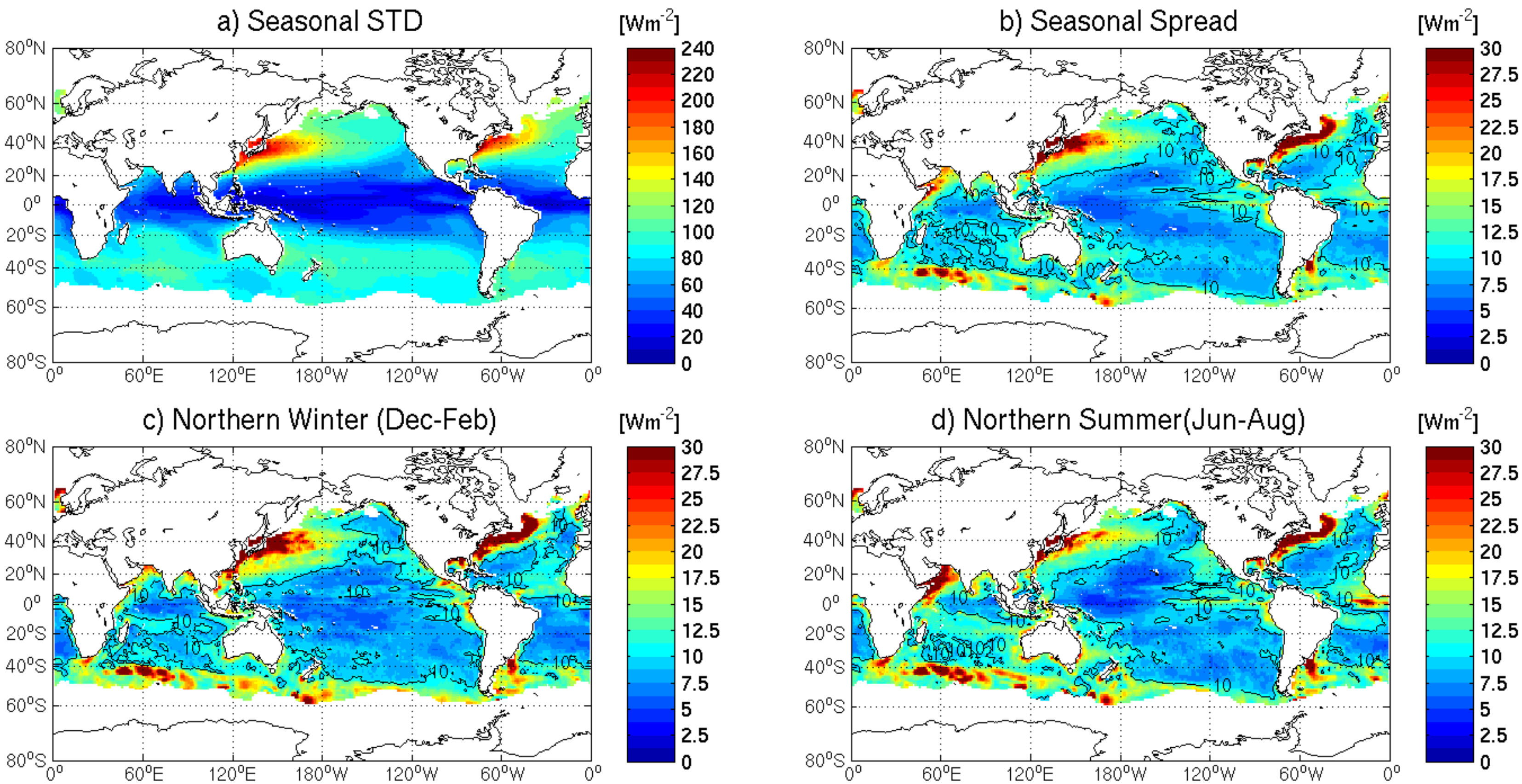
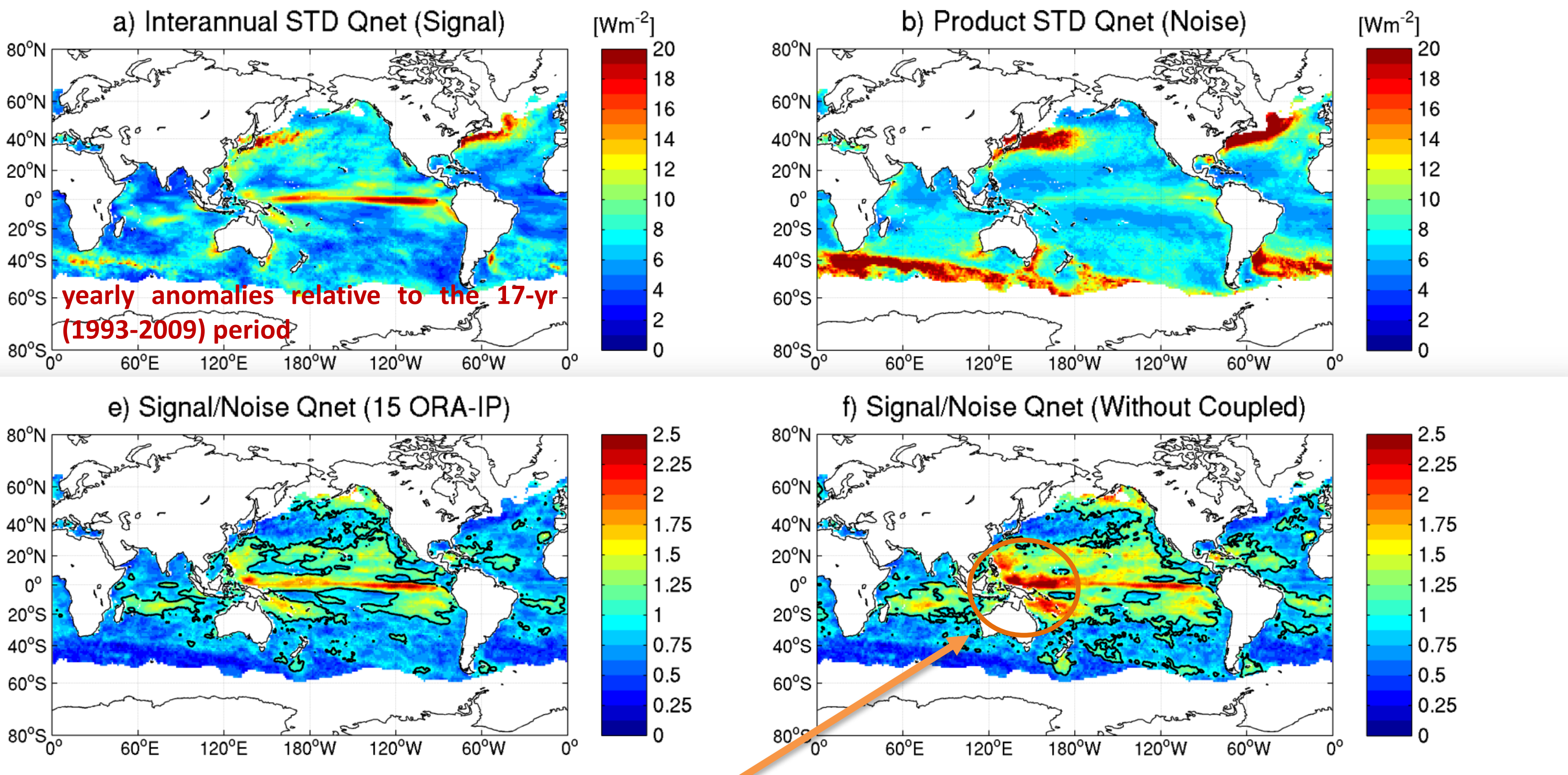
Consistency of the Seasonal Cycle

Seasonal Cycle of the ORA-IP ensemble Qnet (16 members with the long-term mean from each product removed)

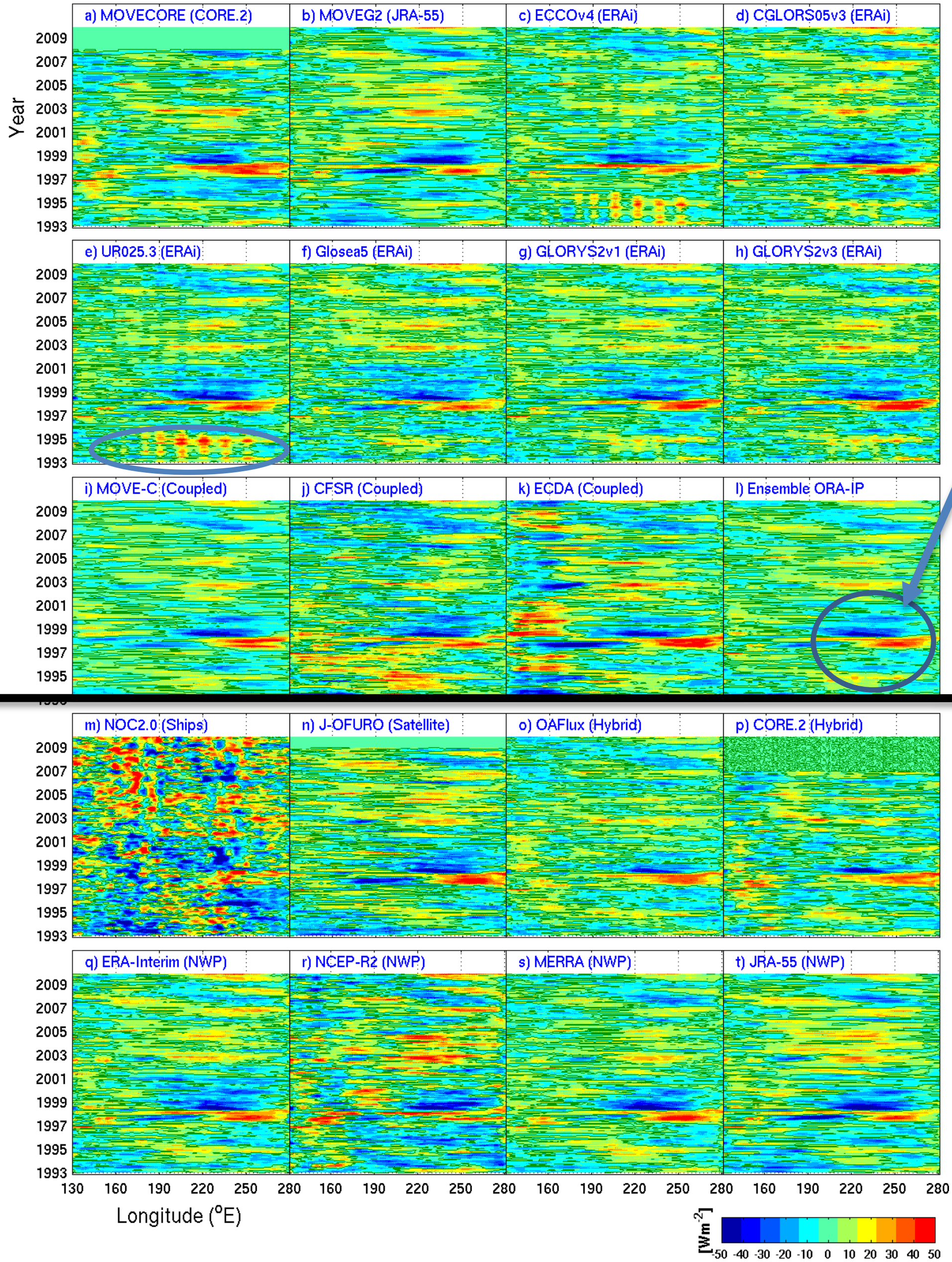


- The ensemble mean seasonal cycle is highly consistent between members, with most areas showing monthly noise spread < 10 Wm^{-2}
- The north western boundary currents, especially in the winter months, show the largest differences (> 25 Wm^{-2}); monsoon upwelling areas off east and west Africa and the Arabian Peninsula also show large variability

Interannual Heat Flux Signals



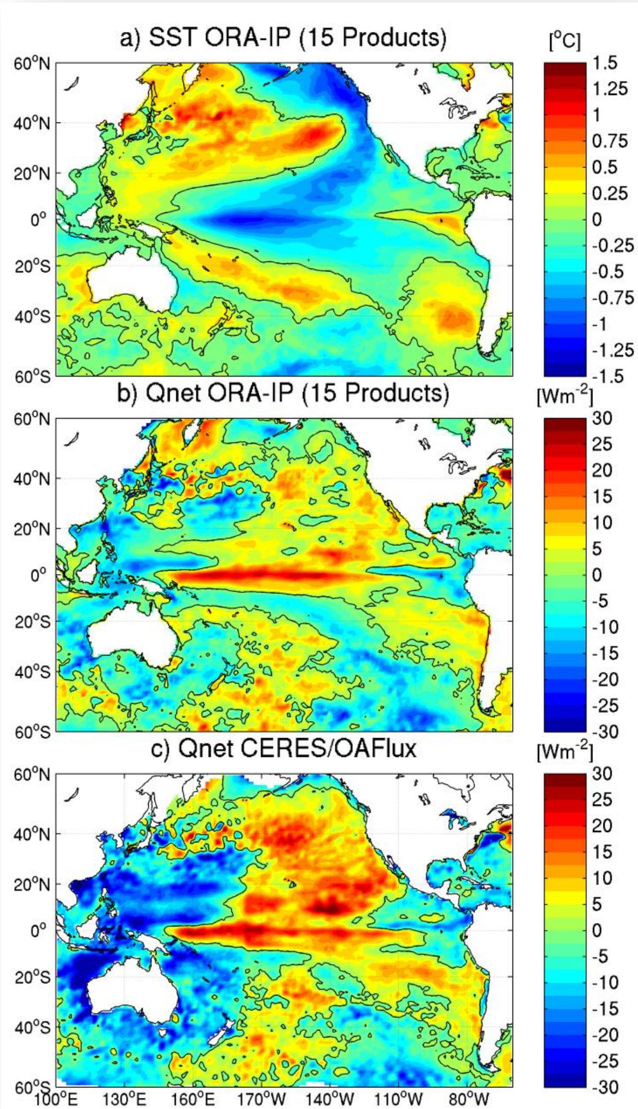
- Consistent Signal to Noise Ratio (up to 2) throughout the equatorial Pacific, reflecting the detection of ENSO, with the areas of detectable signal spreading to 20°N/S in the western Pacific
- The coupled products contribute to a larger ensemble noise in the tropics, especially in the **western Pacific warm pool**
- At higher latitudes, the signal/noise ratios reach values of 1.2-1.3 near the Gulf of Alaska that may be associated with the Pacific Decadal Oscillation (PDO)



Hovmöller plots of the monthly latent heat flux (Qlat) anomalies (removing the 1993-2009 mean seasonal cycles) for the ENSO region of the tropical Pacific (5°N–5°S, 130°E–80°W) from 1993 to 2009

- Differences in the strength and location of the heat flux anomalies associated with the El Nino 1997/98 (Qlat>0) and La Nina 1999/2000 (Qlat<0) are clearly seen in the eastern equatorial cold tongue
- The coupled reanalysis (CFSR, ECDA) are clear outliers in the western tropical Pacific
- Some of the ERAi-forced products have spurious variability (1993-95) that is associated with the assimilation of the TAO array (Josey et al. 2014)
- The NOC2.0 product (ship data as an input) is too noisy, whereas NCEP-R2 has very weak El Nino 1997/98

Regional co-variability of SST and Qnet anomalies in 2008 in the Pacific sector



The PDO index in 2008 was the most negative since 1971 (BAMS, 2009)

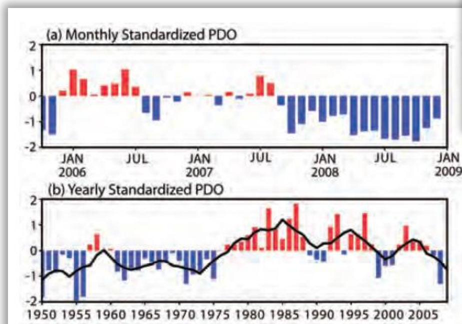
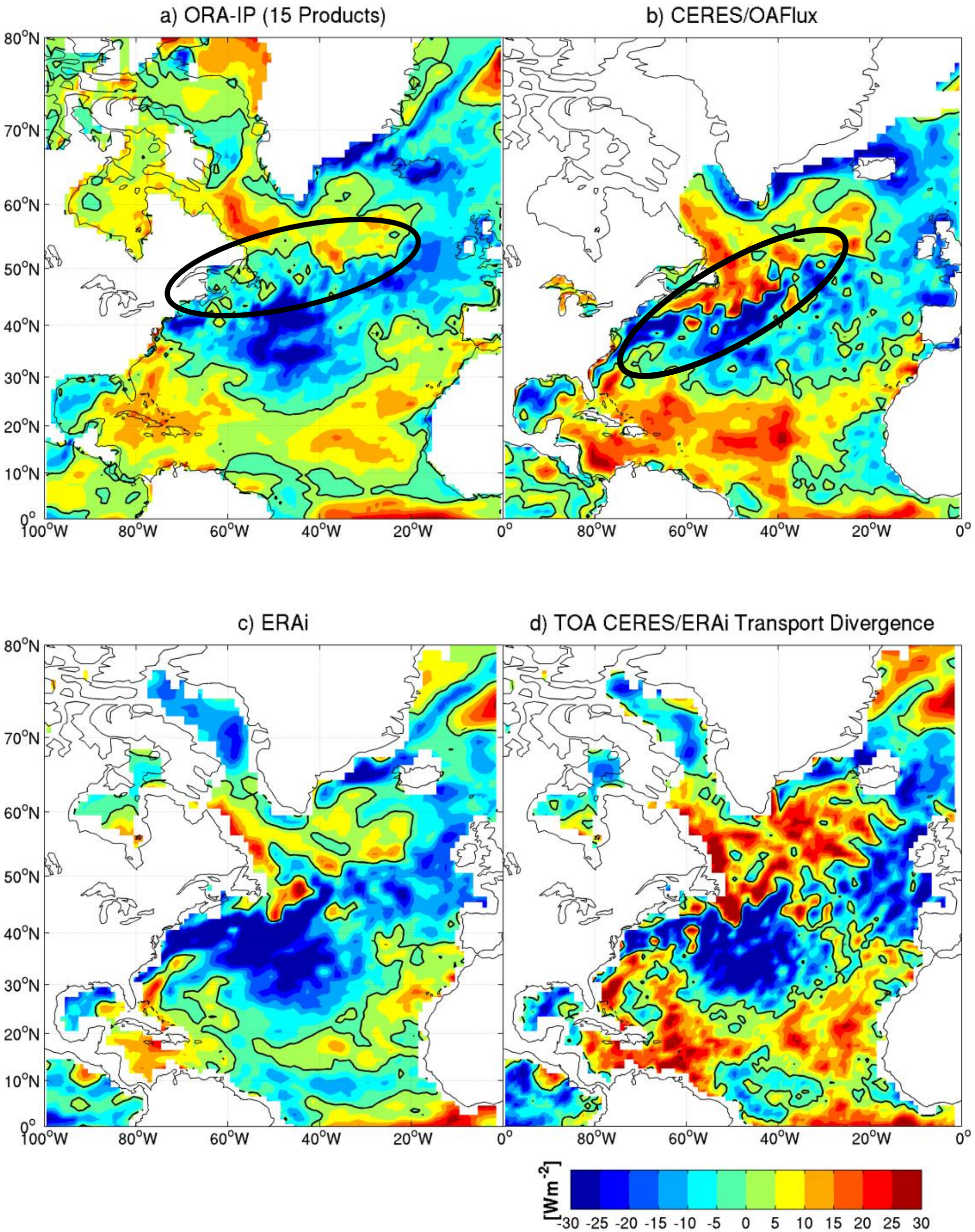


Fig. 3.3. (a) Monthly standardized PDO index (bar) in the past four years and (b) yearly mean of the monthly PDO index (bar) overlapped with the 5-yr running mean of the index (black line) in 1950–2008. The PDO index was downloaded from University of Washington at http://jisao.washington.edu/pdo.

- Pacific basin-scale SST anomaly pattern in 2008 from ORA-IP Ensemble is dominated by the negative PDO pattern, with negative anomalies along the west coast of North America from Alaska to the equator, and positive anomalies in the area to the west extending to up 30° N/S.
- The ORA-IP Qnet anomalies are anti-correlated with the SST anomalies of the cool PDO phase, i.e., increased Qnet (due to reduction in latent and sensible heat loss) over negative SST anomalies, and reduced Qnet over positive SST anomalies.
- The ORA-IP Ensemble shows lower Qnet anomalies compared to that obtained from combined satellite CERES radiation and OAFlux fields, but still reproduces a very similar pattern of variability.

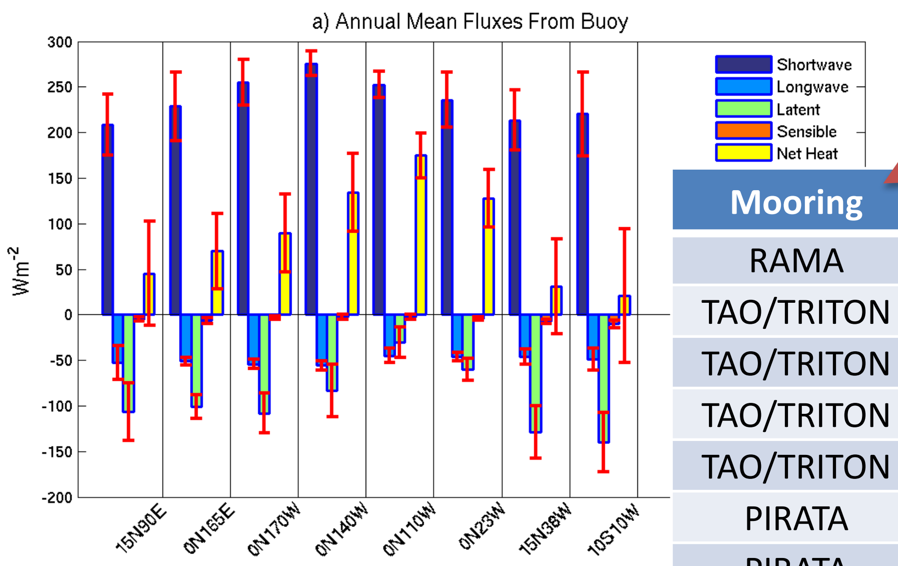
Surface Heat Flux Anomalies in 2009 in the North Atlantic

- Associated with a persistent negative phase of the North Atlantic Oscillation (NAO) (Cayan, 1992), which started in July 2009 (BAMS, 2010)
- The NAO tripole pattern is clearly seen in the Qnet anomaly pattern from the ORA-IP ensemble
- Differences between the ORA-IP Ensemble and CERES/OAFlux toward the mid-latitude western boundaries suggest incorrect positioning of the Gulf Stream and the North Atlantic Current, which is too zonal in some of the models
- TOA CERES/ERAi heat flux divergences (Liu et al. 2015) contains short-scale anomalies associated with atmospheric winds that are not seen in the original ERAi net heat flux anomalies



Net surface heat flux (Qnet) anomalies between July and December 2009 in the North Atlantic sector

▪ Comparisons with Tropical Buoy Data (1)



http://www.pmel.noaa.gov/tao/oceansites/flux/main.html

COARE3.0b Bulk Flux Algorithm (Fairall et al. 2003)

Mooring	Location
RAMA	15N, 90E
TAO/TRITON	0N, 165E
TAO/TRITON	0N, 170W
TAO/TRITON	0N, 140W
TAO/TRITON	0N, 110W
PIRATA	0N, 23W
PIRATA	15N, 38W
PIRATA	10S, 10W

- 8 buoy locations of the operational tropical moored buoy arrays within the 10°S-15°N latitude band during 2007-2009 (data available via the OceanSITES project)
- Net heat gain area; max heating rate ~175 Wm^{-2} at the TAO site in the eastern Pacific cold tongue; net fluxes off the Eq. are smaller; Qlw vary little btw buoys; Qsw and Qlat dominant heat flux components

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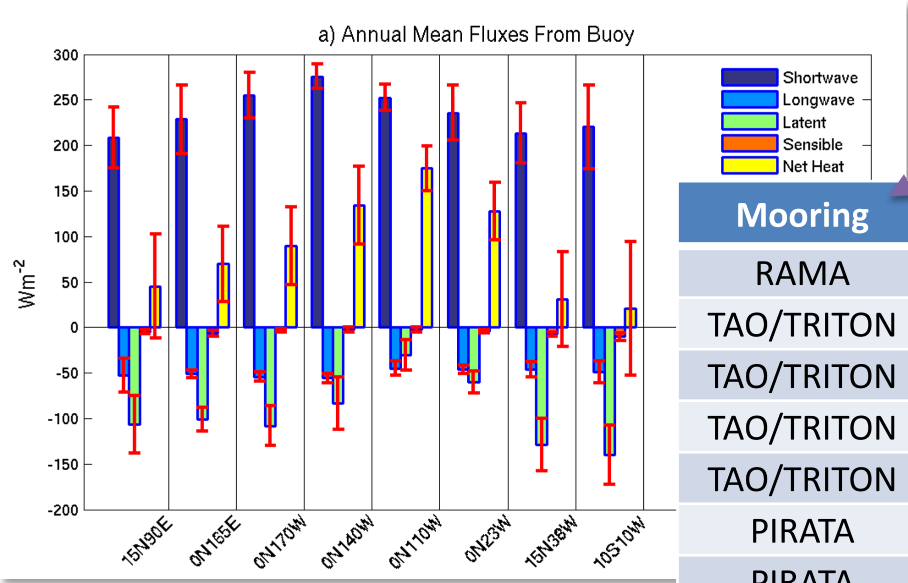

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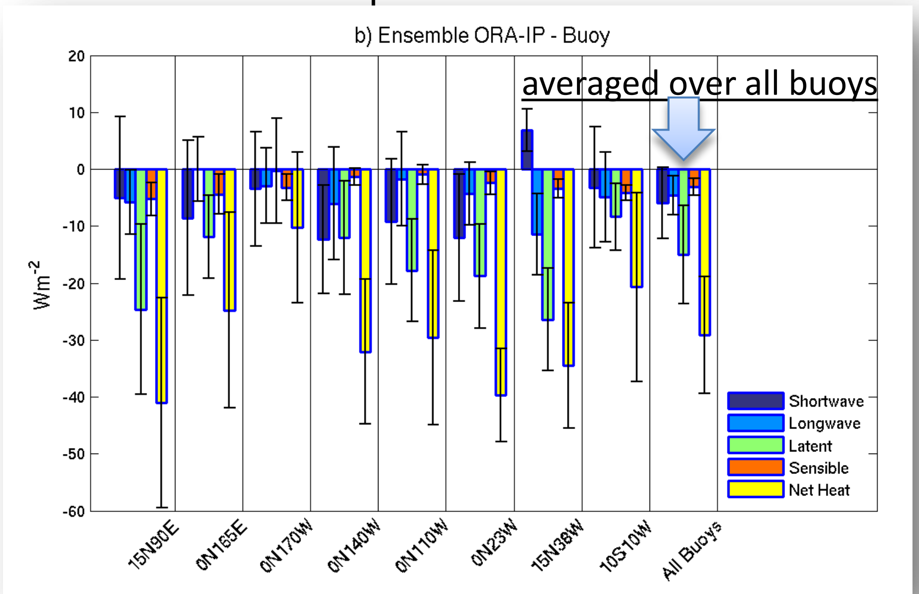
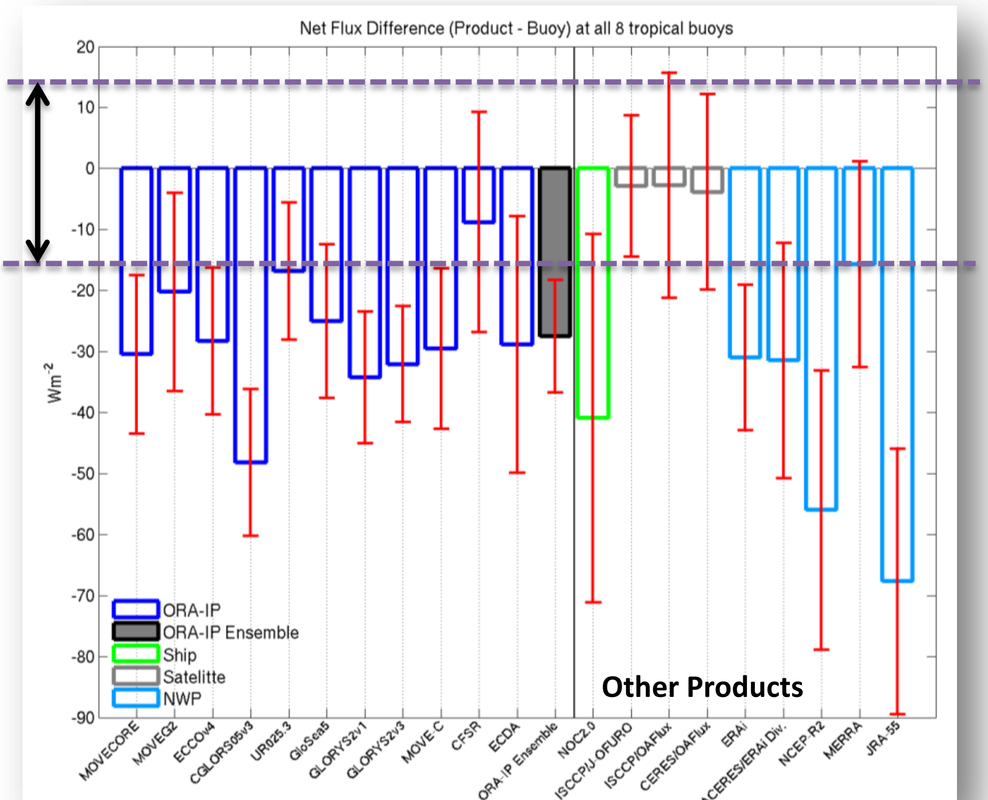
- Annual differences (biases) for nearly all flux components are **negative**
- Mean offsets (Ensemble ORA-IP – Buoy) averaged across all buoys are: **-6 Wm^{-2} for shortwave radiation, -5 Wm^{-2} for longwave radiation, -15 Wm^{-2} for latent heat flux, -3 Wm^{-2} for sensible heat flux,** and **-29 Wm^{-2} for net fluxes (~1/3 less than observed)**, indicating underestimation of tropical ocean heat gain in ORA-IP primarily due to overestimated latent heat loss in the reanalysis models



▪ Comparisons with Tropical Buoy Data (2)

Mean Qnet Differences From Buoy – averaged across all 8 Tropical Buoys over 2007-2009

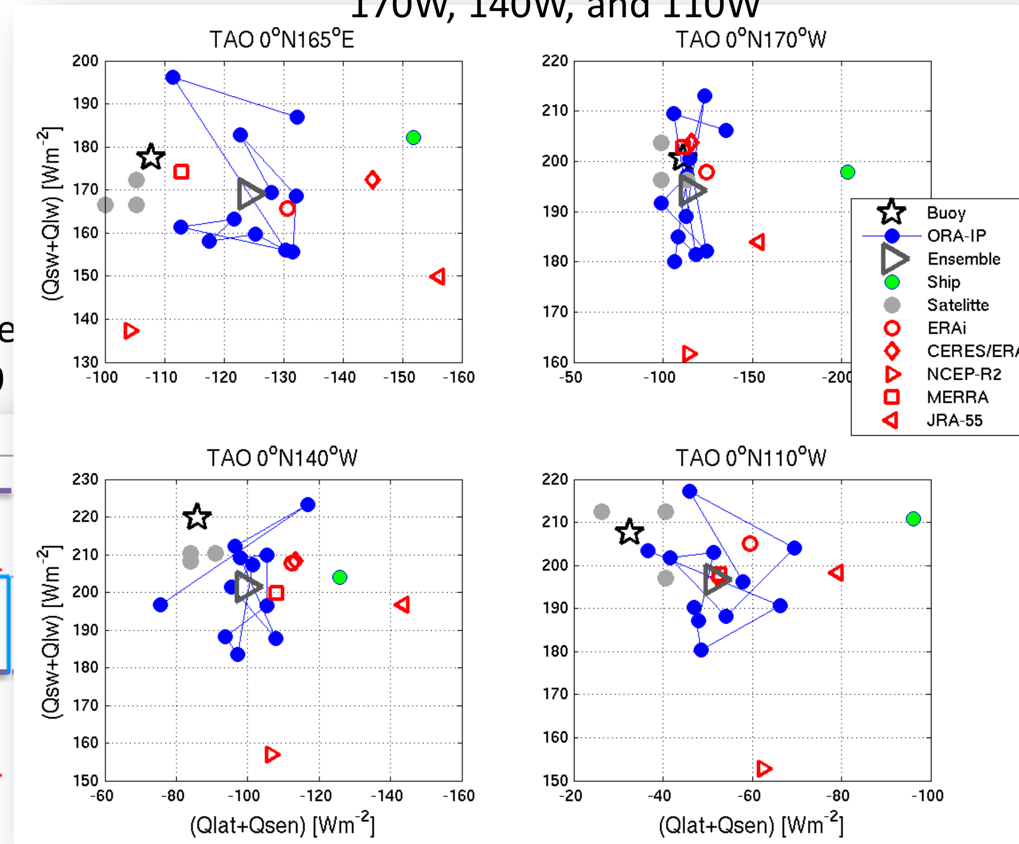


Individual Members of ORA-IP Ensemble

- Mean offsets, (Product – Buoy), are negative indicating underestimation of tropical ocean heat gain in all products.
- The closest agreement is found for satellite-based radiation (ISCCP, CERES) combined with OAFlux (J-OFURO) –all within 5 Wm-2 of buoy values *(error bounds of TAO Qnet data are ± 18 Wm-2, averaged over 4 sites at 165E, 170W, 140W, 110W, Wang and McPhaden, 2001)*.

- *The net bias in the ship-based NOC2.0 product is larger (~40 Wm^{-2})*
- *The atmospheric reanalyses products show biases of between 14 Wm^{-2} (MERRA) and 67 Wm^{-2} (JRA-55), dominated by latent heat flux and shortwave radiation*
- *The NCEP-R2 has a negative bias of 55 Wm-2 dominated by the shortwave errors (too high surface albedo; Wang and McPhaden, 2001)*

Comparisons with TAO data on the equator at 165E, 170W, 140W, and 110W



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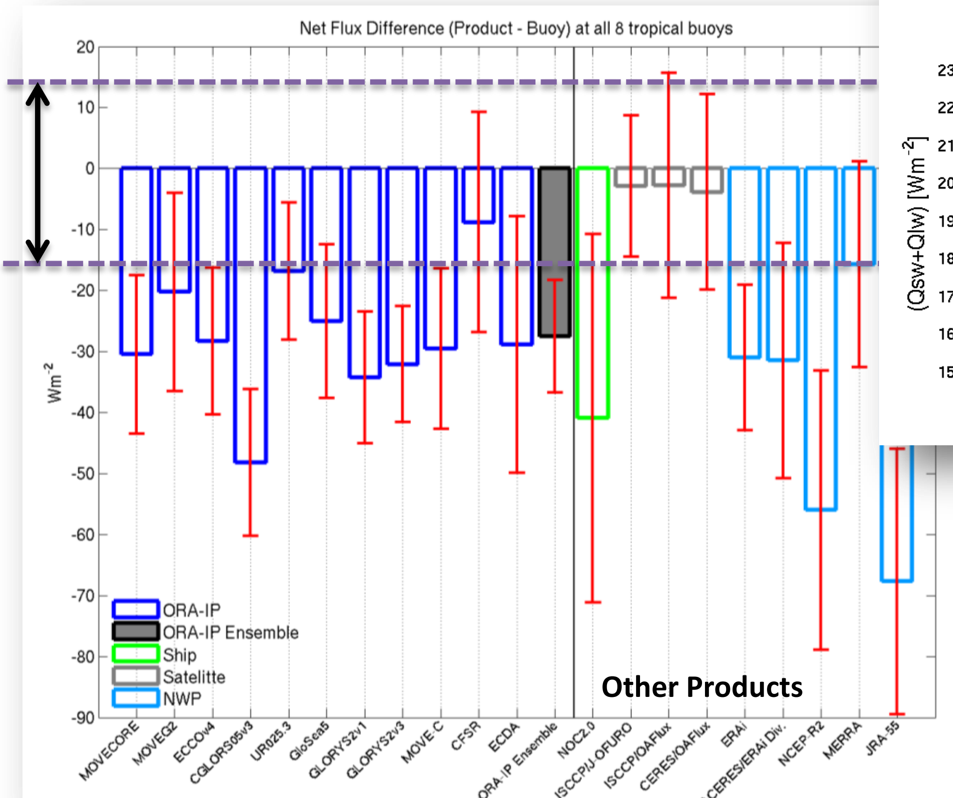


Individual Members of ORA-IP Ensemble

- Greatest agreement at 170W (central equatorial Pacific)→ The ORA-IP ensemble average is a better approx. to the TAO values than most of individual members.
- In the equatorial cold tongue (110W and 140W), and western Pacific warm pool (170W) the ORA-IP reanalyses are biased and those errors are not reduced through the ensemble averaging.

Summary

- Positive imbalances in global surface heating ~ 4 Wm-2 (1993 – 2009) in ORA-IP ensemble. Imbalances are reduced to ~ 1-2 Wm^{-2} by combining the surface fluxes and the assimilation increments. This is larger than the observed global OHC change (< 1 Wm^{-2}), but down from the 15-25 Wm-2 found in observational derived products.

- Implied mean meridional heat transports are also in better agreement with direct estimates by combining the Surface and Assimilation fluxes, except in the tropics (bias correction issues).

- The ensemble mean seasonal cycle is highly consistent between the ORA-IP products, with variability between products of <10 Wm^{-2} in most areas.

- The interannual variability from the ORA-IP ensemble of Qnet has a clearly consistent Signal to Noise Ratio (up to 2) throughout the equatorial Pacific, reflecting the detection of El Niño/La Niña cycles. Net flux anomalies from ORA-IP compare favourably with CERES/OAFlux combined during a large negative PDO in the Pacific in 2008.

- The mean offsets (Ensemble ORA-IP – Buoy) averaged across 8 tropical buoys (15N-10S) are negative (less ocean heat gain in ORA-IP than observed), primarily due to overestimated latent heat loss in the reanalysis. Satellite-based products are better, all within 5 Wm^{-2}, of the tropical buoy values.

- *See M. Valdivieso et al. (2015): An assessment of air-sea heat fluxes from ocean and coupled reanalyses (Submitted to Climate Dynamics, Special Issue: Ocean Reanalyses, 15 February 2015) for further details.*

VALDIVIESO ET AL.: TRANSPORTS FROM GLOBAL OCEAN SYNTHESIS

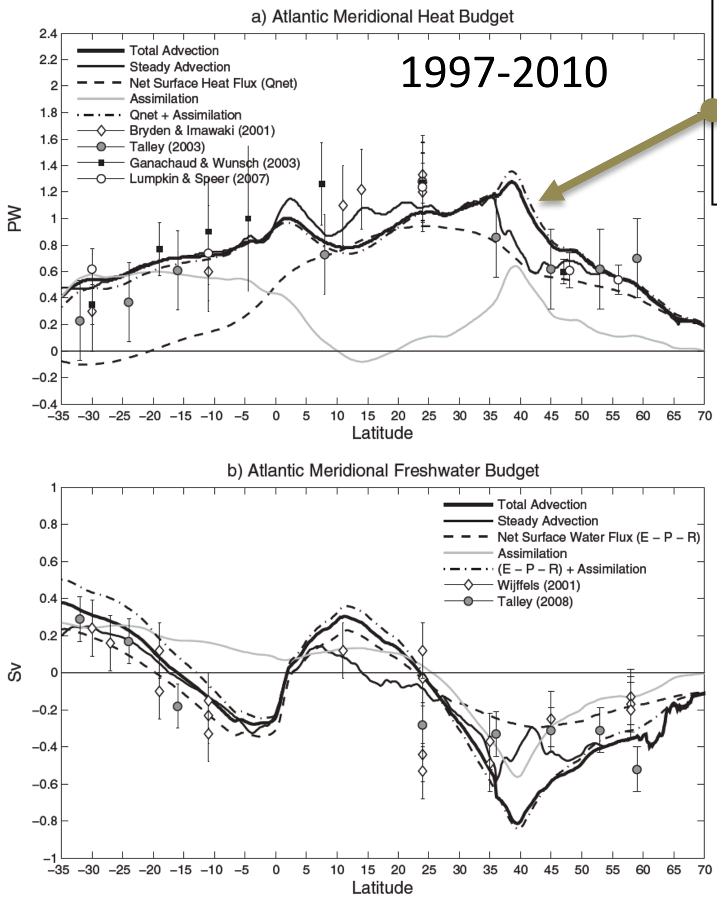


Figure 5. Total (a) heat and (b) freshwater transport divergences north of the zonal sections in the Atlantic and the Bering Strait, along with the source/sink implied transports based on a steady-state assumption through the period 1997–2010. As the net surface heat (Qnet) and freshwater (E − P − R) fluxes do not take into account the transports entering the domain via the Bering Strait, the advective transports of heat and freshwater at 70°N have been added to the surface fluxes to allow the comparison. The surface heat and freshwater fluxes alone clearly do not imply consistent meridional transports, but when the Assimilation terms are included the match with the observed transports is very close. The observational transport estimates at various sections are also included for comparison. Positive represents ocean heating and net evaporation in the region. Units are in PW and Sv, respectively.

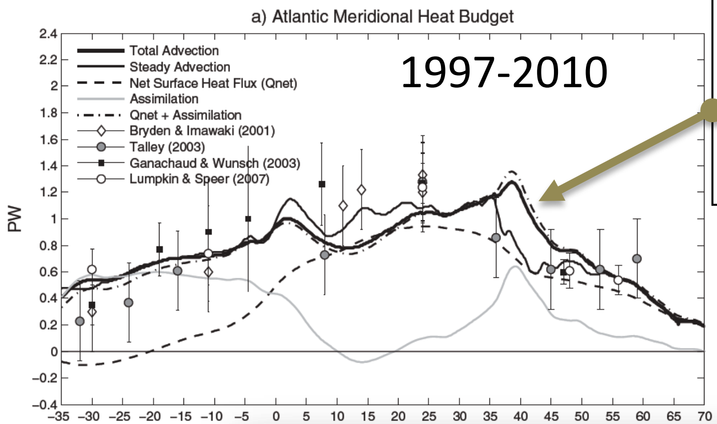
The surface heat flux **(Qnet, dashed line)** alone clearly does not imply consistent meridional heat transports, but when the assimilation increments terms are included **(Qnet + Assimilation; dashed-dotted line),** the match with the estimated advective transports is much closer.

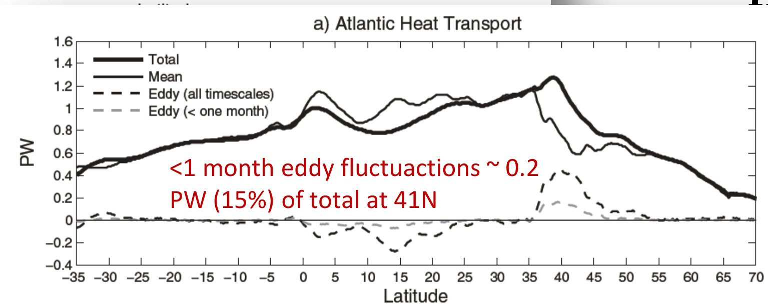
Transports and budgets of heat (and freshwater) in global 1/4°reanalyses

- Make comparisons between reanalysis transports and published estimates based on observations, globally and in each basin
- Look at how ocean reanalysis transports are maintained through surface fluxes, data assimilation and the contribution of temporal eddy transports
- Details *in Valdivieso, M., Haines, K., Zuo H. and Lea D. (2014), Freshwater and heat transports from global ocean synthesis, J. Geophys, Res. Oceans, 119, doi:10.1002/2013JC009357*

Product	Model	Data Assimilation	Obs	Surface Forcing	Initial Condition
UR025.4 MyOcean v2.1	NEMO v3.2 ORCA025_LIM2 (1/4° by 75L)	UK Met Office FOAM System Storkey et al. (2010), Martin et al. (2007)	**EN3_v2a_ XBTMBTBiasC Satellite + in situ SST, AVISO SLA, OSI-SAF Sea Ice Conc**	CORE Bulk Forcing using ERAi fields + Dai&Trenberth (2002) Runoff No SSS restoring	EN3 Climatology

VALDIVIESO ET AL.: TRANSPORTS FROM GLOBAL OCEAN SYNTHESIS





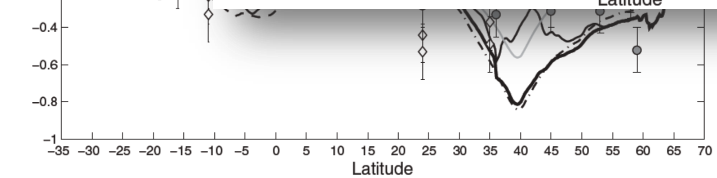


Figure 5. Total (a) heat and (b) freshwater transport divergences north of the zonal sections in the Atlantic and the Bering Strait, along with the source/sink implied transports based on a steady-state assumption through the period 1997–2010. As the net surface heat (Qnet) and freshwater (E − P − R) fluxes do not take into account the transports entering the domain via the Bering Strait, the advective transports of heat and freshwater at 70°N have been added to the surface fluxes to allow the comparison. The surface heat and freshwater fluxes alone clearly do not imply consistent meridional transports, but when the Assimilation terms are included the match with the observed transports is very close. The observational transport estimates at various sections are also included for comparison. Positive represents ocean heating and net evaporation in the region. Units are in PW and Sv, respectively.

The surface heat flux **(Qnet, dashed line)** alone clearly does not imply consistent meridional heat transports, but when the assimilation increments terms are included **(Qnet + Assimilation; dashed-dotted line),** the match with the estimated advective transports is much closer.

Transports and budgets of heat (and freshwater) in global 1/4°reanalyses

- ake comparisons between reanalysis transports d published estimates based on observations, obally and in each basin
- ok at how ocean reanalysis transports are aintained through surface fluxes, data assimilation and the contribution of temporal eddy transports
- Details *in Valdivieso, M., Haines, K., Zuo H. and Lea D. (2014), Freshwater and heat transports from global ocean synthesis, J. Geophys, Res. Oceans, 119, doi:10.1002/2013JC009357*

Product	Model	Data Assimilation	Obs	Surface Forcing	Initial Condition
UR025.4 MyOcean v2.1	NEMO v3.2 ORCA025_LIM2 (1/4° by 75L)	UK Met Office FOAM System Storkey et al. (2010), Martin et al. (2007)	**EN3_v2a_ XBTMBTBiasC Satellite + in situ SST, AVISO SLA, OSI-SAF Sea Ice Conc**	CORE Bulk Forcing using ERAi fields + Dai&Trenberth (2002) Runoff No SSS restoring	EN3 Climatology