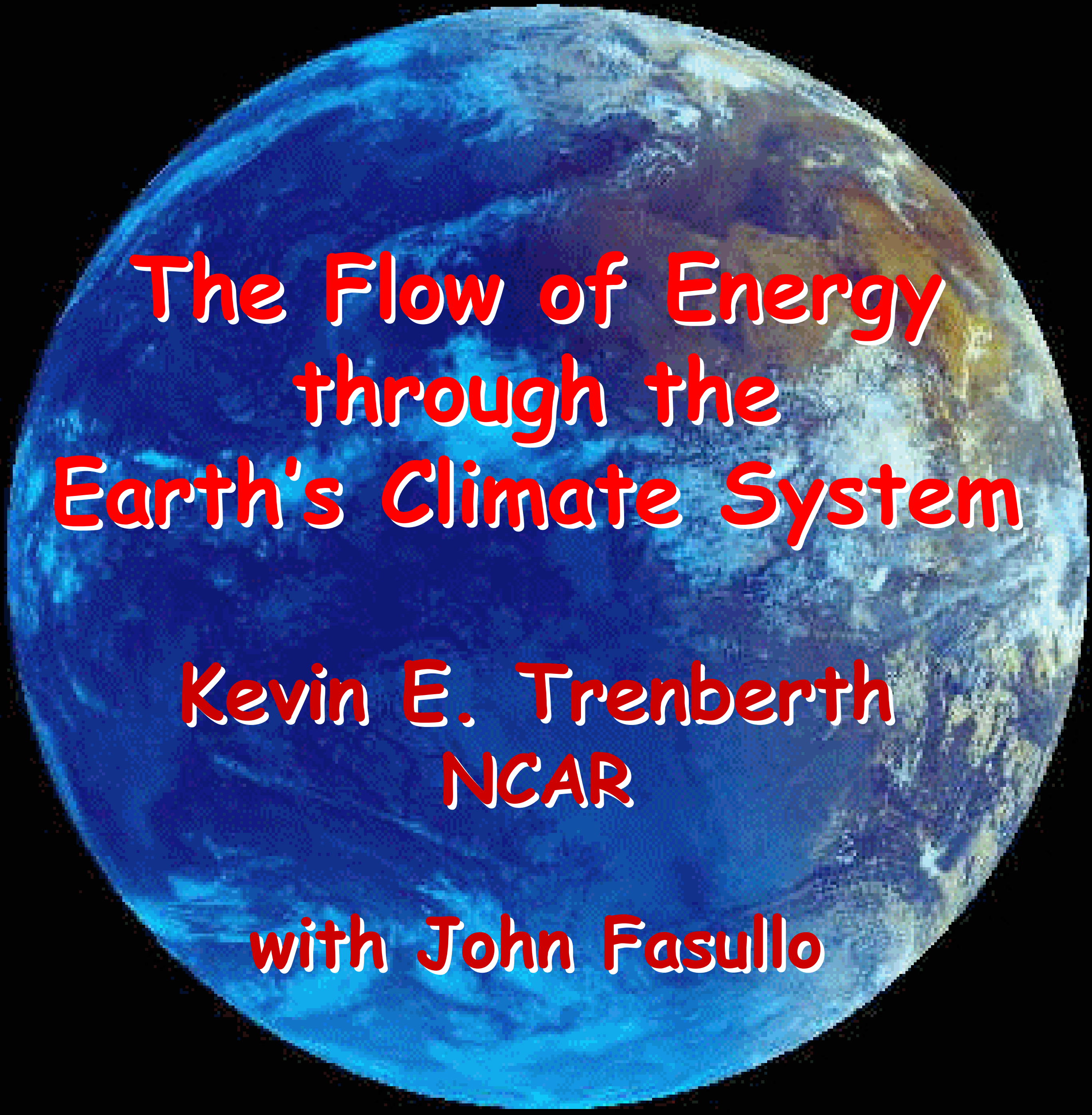
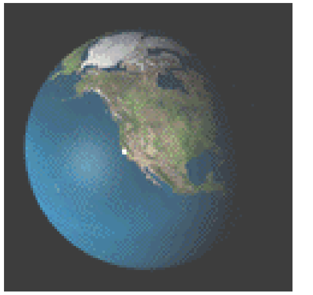


The Flow of Energy through the Earth's Climate System

Kevin E. Trenberth
NCAR

with John Fasullo

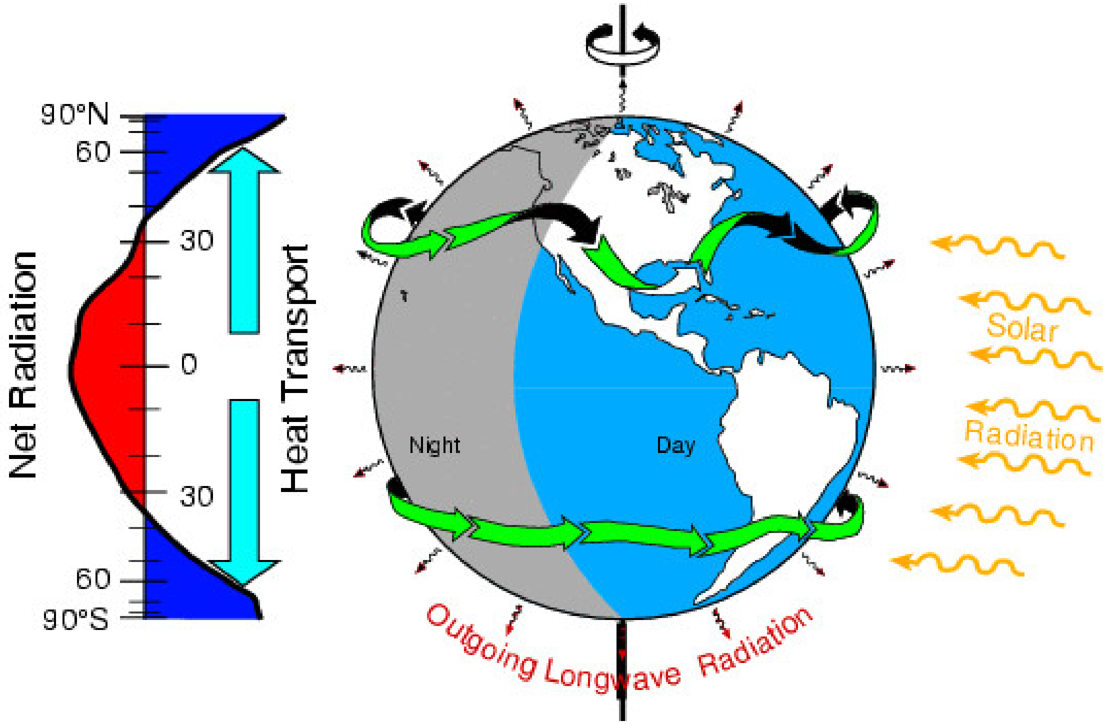
Energy on Earth



The main external influence on planet Earth is from radiation.

Incoming solar shortwave radiation is unevenly distributed owing to the geometry of the Earth-sun system, and the rotation of the Earth.

Outgoing longwave radiation is more uniform.



Energy on Earth

The incoming radiant energy is transformed into various forms (internal heat, potential energy, latent energy, and kinetic energy) moved around in various ways primarily by the atmosphere and oceans, stored and sequestered in the ocean, land, and ice components of the climate system, and ultimately radiated back to space as infrared radiation.

An equilibrium climate mandates a balance between the incoming and outgoing radiation and that the flows of energy are systematic. These drive the weather systems in the atmosphere, currents in the ocean, and fundamentally determine the climate. And they can be perturbed, with climate change.

Energy on Earth

Mean and annual cycle of radiation, energy storage and transport are analyzed holistically using datasets:

ERBE (Feb 1985 - Apr 1989)

3 satellite configuration; 2 polar orbiting satellites and 1 72-day precessing orbit covering 60°N-60°S Failure of NOAA-9 (afternoon crossing) in Feb 1987 left only 1 polar orbit (morning)

CERES (Mar 2000-present)

Terra: single polar orbiting satellite plus Aqua in Jul 2002

NCEP/NCAR Reanalyses

ERA-40 Reanalyses

JRA-25 Reanalyses

World Ocean Atlas ocean data

Japanese Meteorological Agency ocean data

Global Ocean Data Assimilation System (GODAS) NCEP

ECCO: MIT/SCRIPPS/JPL/UH ECCO-GODAE 1992-2004

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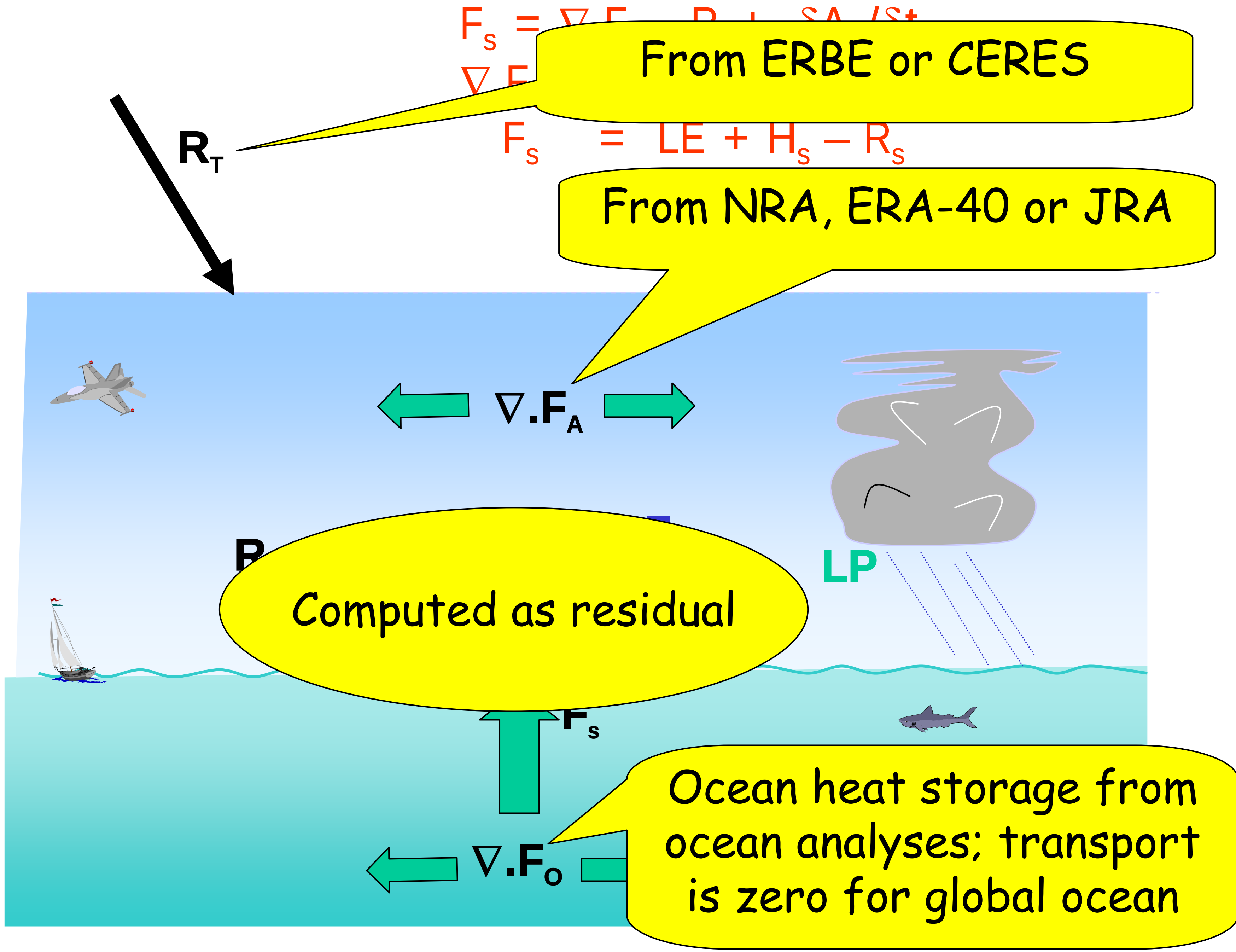
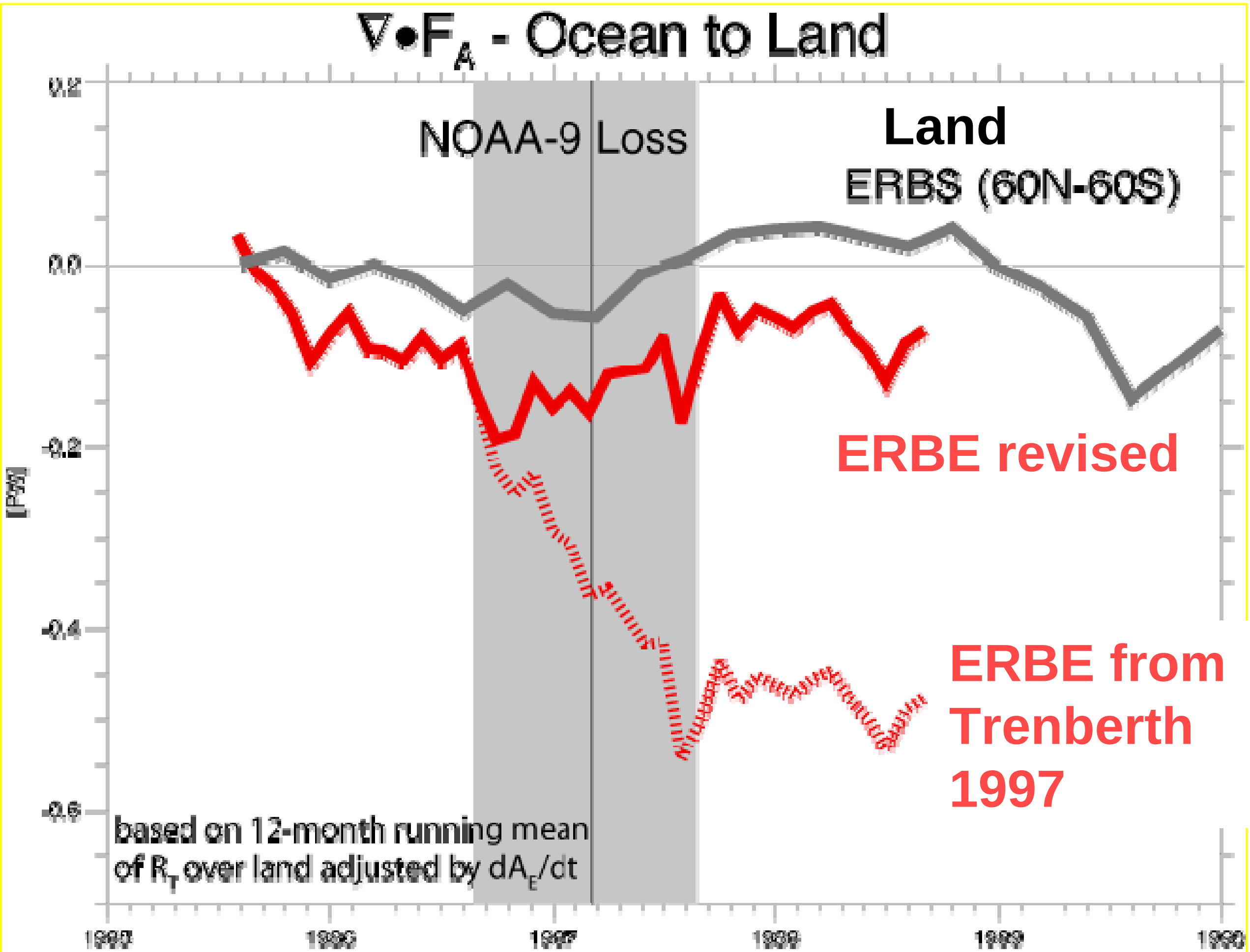

From ERBE or CERES
F = LE + H − R
From NRA, ERA-40 or JRA
R
∇.F
Computed as residual
LP
F
Ocean heat storage from ocean analyses; transport is zero for global ocean
∇.F

ERBE was adjusted to have zero net radiation (consistent with ocean obs).

Original global adjustment **(Trenberth 1997)** was modified separately for land and ocean to remove discontinuities exposed in this analysis

CERES was similarly adjusted: **in OLR to error limits, and albedo to reduce the imbalance of 6.4 W m^{-2} to an acceptable ~0.9 W m^{-2} consistent with models and ocean obs.**

ERBE Tuning: Inferred Ocean to Land transport of energy



The spurious negative trend in implied ocean to land energy transport is addressed in revised tuning.

This also has the beneficial effect of yielding a continuous OLR record.

All 12-month running means

Global net flux balance error budget CERES error:

Wielicki et al. (2006) W m^{-2}.

Error Source	SW	LW	Net
Total Solar Irradiance (1361 vs 1365)	+1.0	0.0	+1.0
Absolute Calibration	1.0	1.0	2.0
Spectral Correction	0.5	0.3	0.8
Spatial Sampling	<0.1	<0.1	<0.1
Angle Sampling	+0.2	-0.1	+0.1
Time Sampling (diurnal)	<0.2	<0.2	<0.2
Reference Altitude (20 km)	0.1	0.2	0.3
Twilight SW Flux (-0.25 Wm^{-2})	<0.1	0.0	<0.1
Near Terminator SW Flux	+0.7	0.0	+0.7
3-D Cloud Optical Depth bias	+0.7	0.0	+0.7
CERES SRBAVG Ed2D R_T			6.4

1.5

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CERES Tuning

- Unadjusted, CERES fields depict a net TOA flux of ~6.4 W m^{-2} which is unrealistic given the reported ocean heat tendency during CERES ~0.4 PW (e.g. Levitus et al. 2005) and model results.
- Estimates of the error sources suggest that multiple small error sources combine constructively to yield a bias in the reported imbalance and that both longwave and shortwave budgets require adjustment (Wielicki et al. 2006).
- We adjusted OLR +1.5 W m^{-2} and albedo (+0.3% to 0.30) to give net 0.9 W m^{-2} consistent with model estimates (e.g. Hansen et al. 2005) and ocean heat uptake (Willis et al. 2004)

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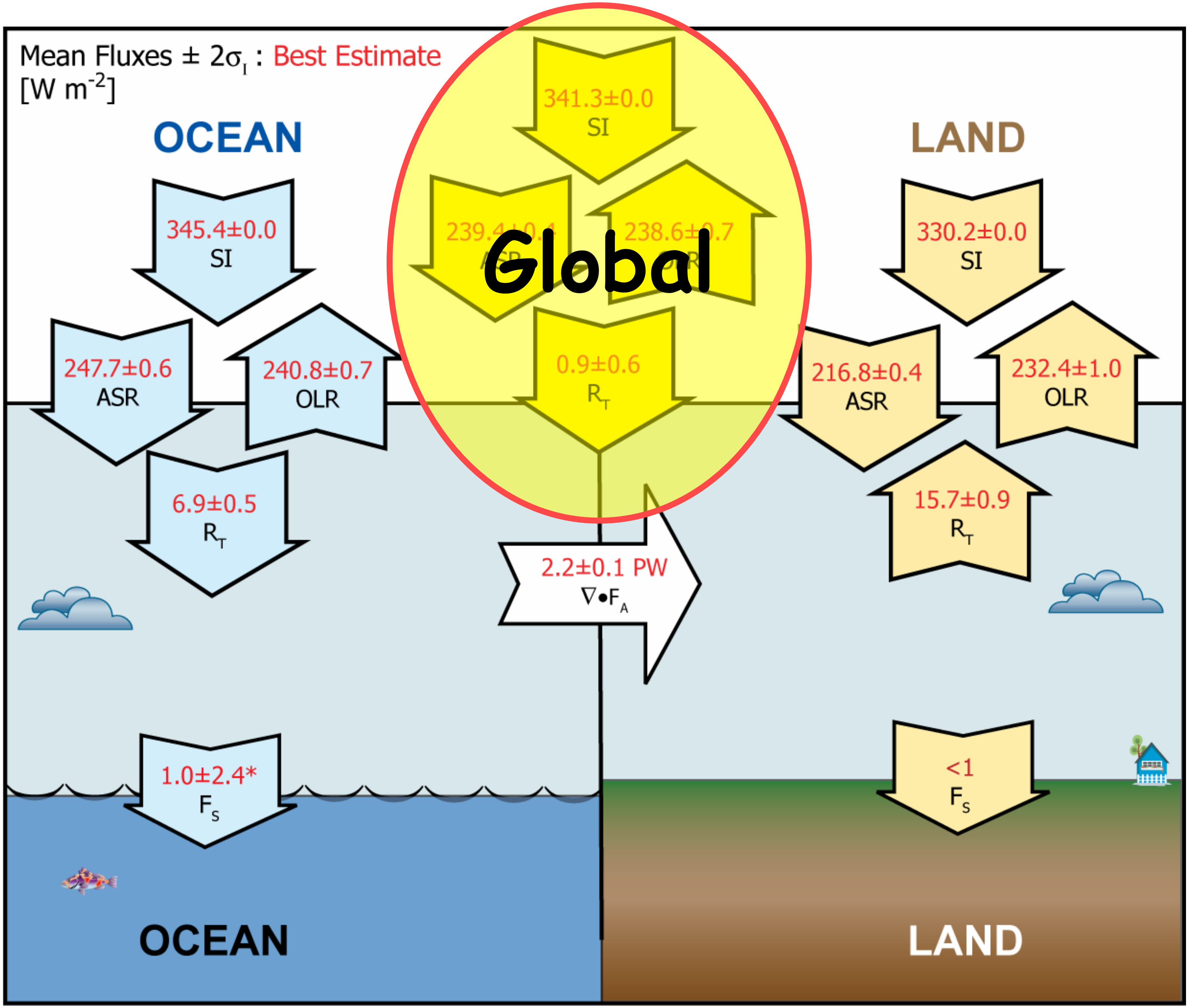
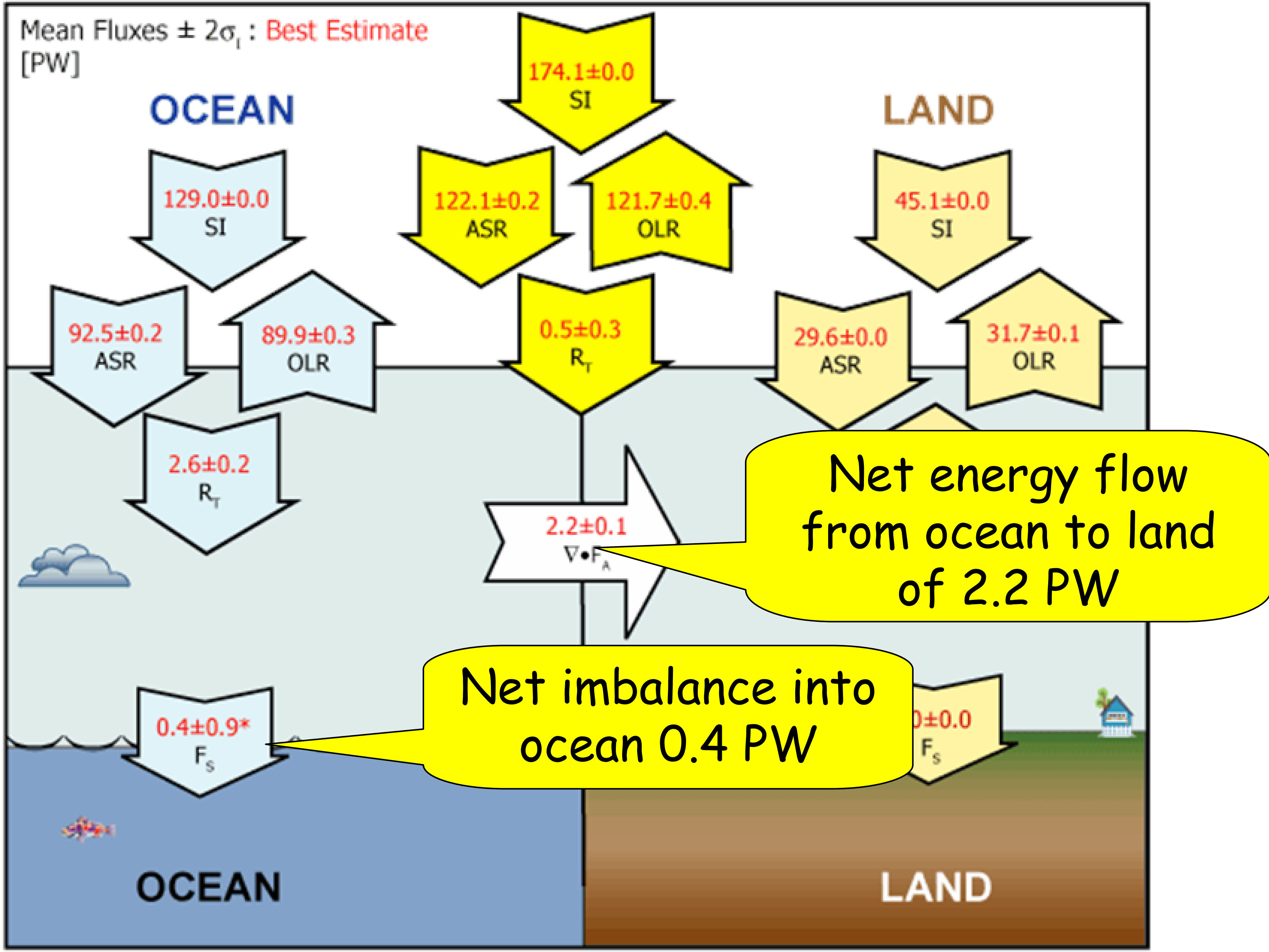
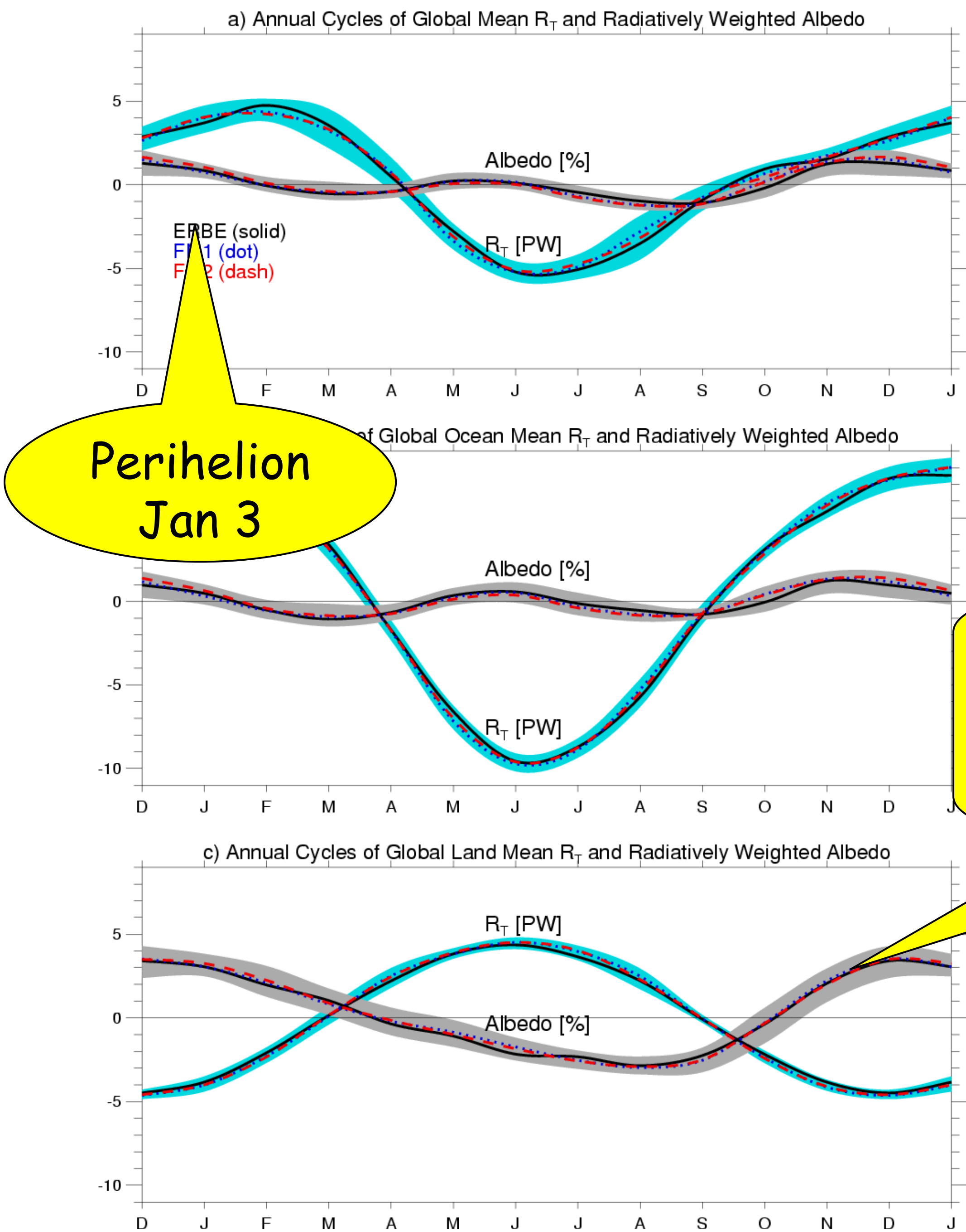


CERES period March 2000 to May 2004



CERES period March 2000 to May 2004

Mean annual cycles of albedo and R_T



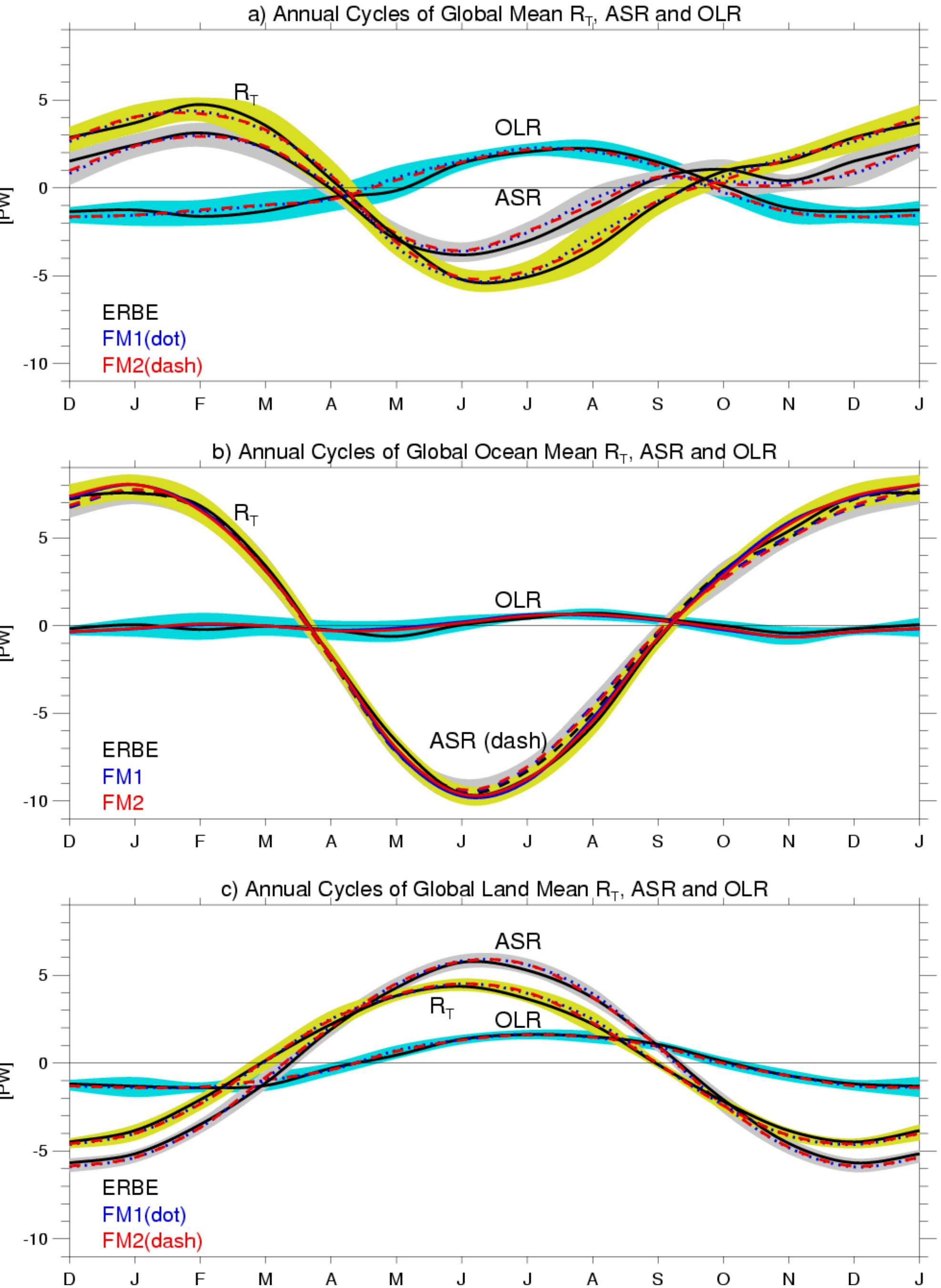
Global

Note albedo lower in February vs January over oceans (cloud)

Shading represents ±2σ sampling of monthly means

Global-land

shading is ±2σ



ASR, OLR, and RT
RT= ASR-OLR

Global

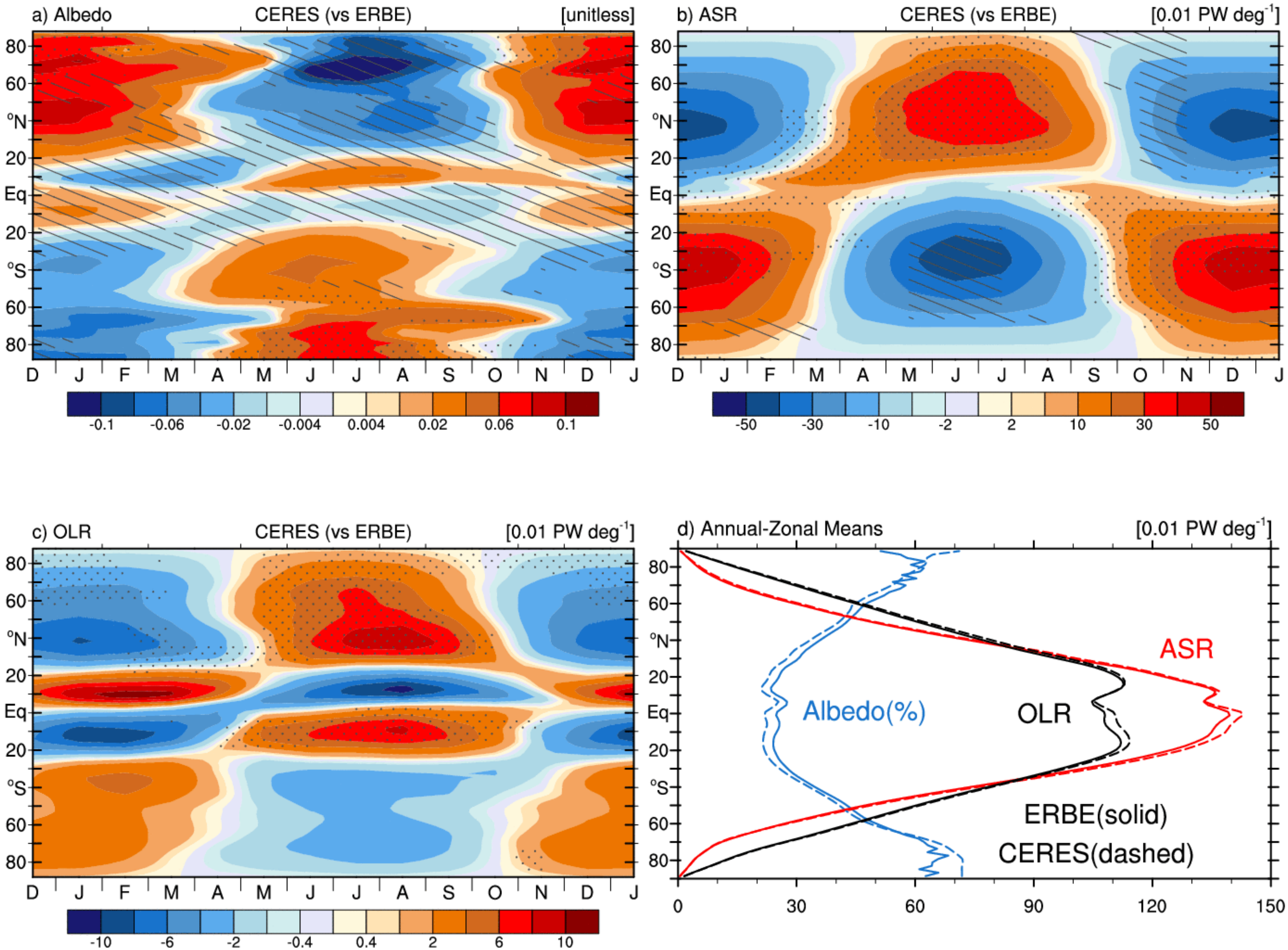
ASR peaks in February, 1 month after perihelion, owing to albedo decrease in February

Global-ocean

Global-land

Main OLR annual cycle from land (snow and temperature)

shading represents ±2σ



\\ CERES<ERBE ......CERES>ERBE

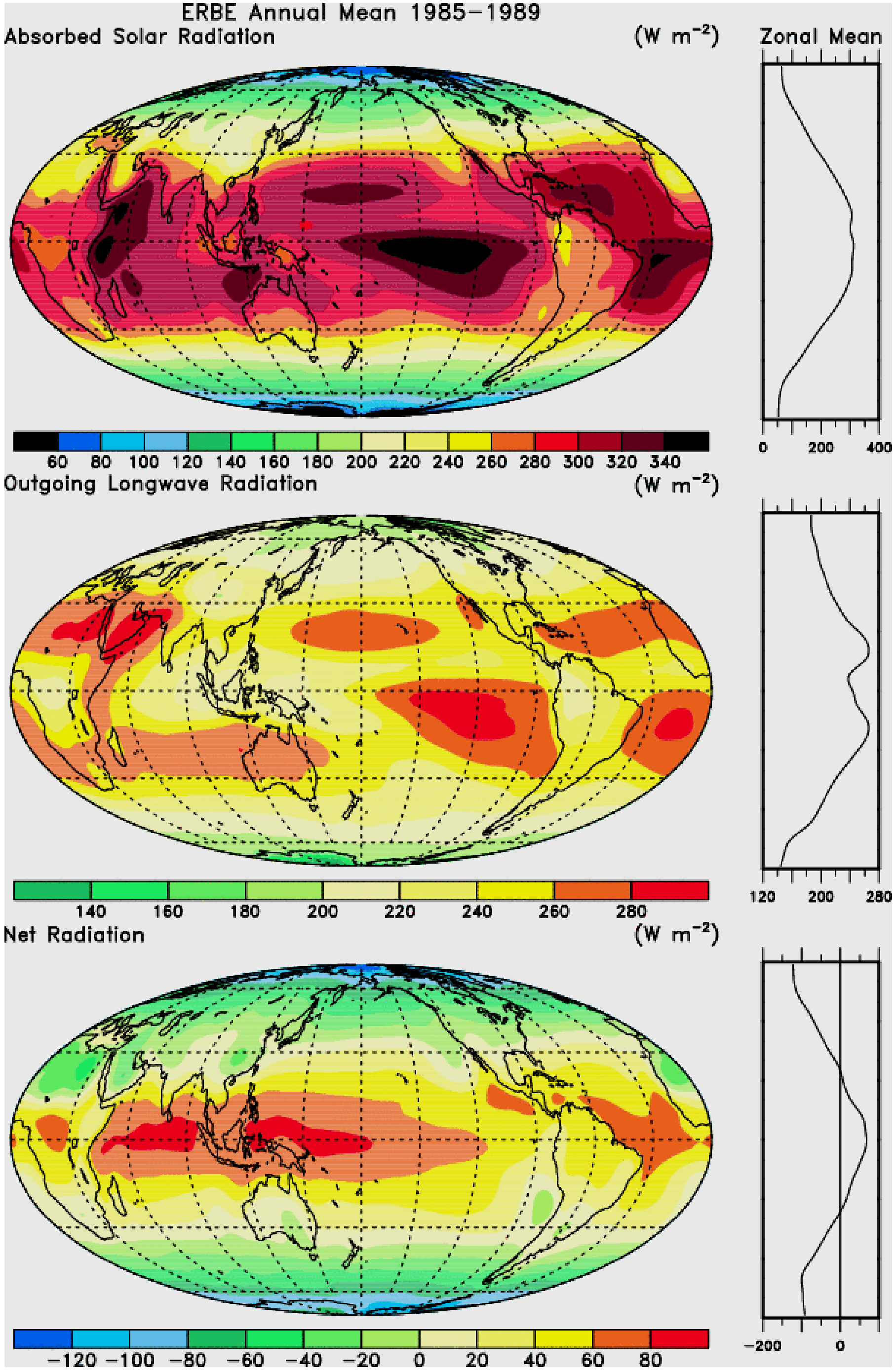
NCAR

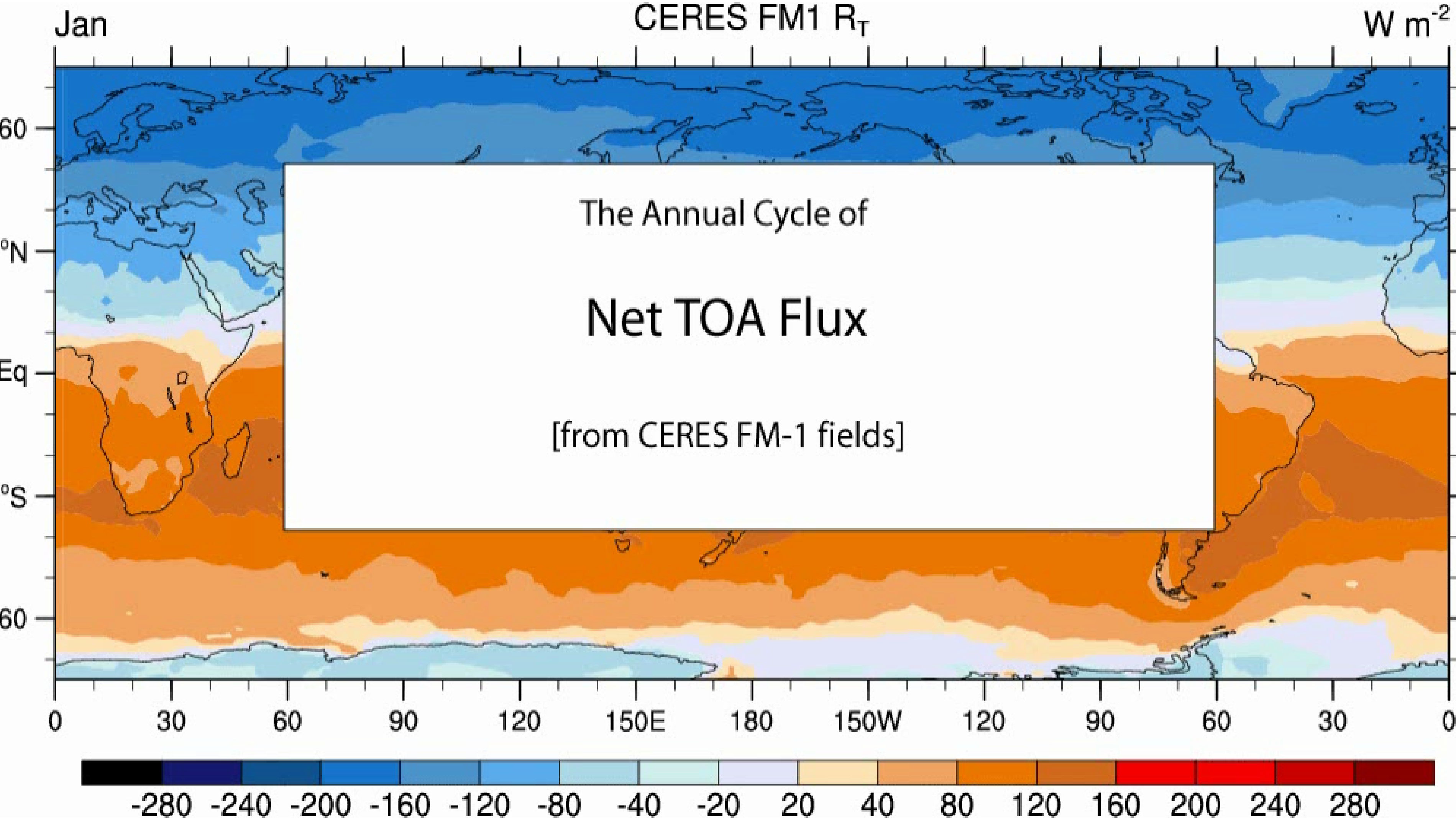
Annual Cycle of R_T (ERBE)

ASR

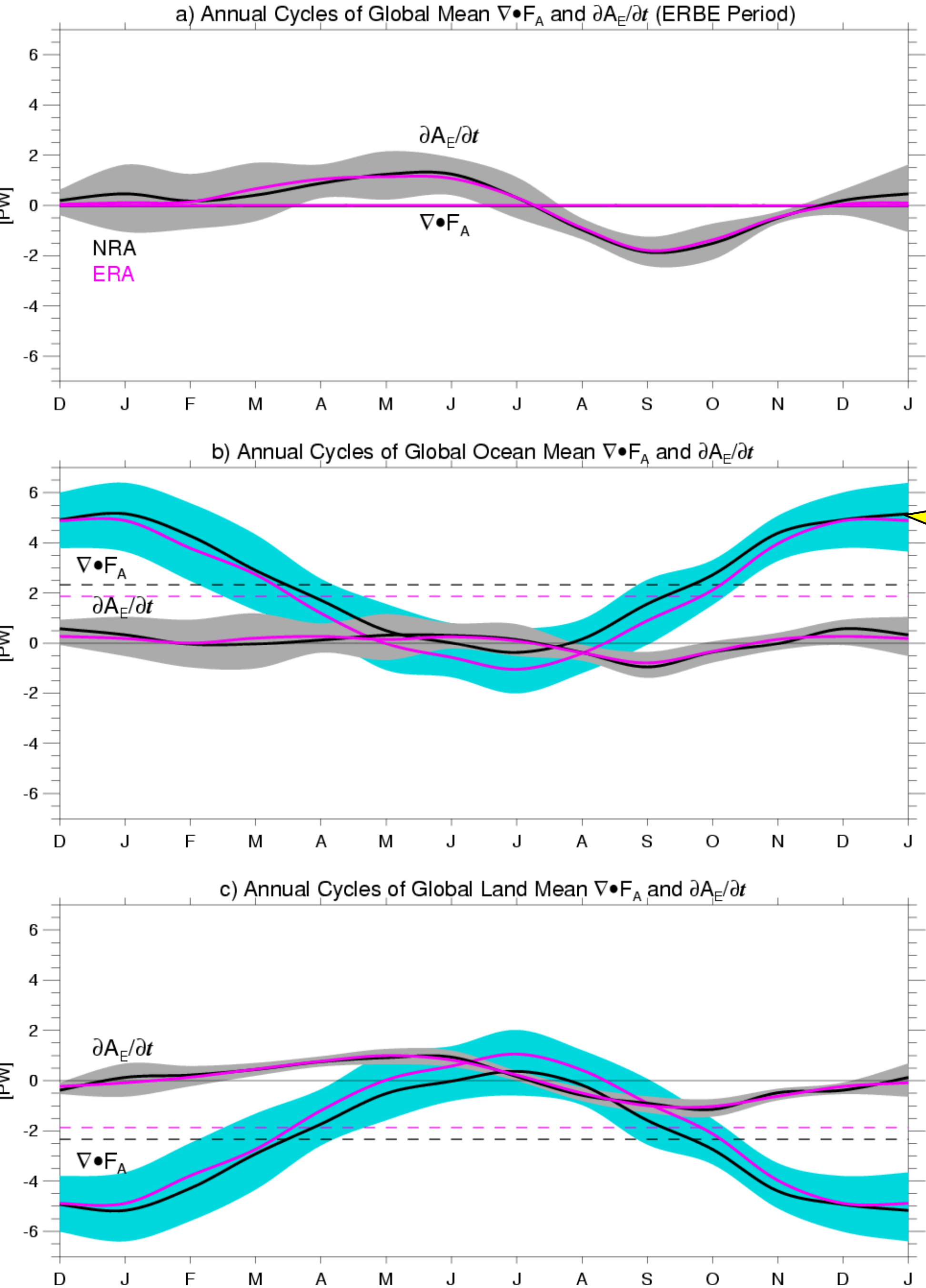
OLR

NET




Jan
CERES FM1 R_T
W m^-2
The Annual Cycle of
Net TOA Flux
[from CERES FM-1 fields]
60
°N
Eq
°S
60
0
30
60
90
120
150E
180
150W
120
90
60
30
0
-280 -240 -200 -160 -120 -80 -40 -20 20 40 80 120 160 200 240 280

Atmospheric total energy divergence ($\nabla \bullet F_A$) and tendency ($\delta A_E/\delta t$)



Global

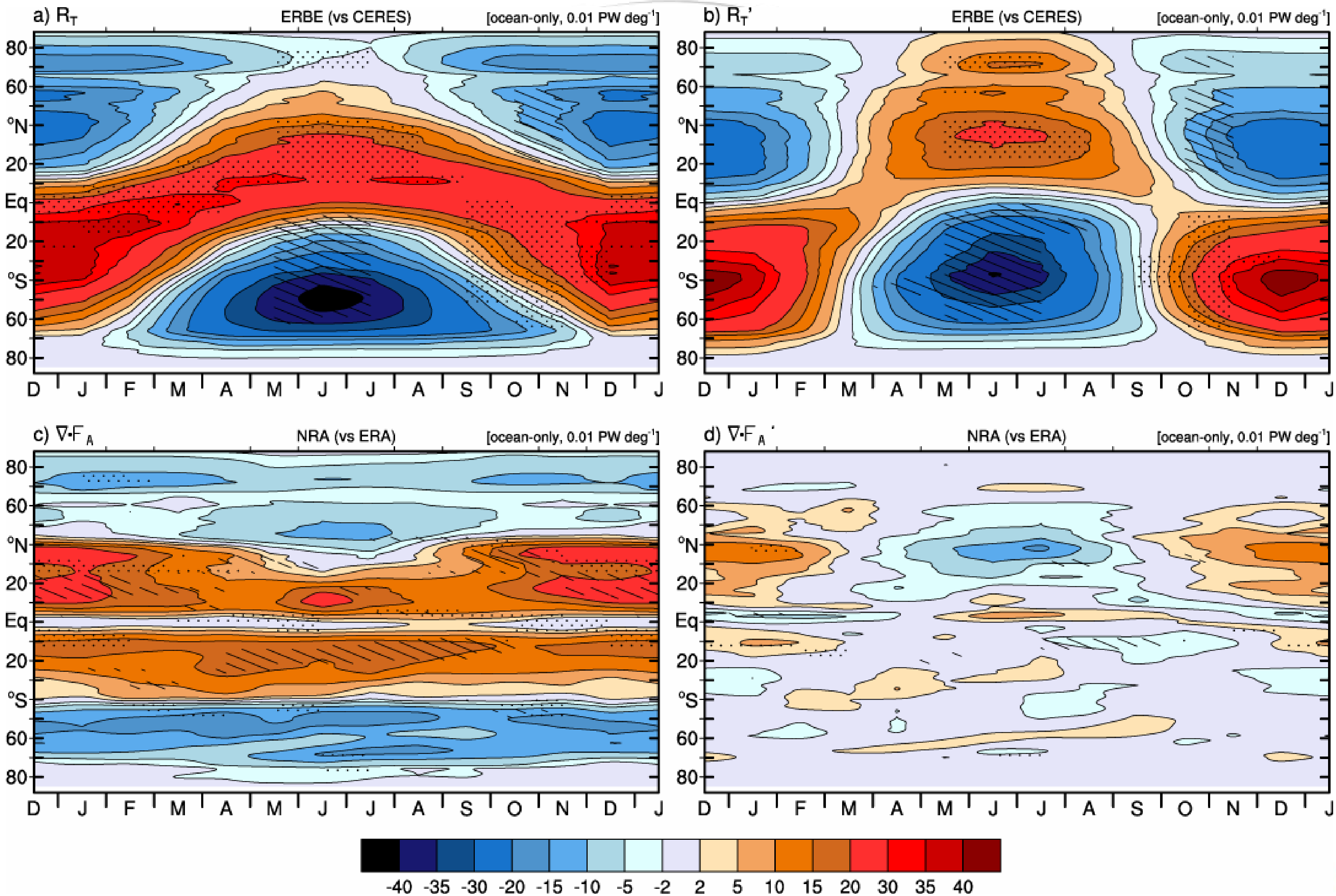
globa

global-land

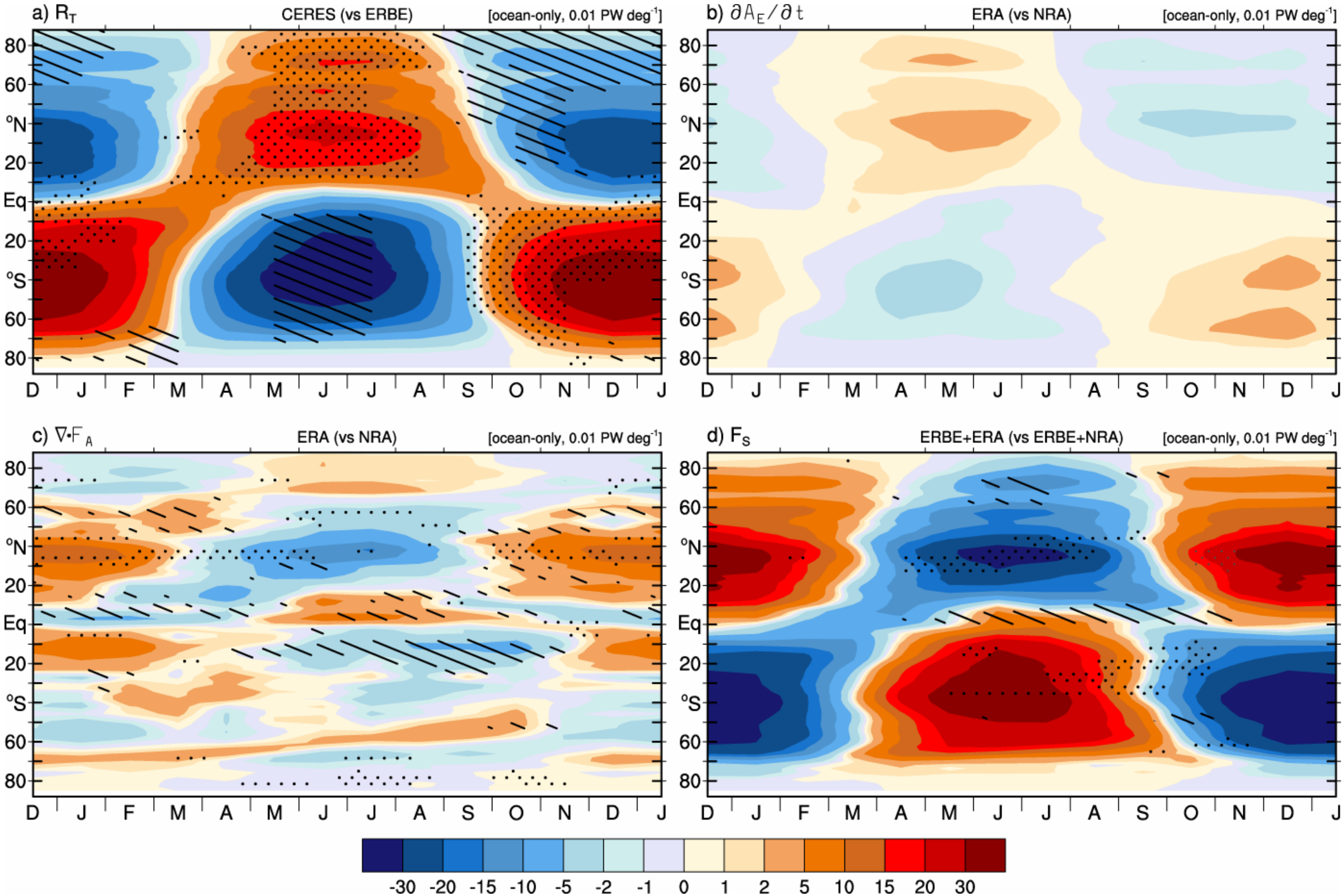
Main ocean to land energy transport is in northern hemisphere in northern winter

Global =0

Ocean only

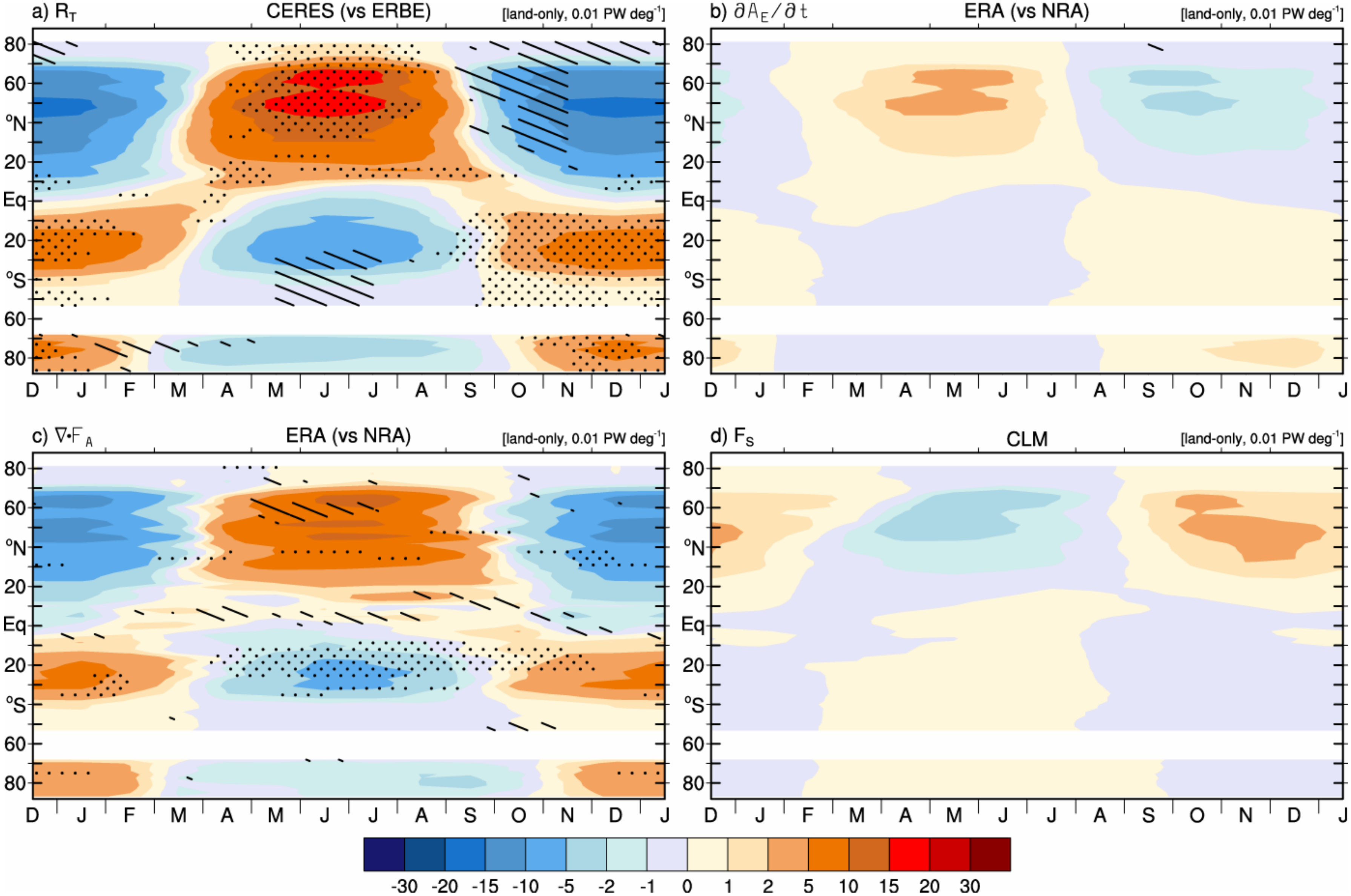


NCAR

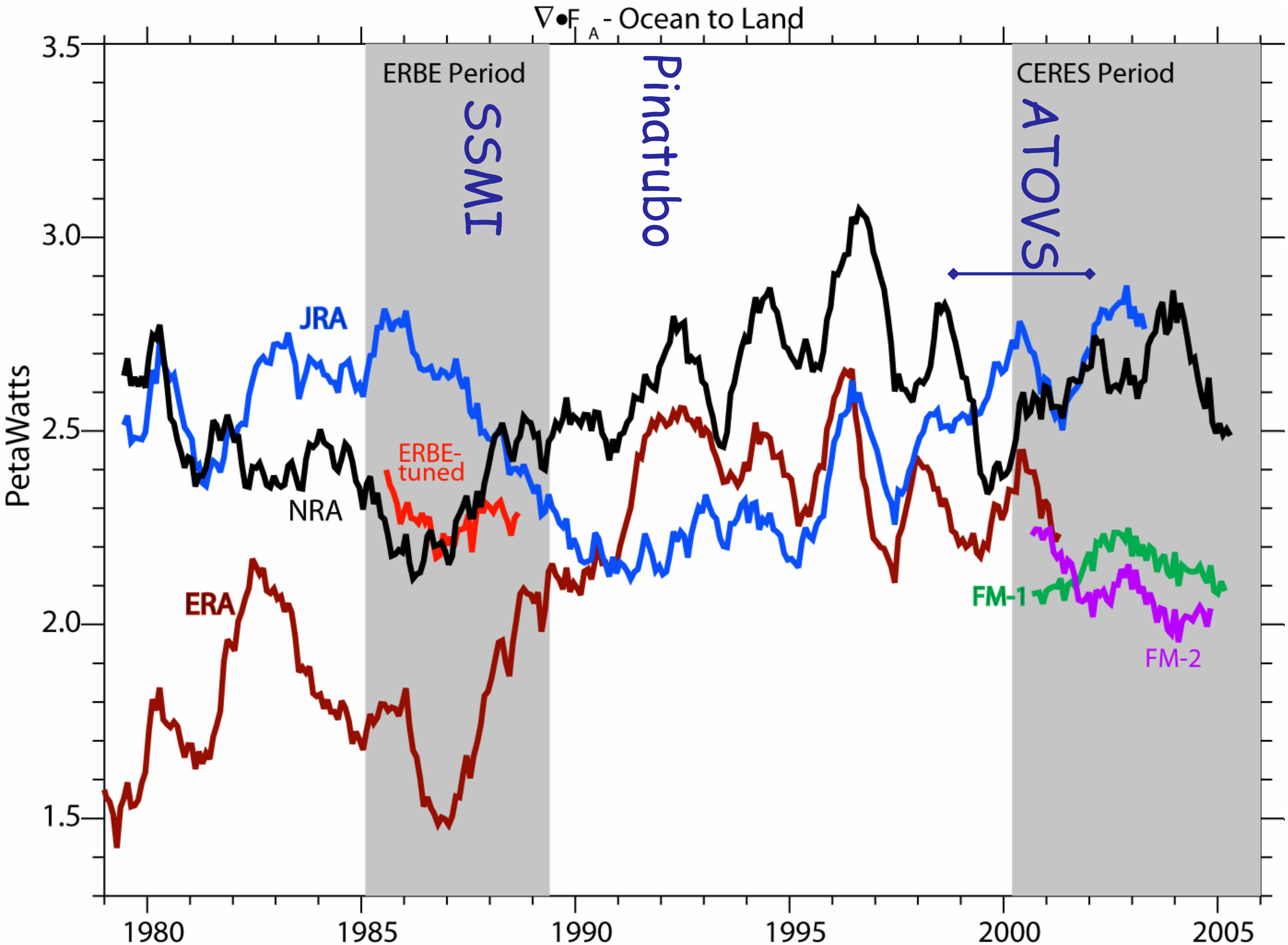


a) R_T
CERES (vs ERBE)
[ocean-only, 0.01 PW deg^{-1}]
b) $\partial A_E/\partial t$
ERA (vs NRA)
[ocean-only, 0.01 PW deg^{-1}]
c) $\nabla\cdot F_A$
ERA (vs NRA)
[ocean-only, 0.01 PW deg^{-1}]
d) F_S
ERBE+ERA (vs ERBE+NRA)
[ocean-only, 0.01 PW deg^{-1}]
80
60
°N
20
Eq
20
°S
60
80
D J F M A M J J A S O N D J
-30 -20 -15 -10 -5 -2 -1 0 1 2 5 10 15 20 30

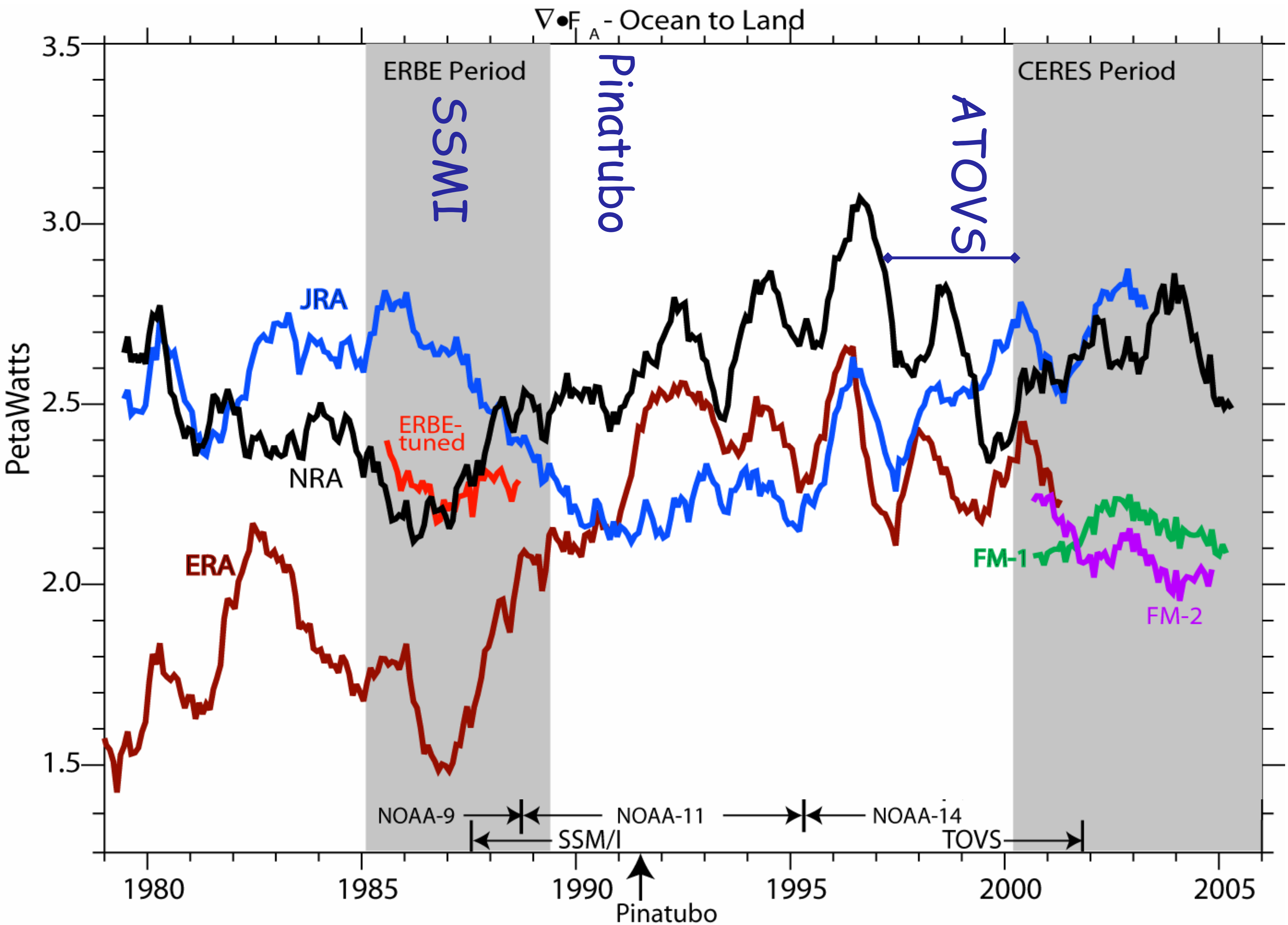
OCEAN


a) R_T
CERES (vs ERBE)
[land-only, 0.01 PW deg^{-1}]
b) $\partial A_E/\partial t$
ERA (vs NRA)
[land-only, 0.01 PW deg^{-1}]
c) $\nabla \cdot F_A$
ERA (vs NRA)
[land-only, 0.01 PW deg^{-1}]
d) F_S
CLM
[land-only, 0.01 PW deg^{-1}]
80 60 °N 20 Eq 20 °S 60 80
D J F M A M J J A S O N D J
-30 -20 -15 -10 -5 -2 -1 0 1 2 5 10 15 20 30

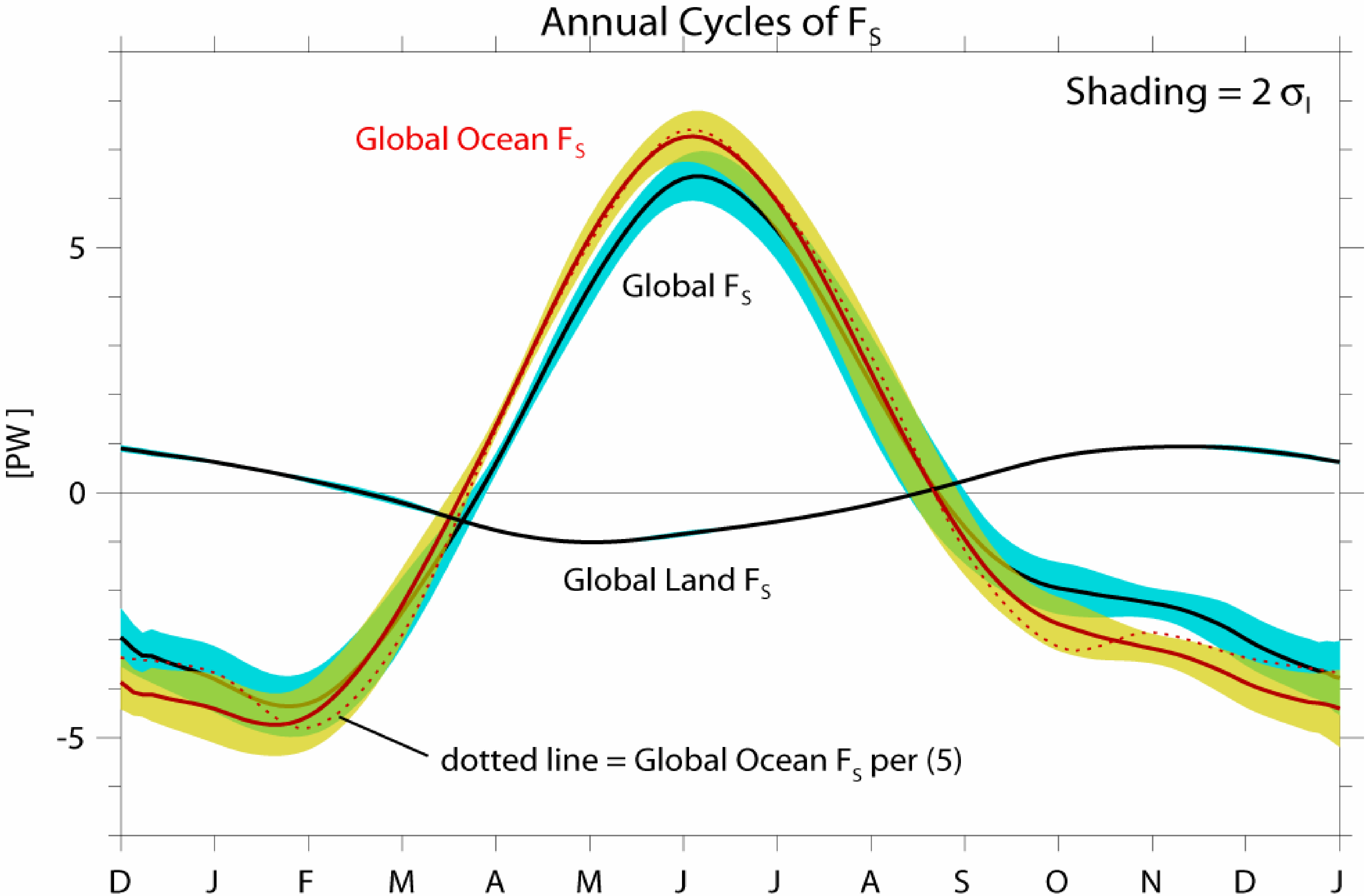
LAND



Net ocean to land energy transport 12-month running means for ERBE and CERES R_T over land and $\delta A_E/\delta t$.

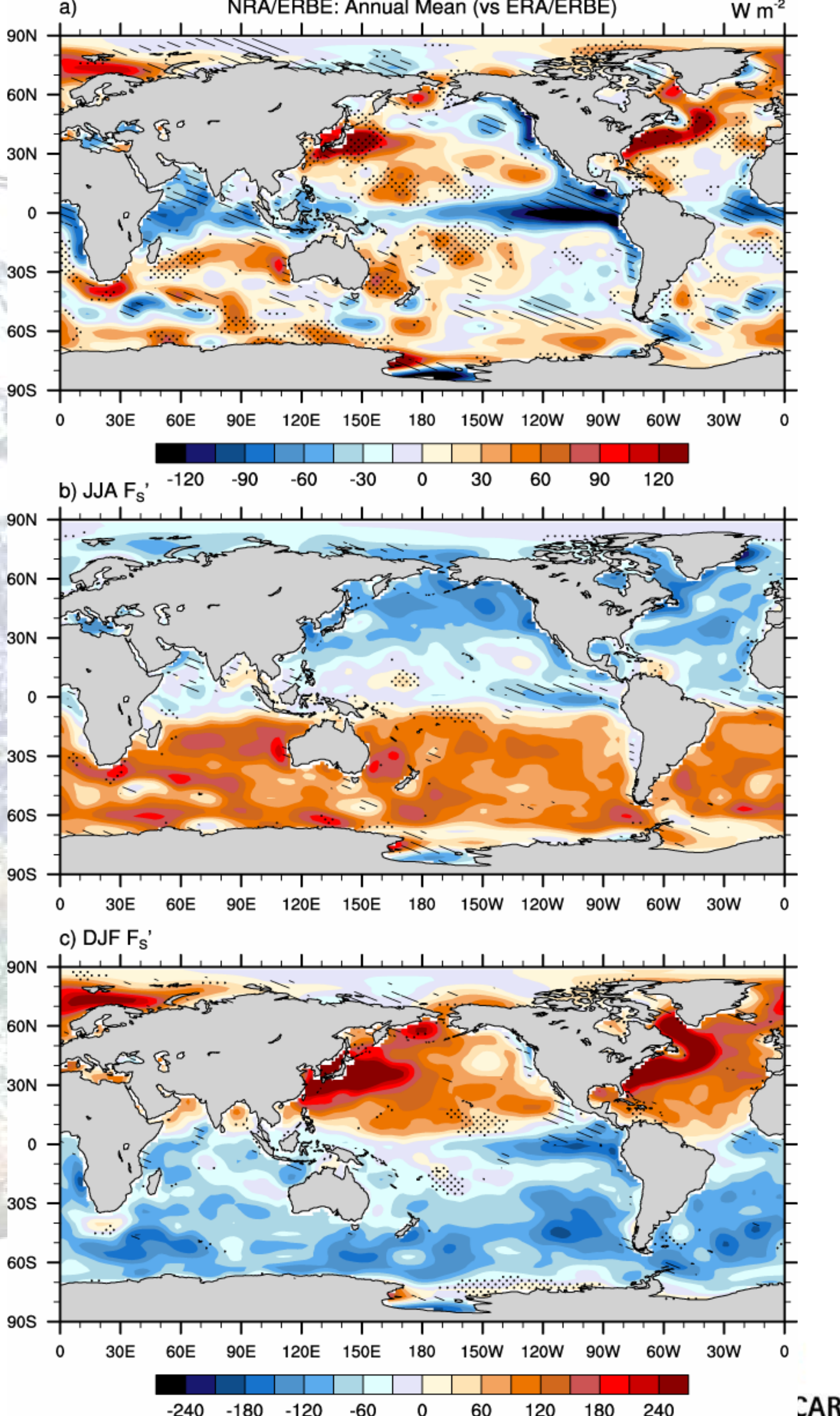


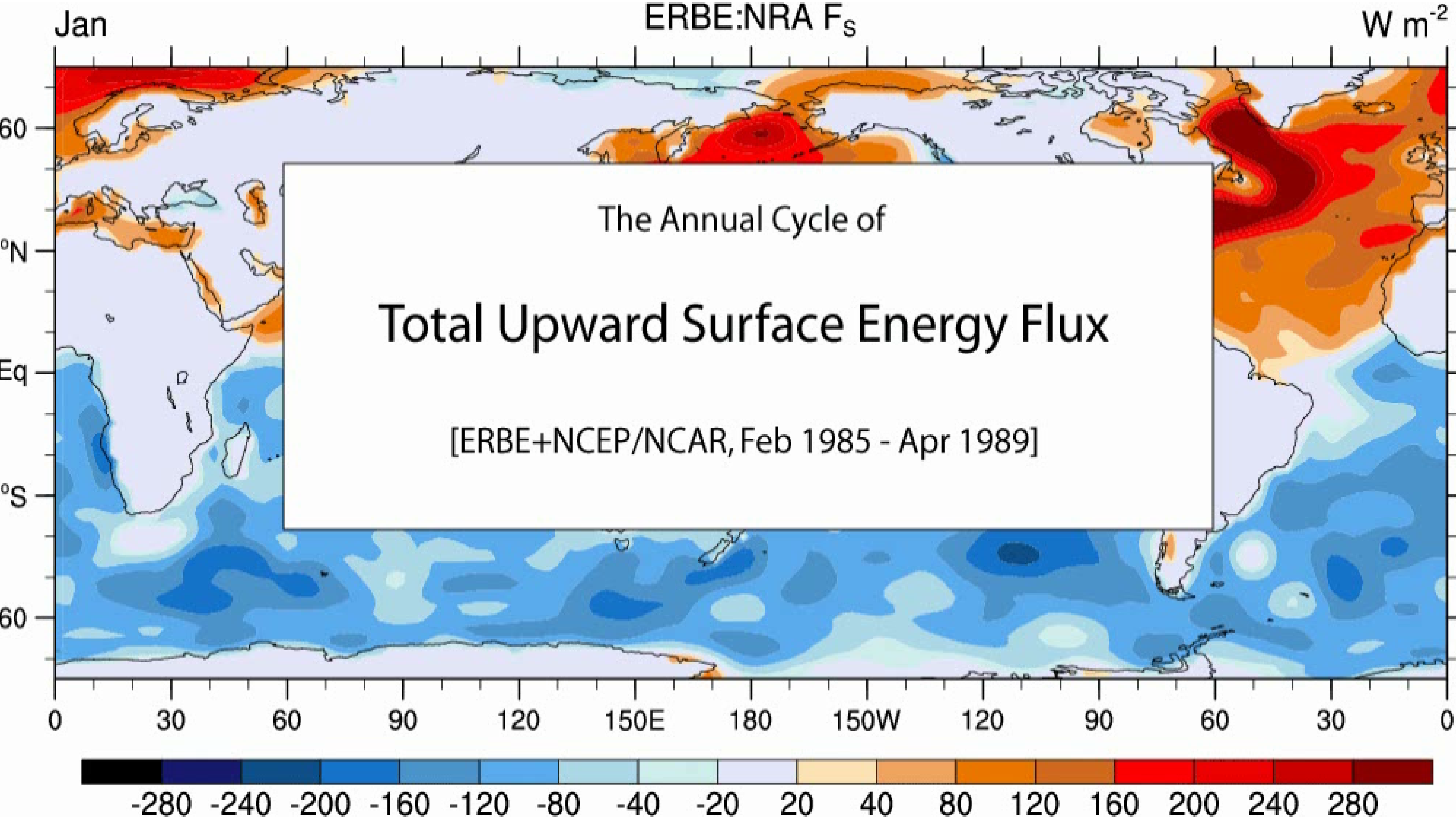
Net ocean to land energy transport 12-month running means for ERBE and CERES R_T over land and $\delta A_E/\delta t$.

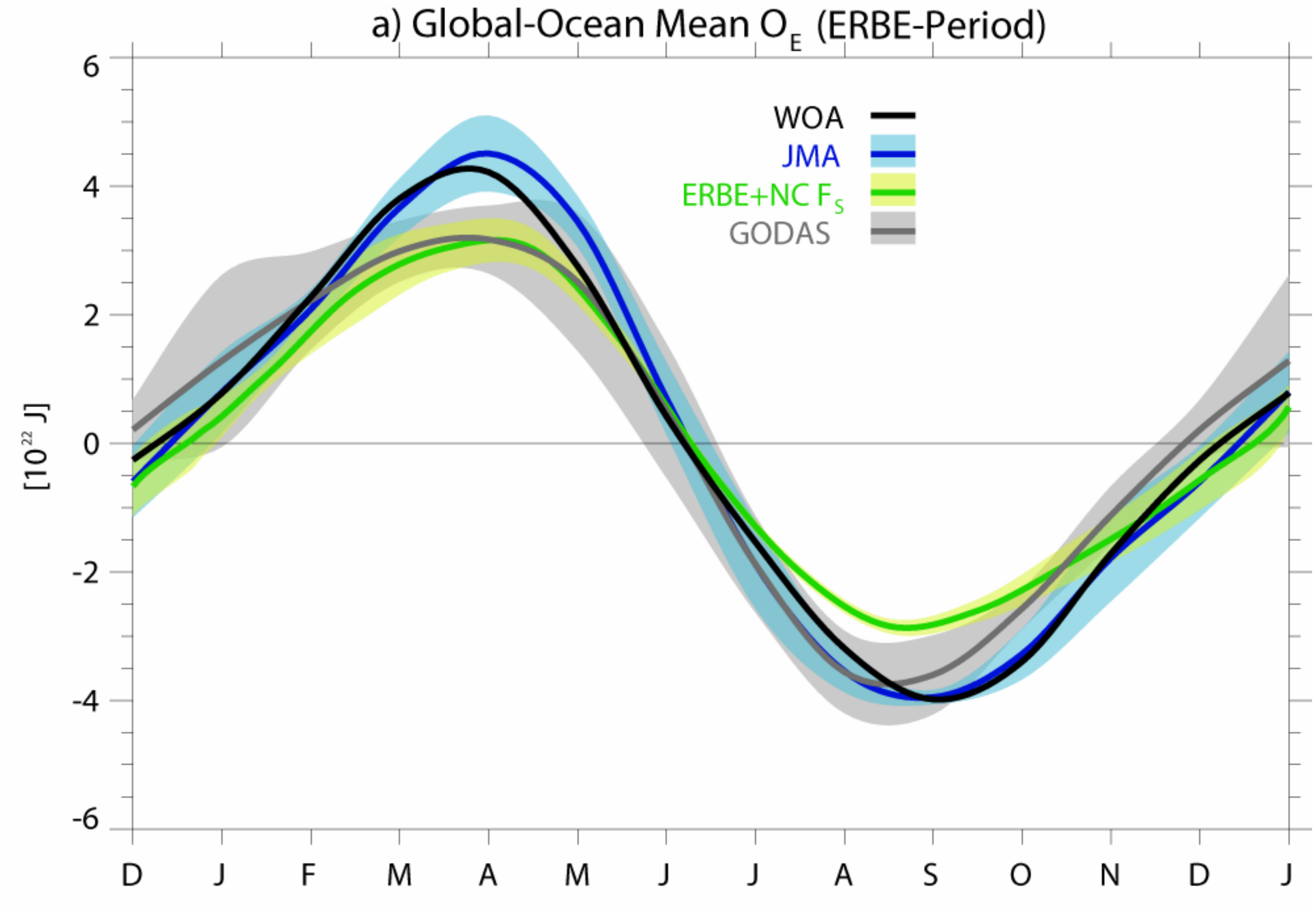


Global, global-ocean, and global-land (from CLM3) estimates of net upwards surface flux (F_S) using ocean (red) and land (dotted red).

Annual cycle of Fs



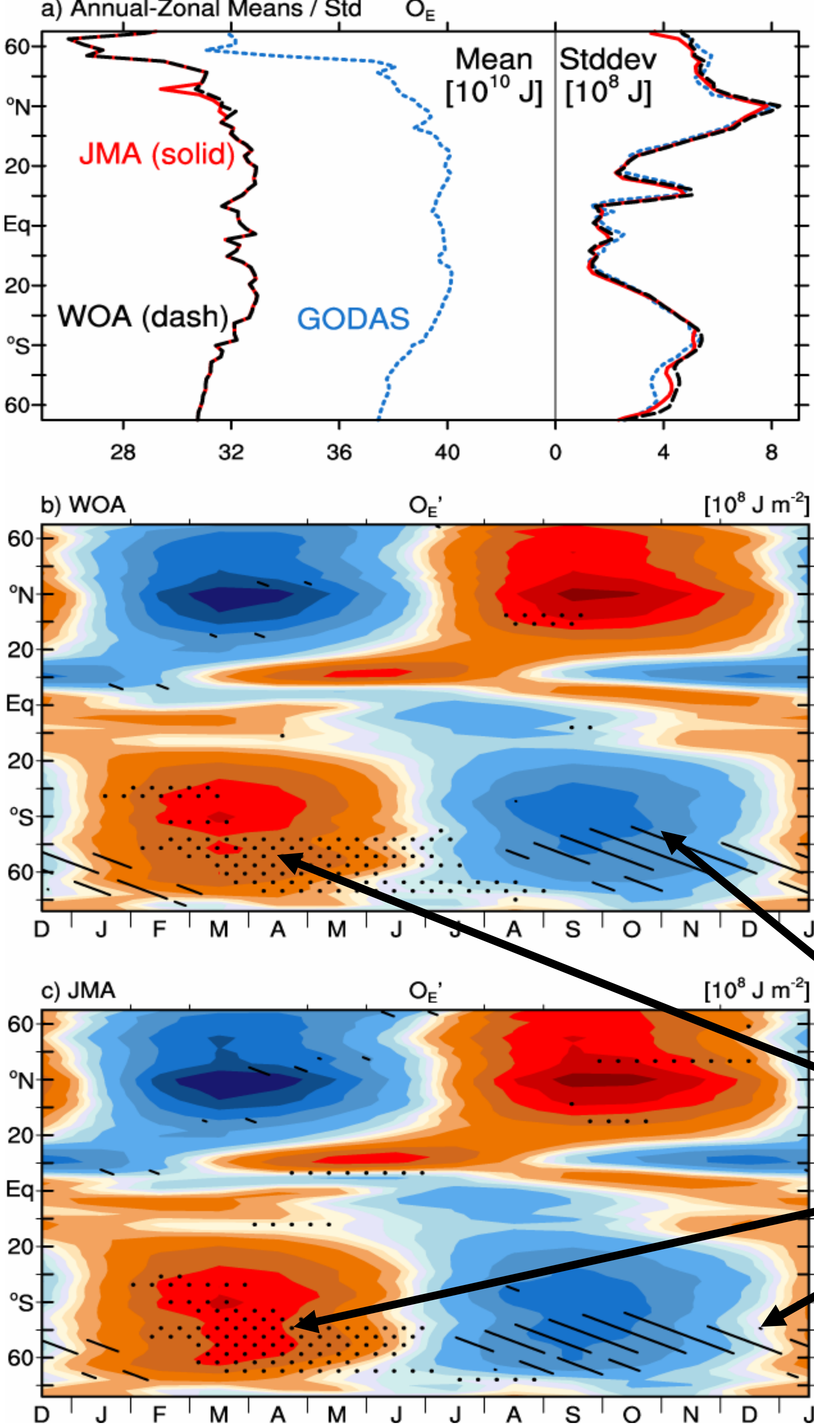

Jan
ERBE:NRA F_S
W m^{-2}
The Annual Cycle of
Total Upward Surface Energy Flux
[ERBE+NCEP/NCAR, Feb 1985 - Apr 1989]
60
°N
Eq
°S
60
0
30
60
90
120
150E
180
150W
120
90
60
30
0
-280
-240
-200
-160
-120
-80
-40
-20
20
40
80
120
160
200
240
280



Amplitude of O_E much too large: we can show that the main discrepancies arise from south of 30°S where ocean sampling poor.
GODAS better than WOA.

O_E from WOA, GODAS and JMA (shading).

F_S has been integrated in time to provide O_E anomalies



Annual zonal means

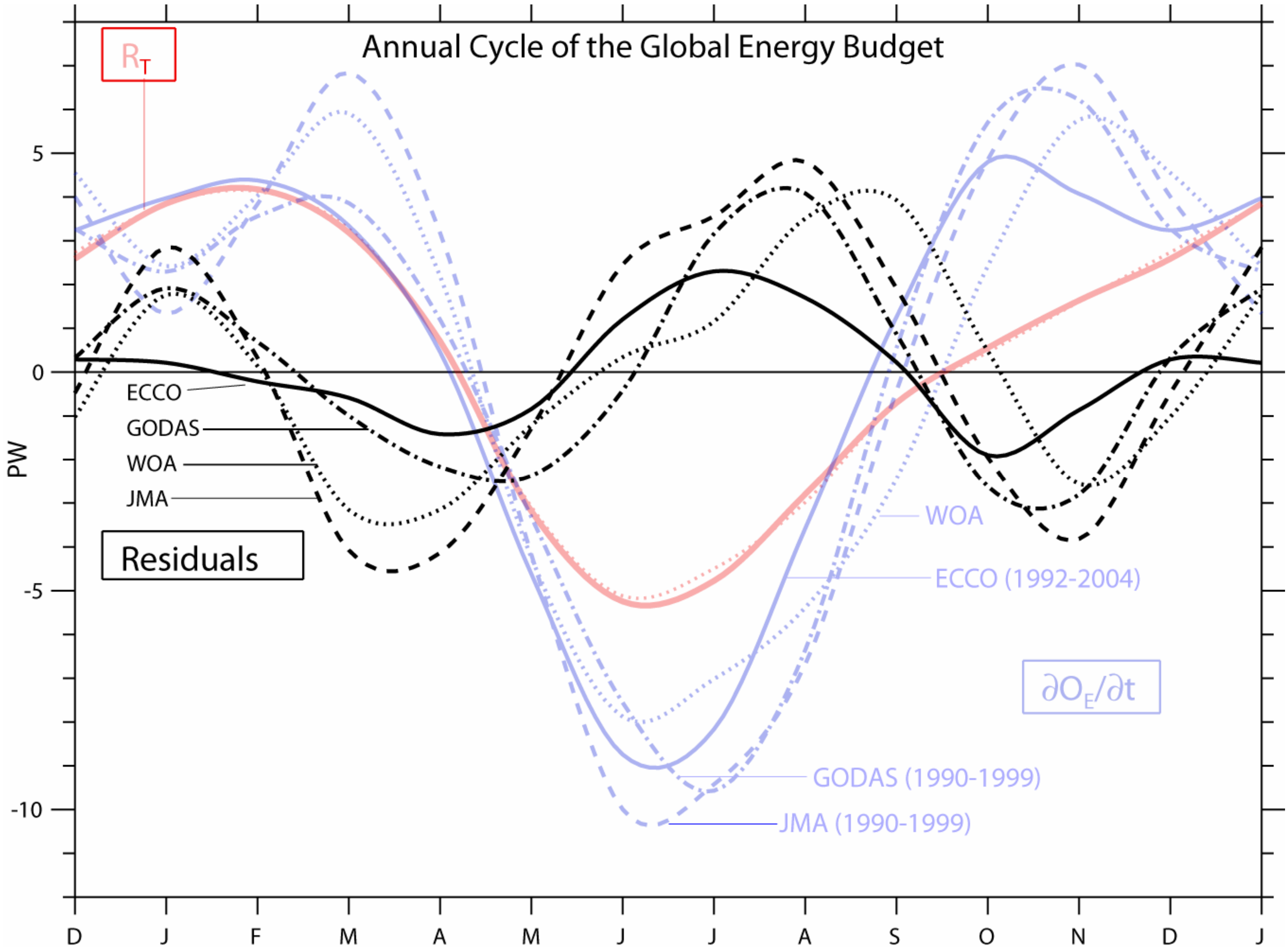
GODAS > JMA,WOA

Departures from annual mean

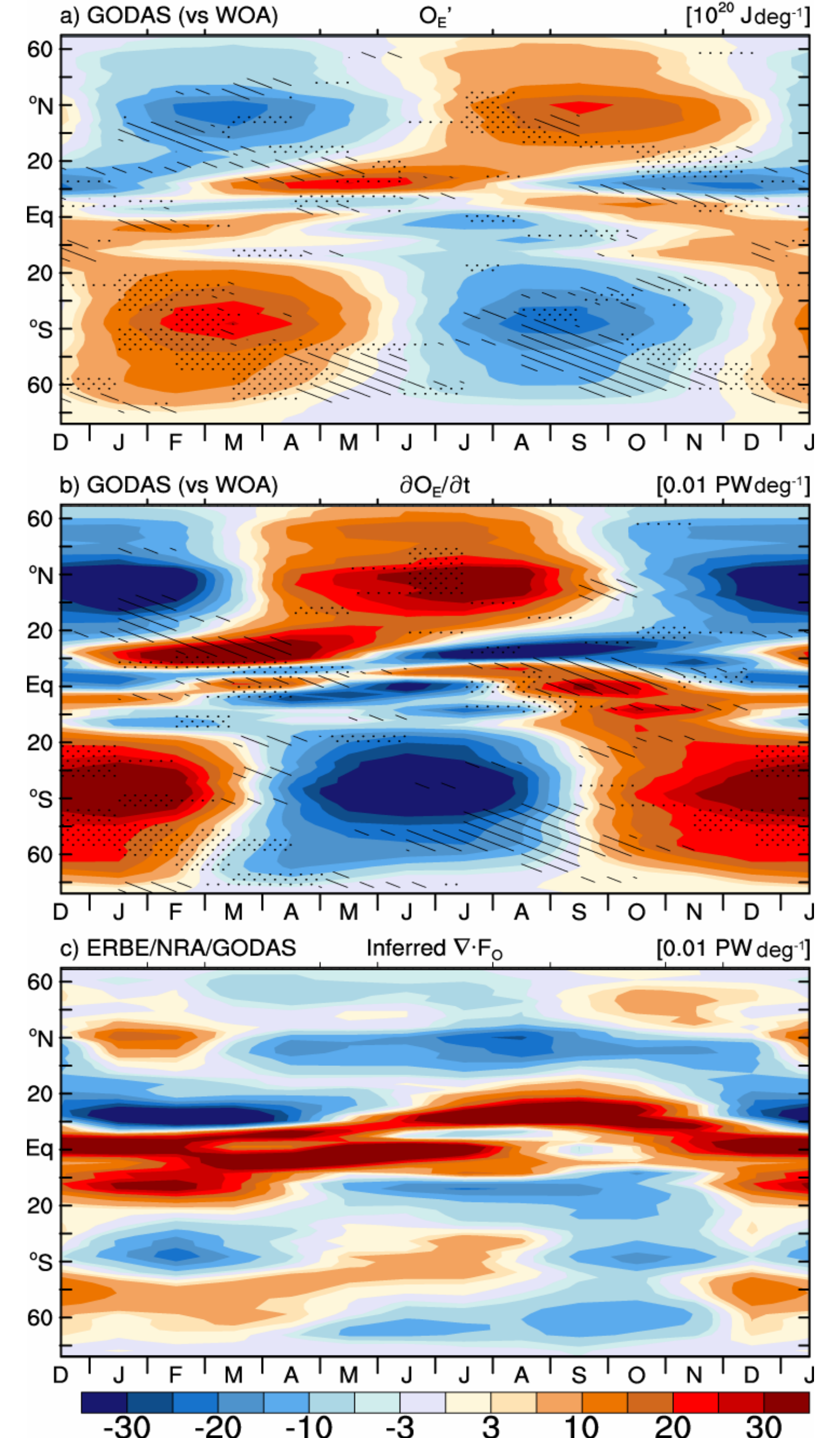
Differences from GODAS exceeding $\pm 2\sigma$ over southern oceans

....WOA>GODAS

\\WOA<GODAS



Annual Cycle of the Global Energy Budget
R_T
5
0
-5
-10
PW
ECCO
GODAS
WOA
JMA
Residuals
WOA
ECCO (1992-2004)
$\partial O_E/\partial t$
GODAS (1990-1999)
JMA (1990-1999)
D
J
F
M
A
M
J
J
A
S
O
N
D
J



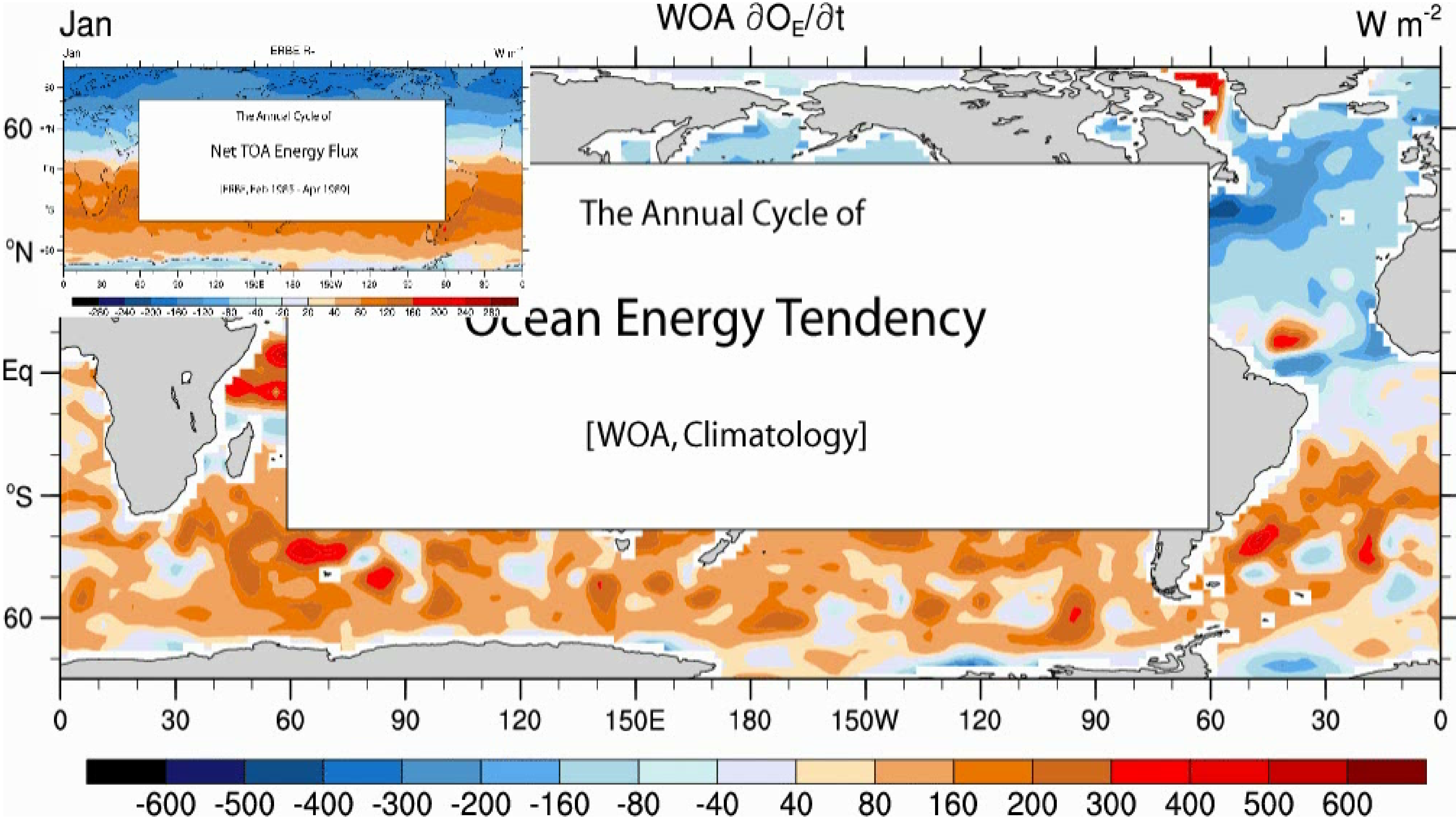
Zonal integral over the world oceans of

a) O_E'

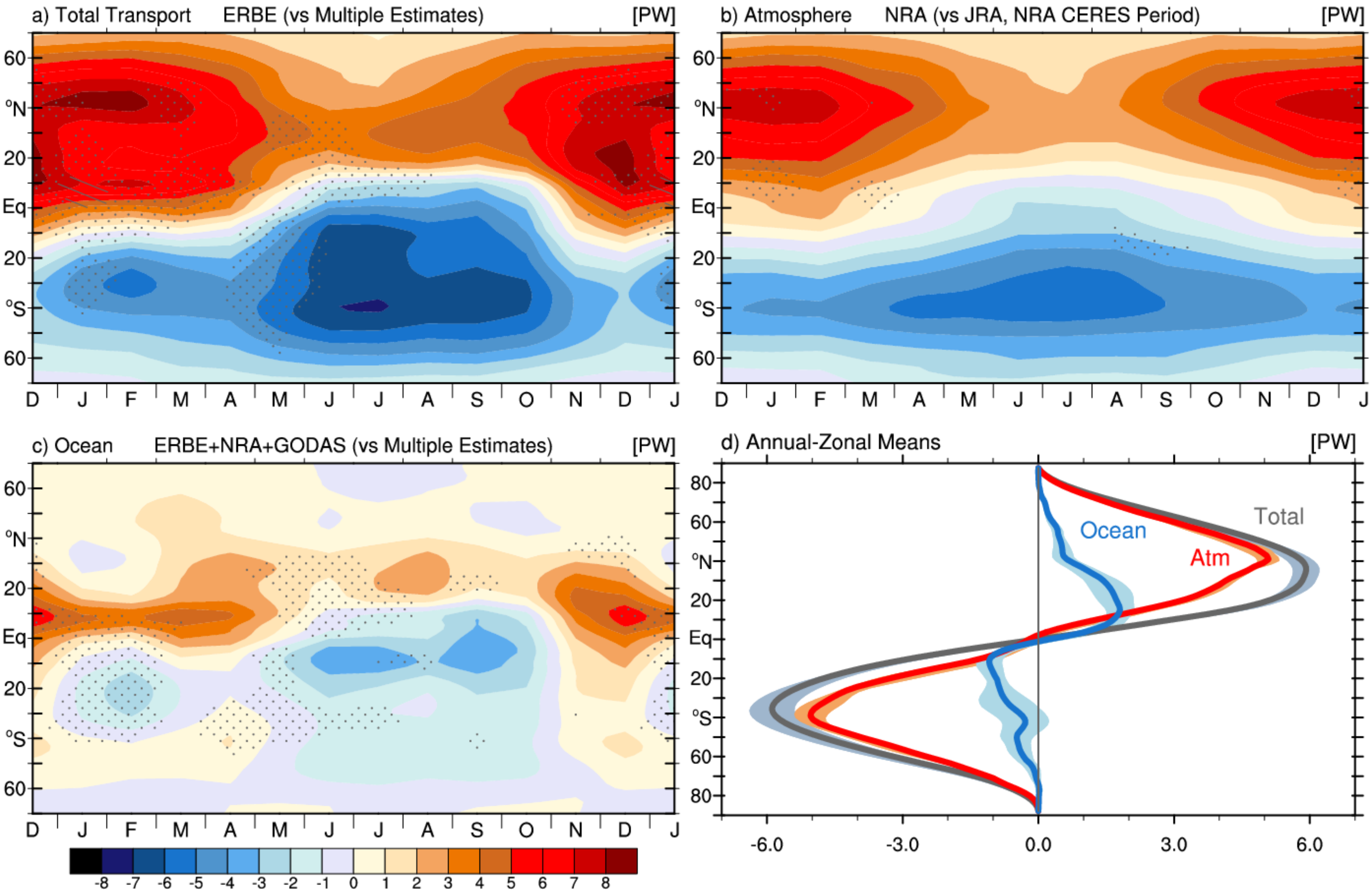
b) $\delta O_E/\delta t$

c) $\nabla\cdot\mathbf{F}_O$

in PW deg^{-1}.

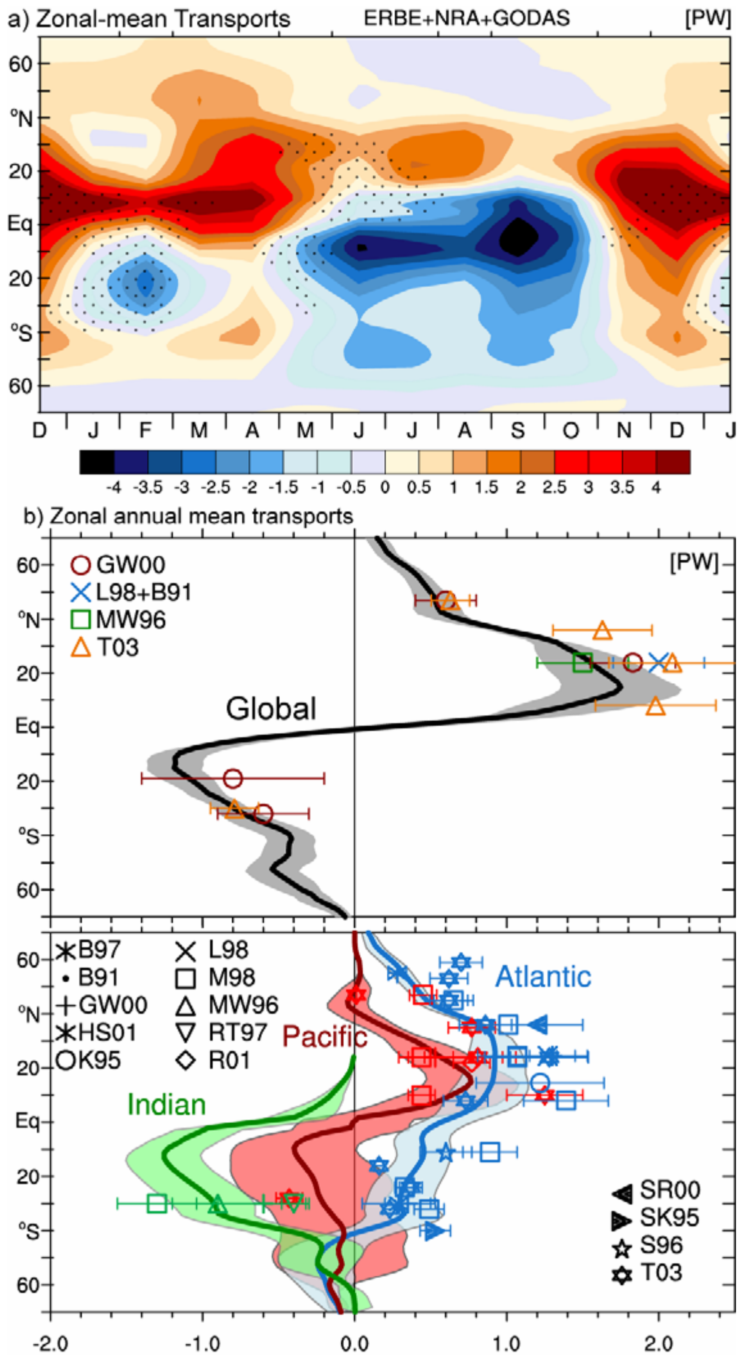


Jan
WOA ∂O_E/∂t
W m^-2
The Annual Cycle of
Net TOA Energy Flux
The Annual Cycle of
Ocean Energy Tendency
[WOA, Climatology]
60
°N
Eq
°S
60
0 30 60 90 120 150E 180 150W 120 90 60 30 0
-600 -500 -400 -300 -200 -160 -80 -40 40 80 160 200 300 400 500 600

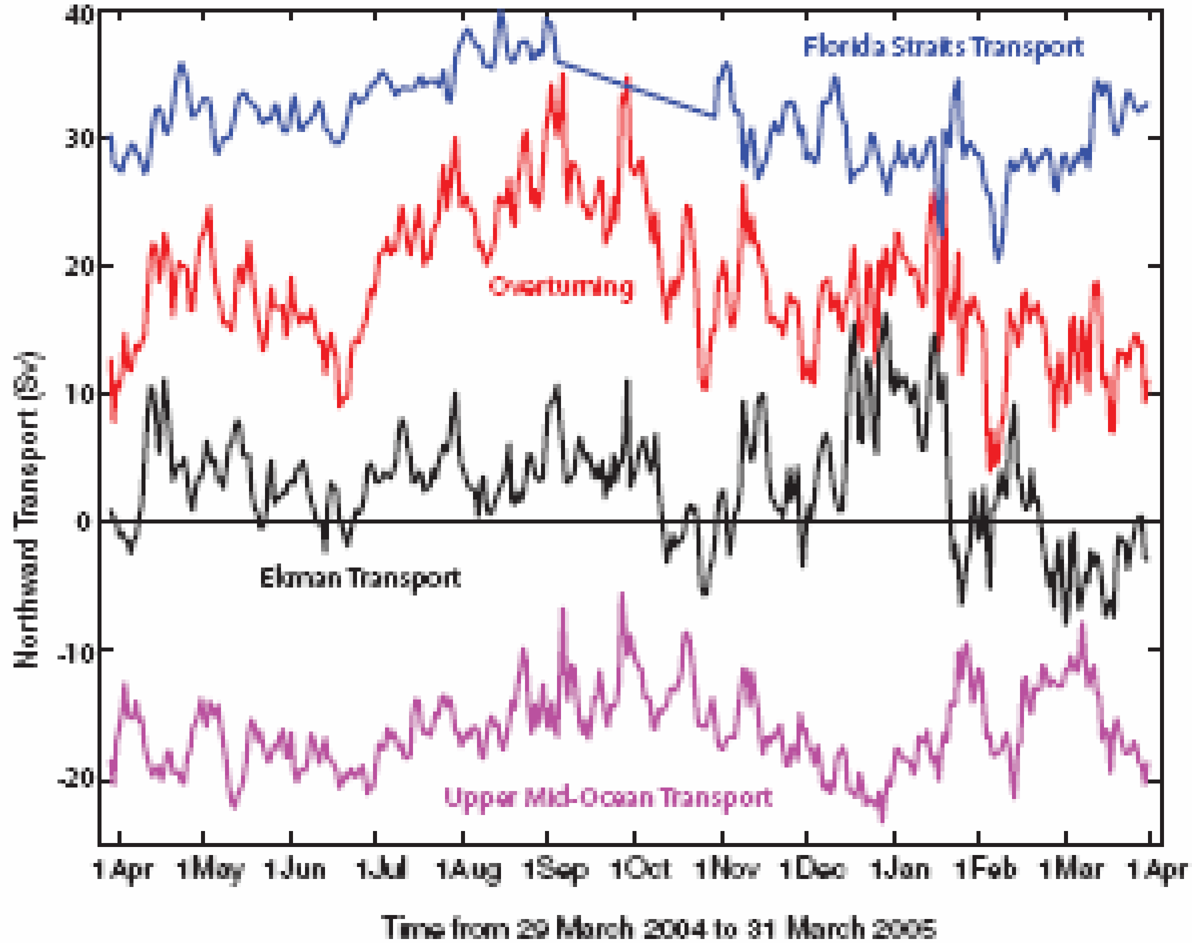


ERBE-period meridional energy transport

Ocean Transports



Comparisons of annual means with direct ocean transect estimates shows good results except slightly lower for Atlantic and global mean

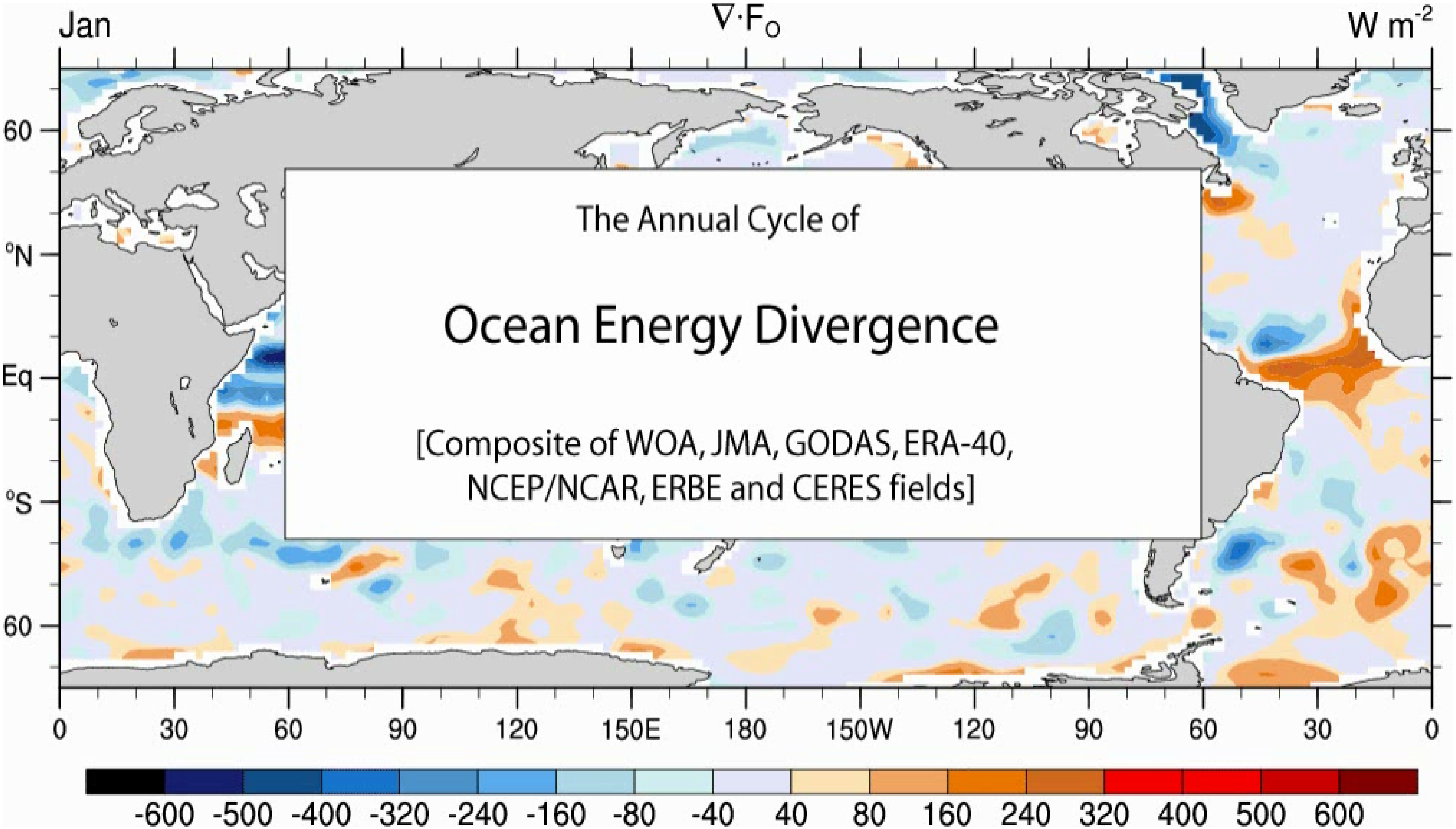


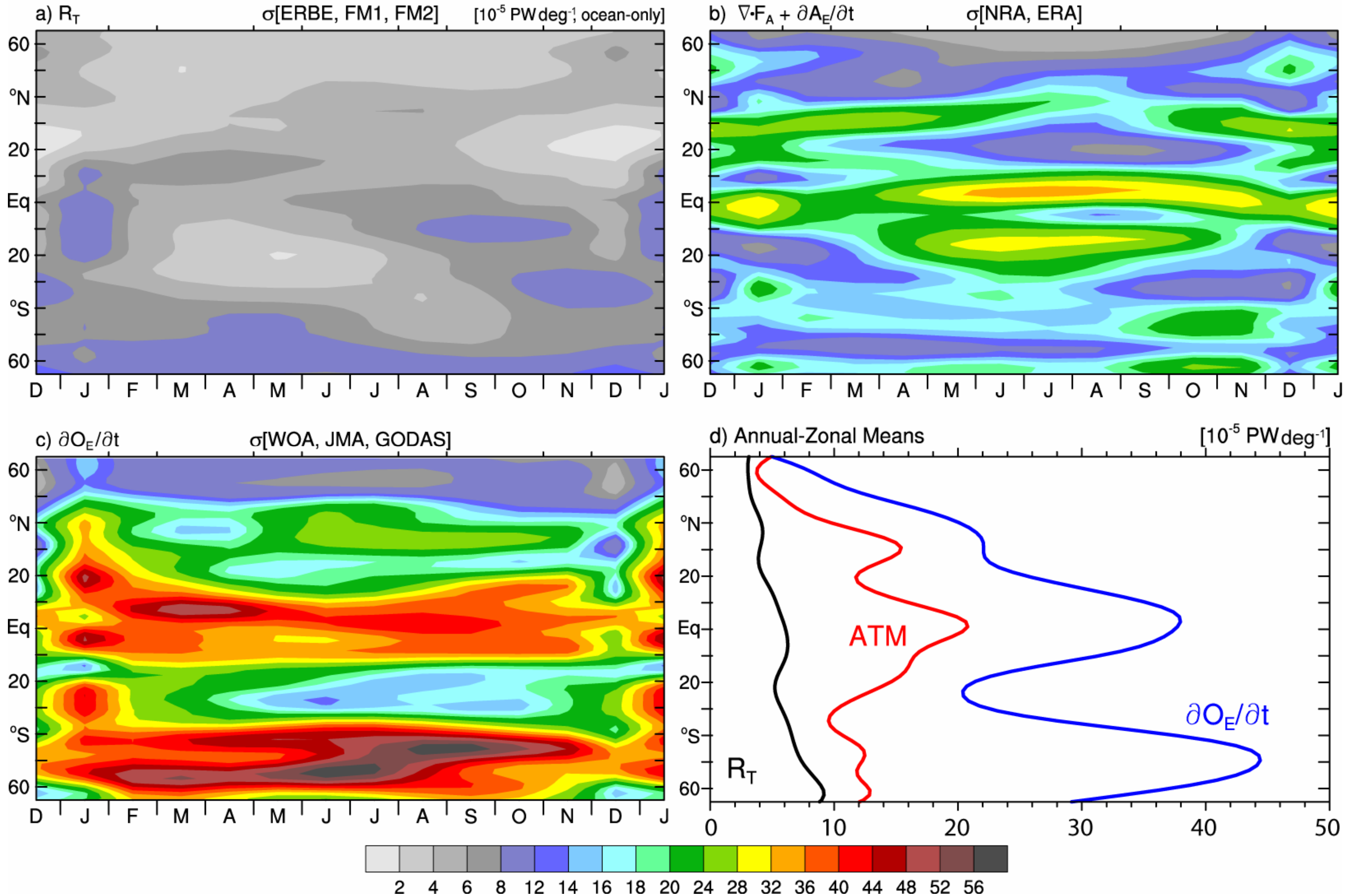
26.5°N Atlantic

Variability of MOC is large: average overturning is 18.7 ± 5.6 Sv (1 s.d)

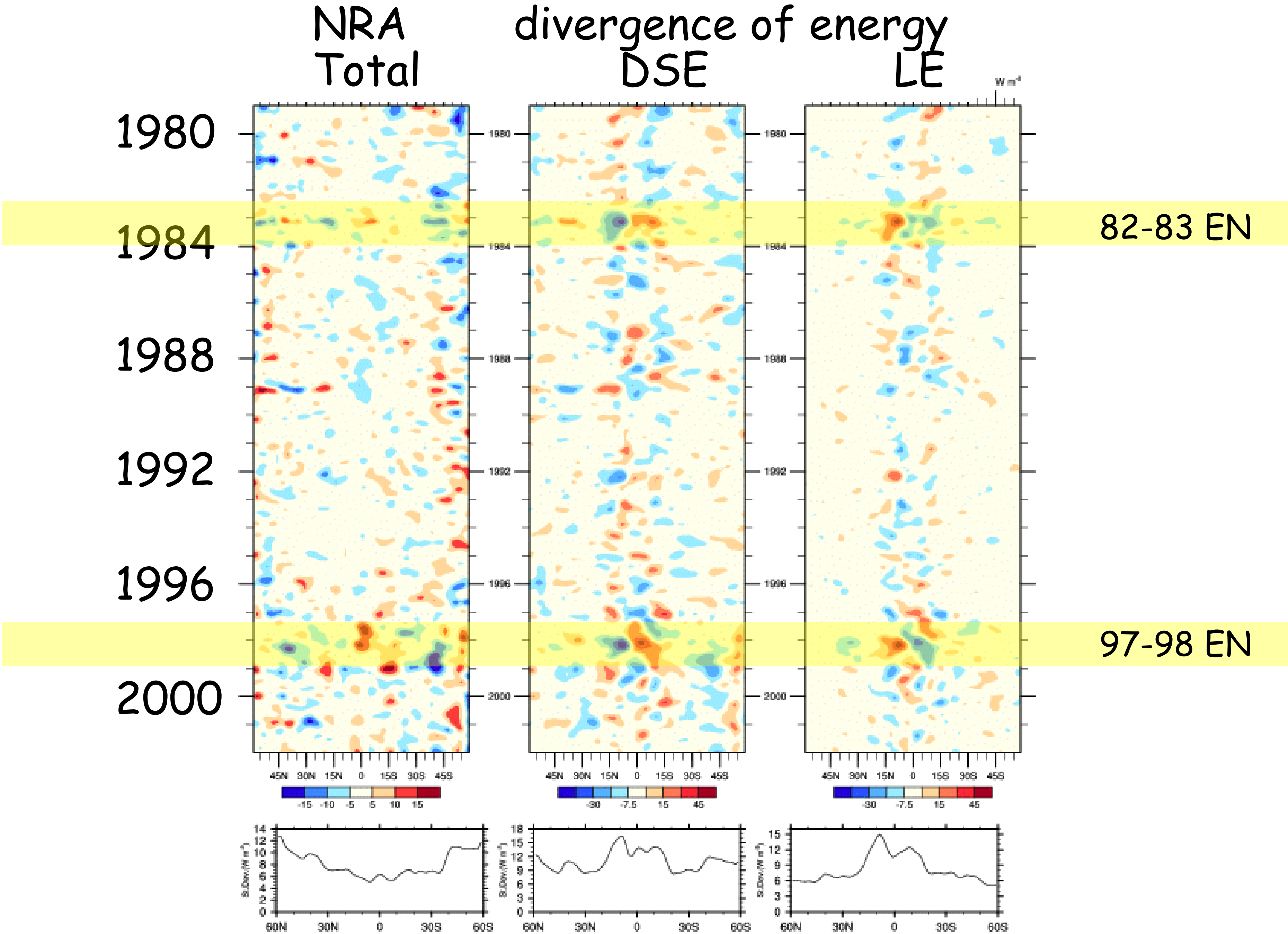
(range: 4.0 to 34.9 Sv)

Cunningham et al 2007 *Science*

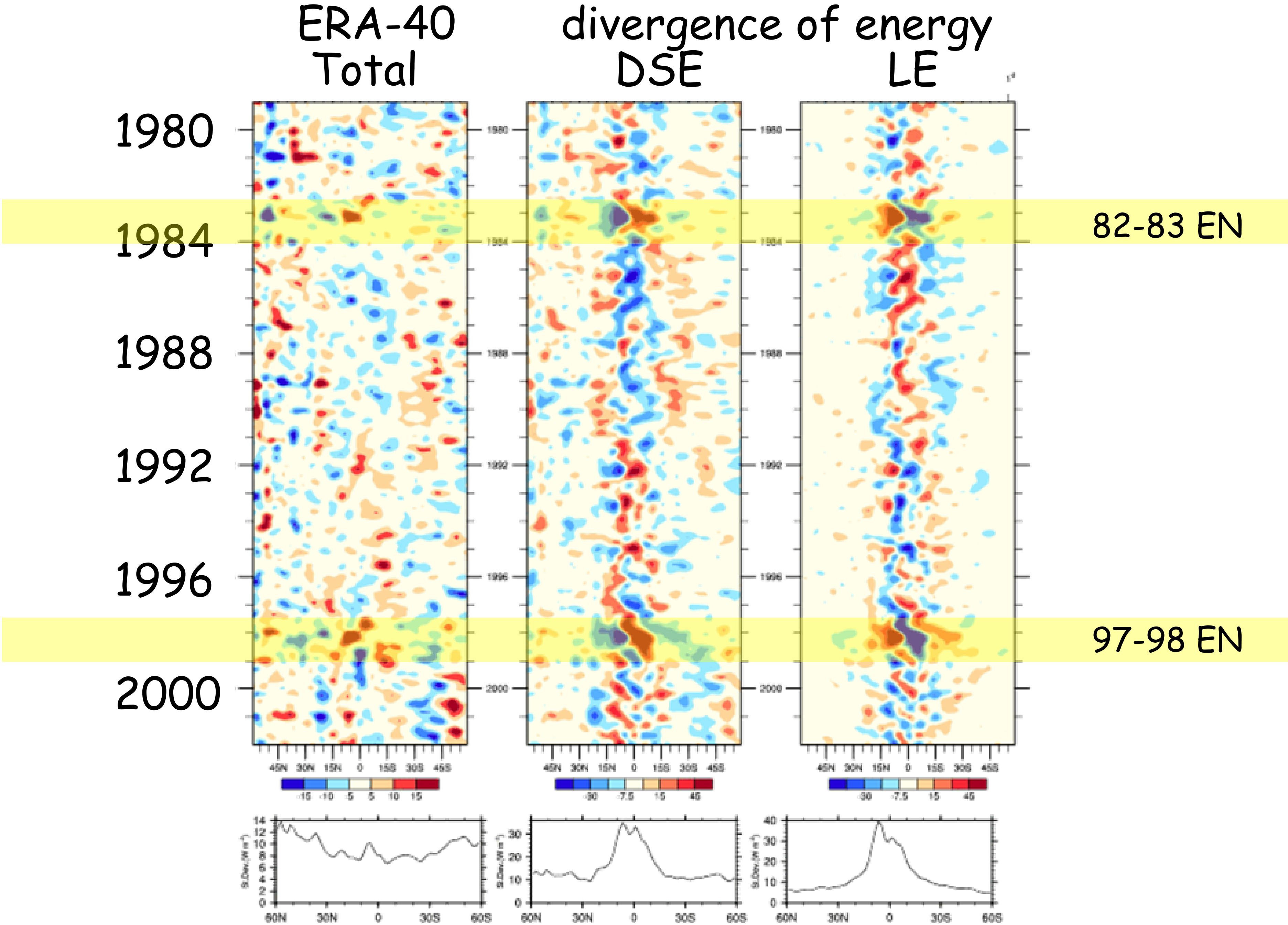

Jan
∇·F_O
W m^-2
The Annual Cycle of
Ocean Energy Divergence
[Composite of WOA, JMA, GODAS, ERA-40,
NCEP/NCAR, ERBE and CERES fields]
60
°N
Eq
°S
60
0 30 60 90 120 150E 180 150W 120 90 60 30 0
-600 -500 -400 -320 -240 -160 -80 -40 40 80 160 240 320 400 500 600



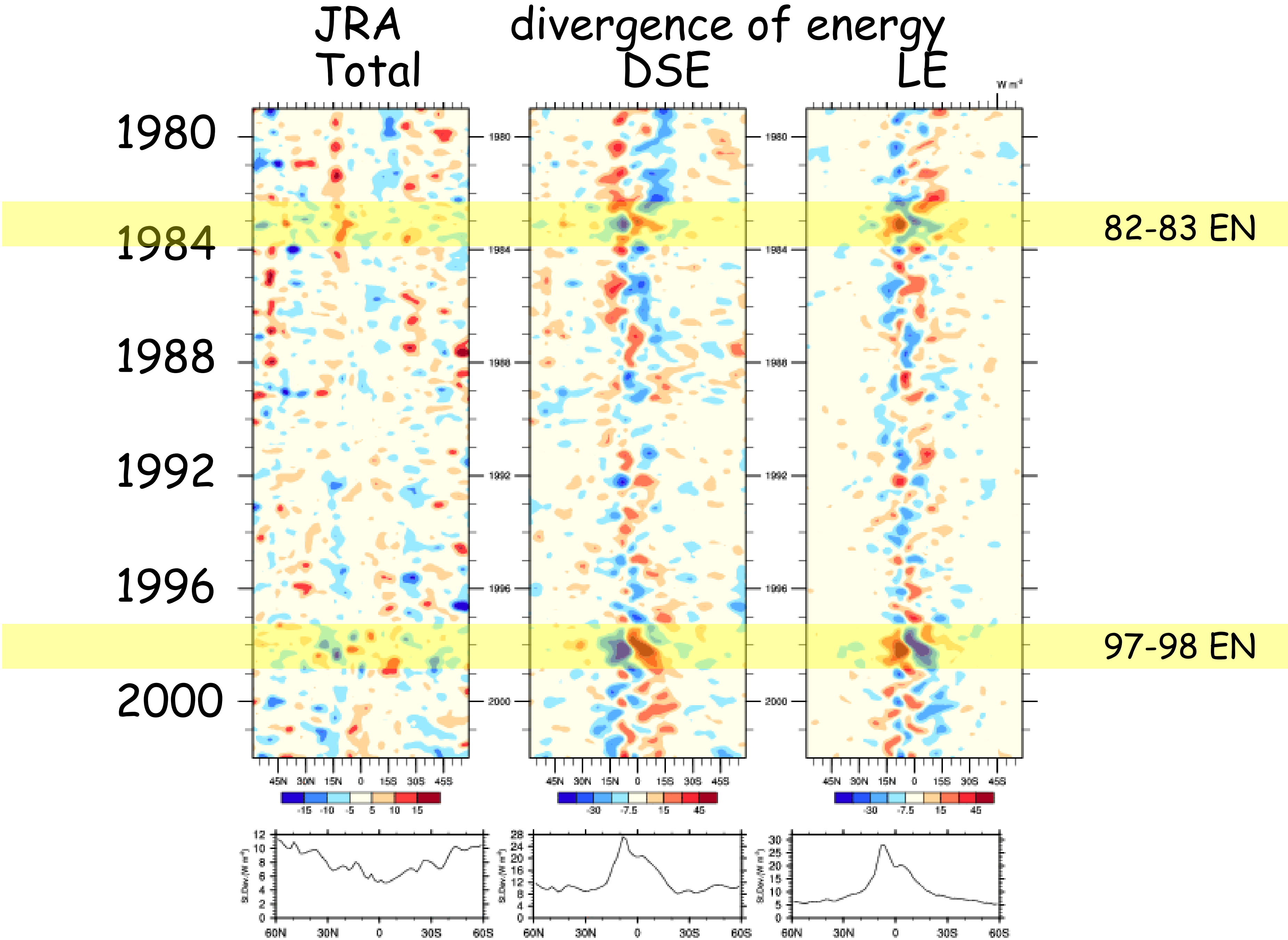
a) R_T
σ[ERBE, FM1, FM2]
[10^{-5} PW deg^{-1}; ocean-only]
b) $\nabla\cdot F_A + \partial A_E/\partial t$
σ[NRA, ERA]
c) $\partial O_E/\partial t$
σ[WOA, JMA, GODAS]
d) Annual-Zonal Means
[10^{-5} PW deg^{-1}]
ATM
$\partial O_E/\partial t$
R_T
60 °N 20 Eq 20 °S 60
D J F M A M J J A S O N D J
0 10 20 30 40 50
2 4 6 8 12 14 16 18 20 24 28 32 36 40 44 48 52 56



NRA
divergence of energy
Total
DSE
LE
1980
1984
1988
1992
1996
2000
82-83 EN
97-98 EN
45N 30N 15N 0 15S 30S 45S
-15 -10 -5 5 10 15
-30 -7.5 15 45
60N 30N 0 30S 60S

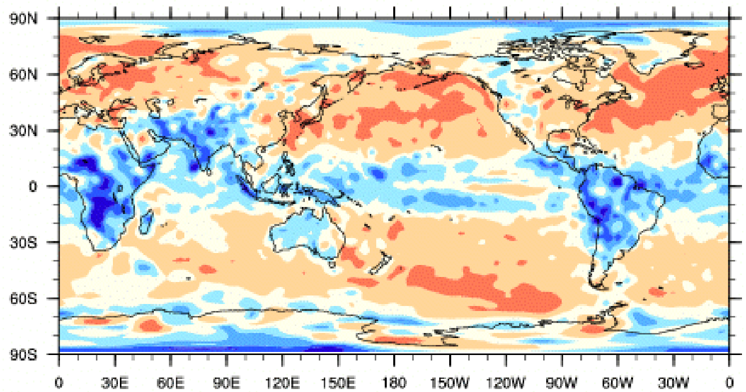


ERA-40
Total
divergence of energy
DSE
LE
1980
1984
1988
1992
1996
2000
82-83 EN
97-98 EN
45N 30N 15N 0 15S 30S 45S
-15 -10 -5 5 10 15
-30 -7.5 15 45
60N 30N 0 30S 60S

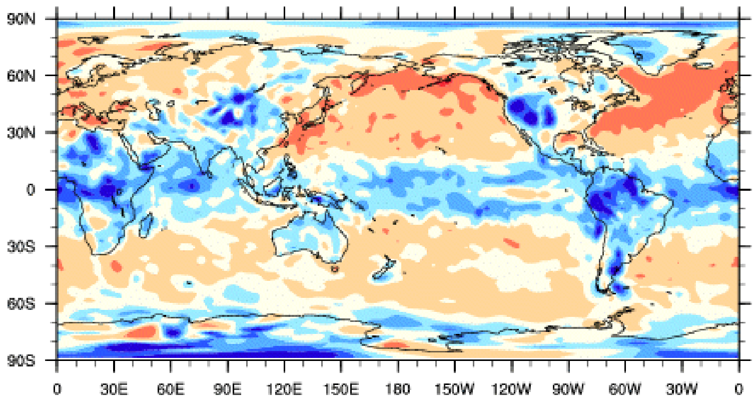


JRA
divergence of energy
Total
DSE
LE
1980
1984
1988
1992
1996
2000
82-83 EN
97-98 EN
45N 30N 15N 0 15S 30S 45S
-15 -10 -5 5 10 15
-30 -7.5 15 45
60N 30N 0 30S 60S

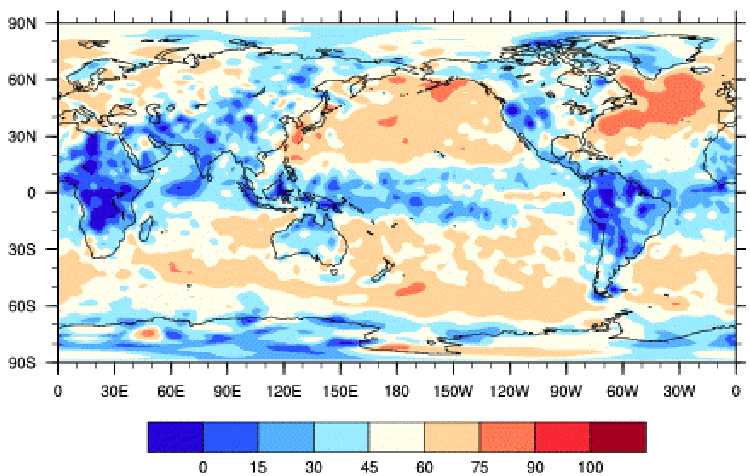
Correlations total energy divergence: Monthly Anomalies



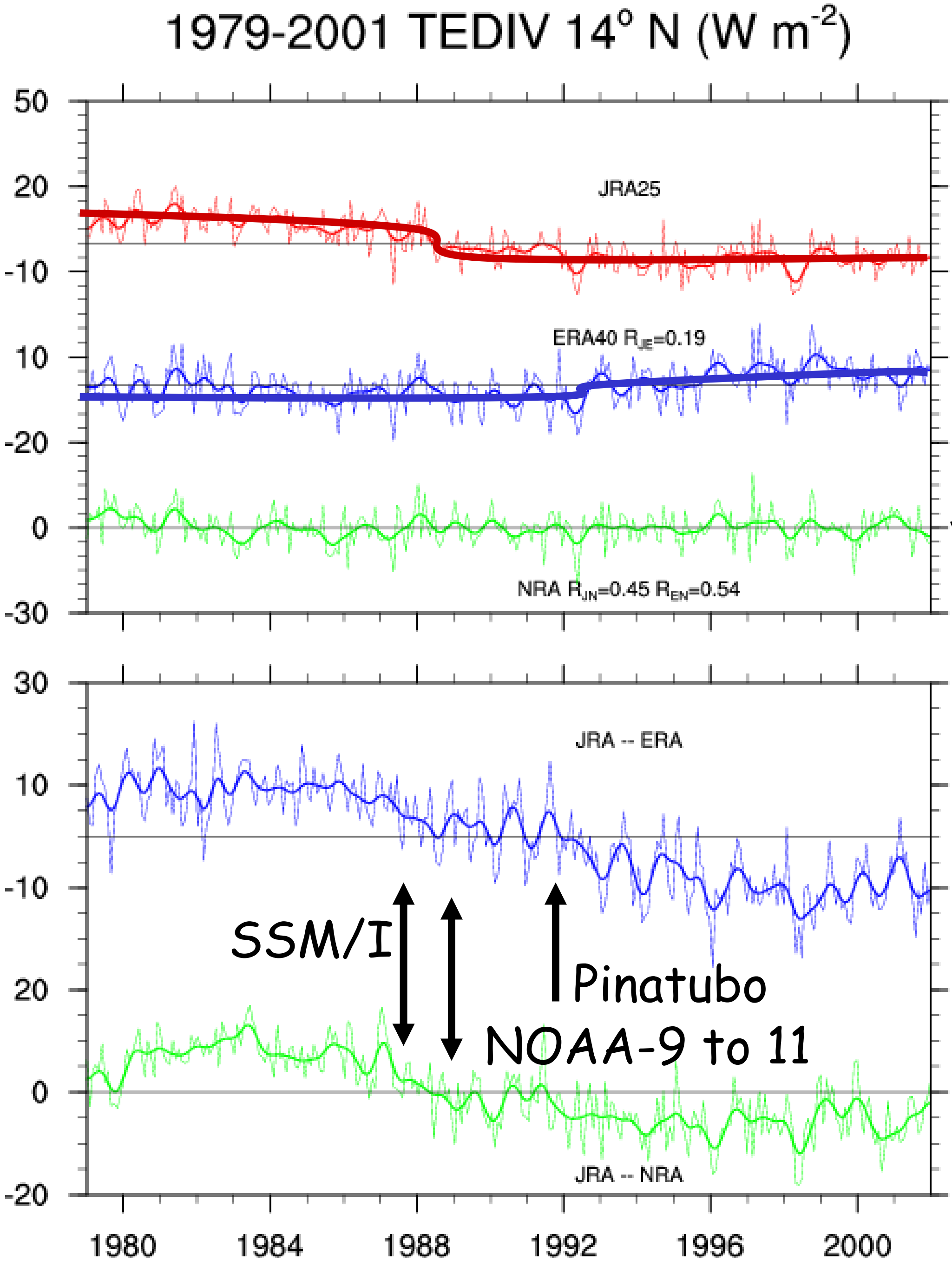
JRA vs ERA-40



JRA vs NRA



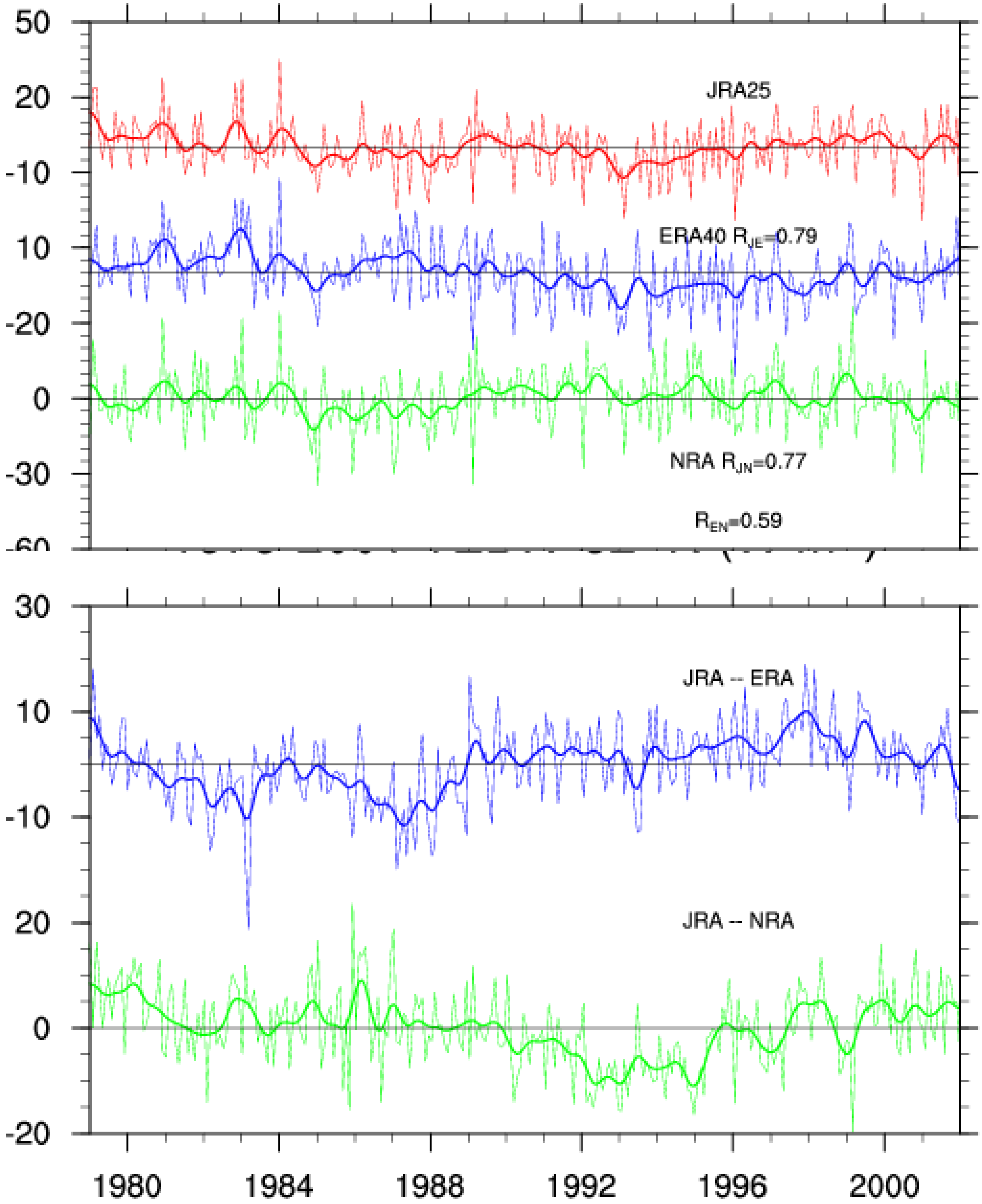
NRA vs ERA-40

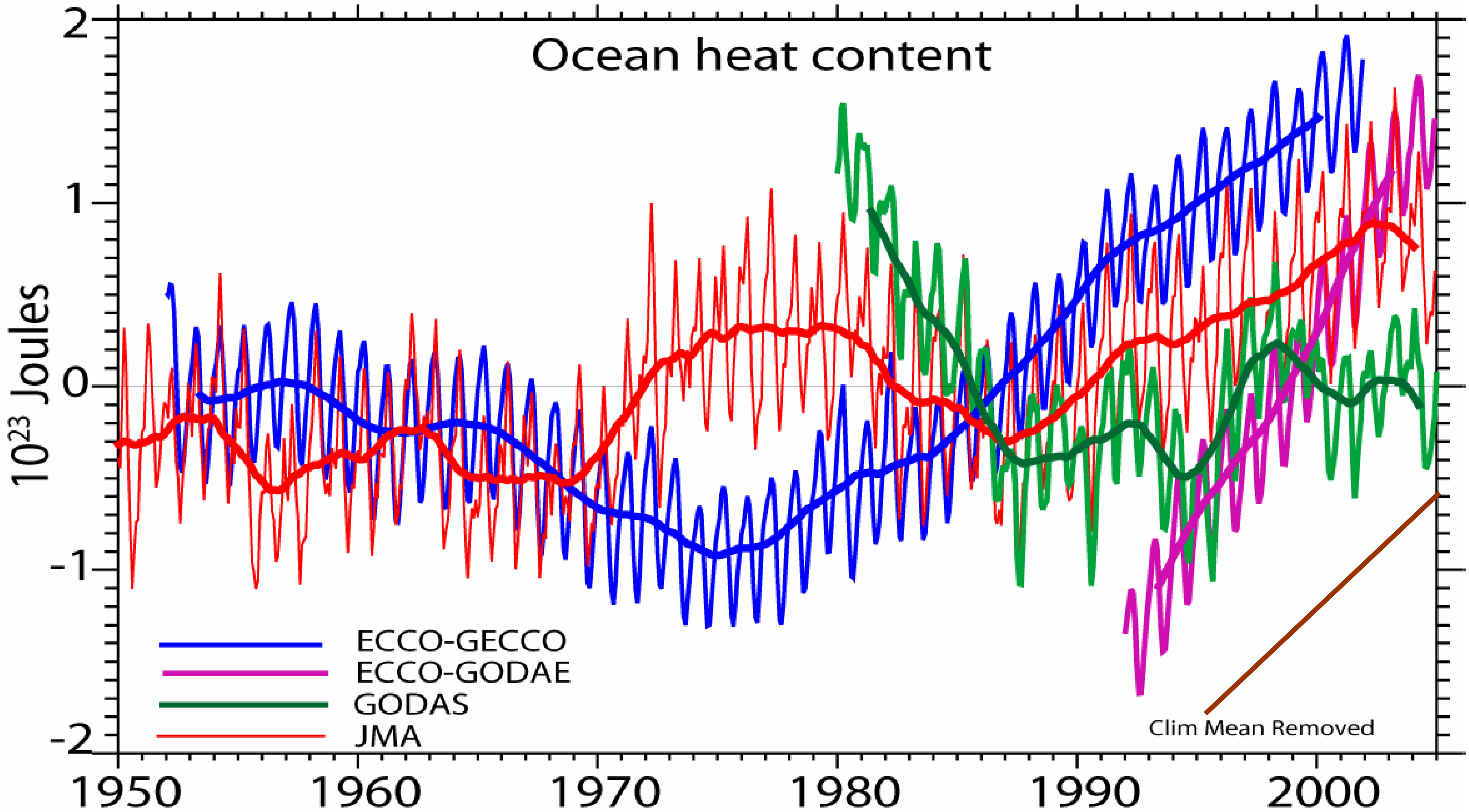


Spurious low frequency variability

Deficient low frequency variability on all time scales

1979-2001 TEDIV 62° N (W m^{-2})





0.4 PW into ocean
implies 1.26x10^{23} J/decade

To 700 or 800 m depth

JRA Reanalyses

Large spurious variability associated with satellite transitions

- TOVS to ATOVS in Nov 1998
- NOAA-11 to 14 in 1995
- NOAA-9 to 11, late 1988
- SSM/I in July 1987

ERA-40 Reanalyses

Large spurious variability associated with Pinatubo and satellite transitions

NRA Reanalyses

Variability much too low

Ocean analyses

Large spurious variability associated with inadequate sampling (esp. southern hemisphere) and changing observations (esp. XBT to ARGO), and uncertainties in XBT drop rates

Satellite data

Lack of continuity and absolute calibration also gives spurious variability and unreliable trends

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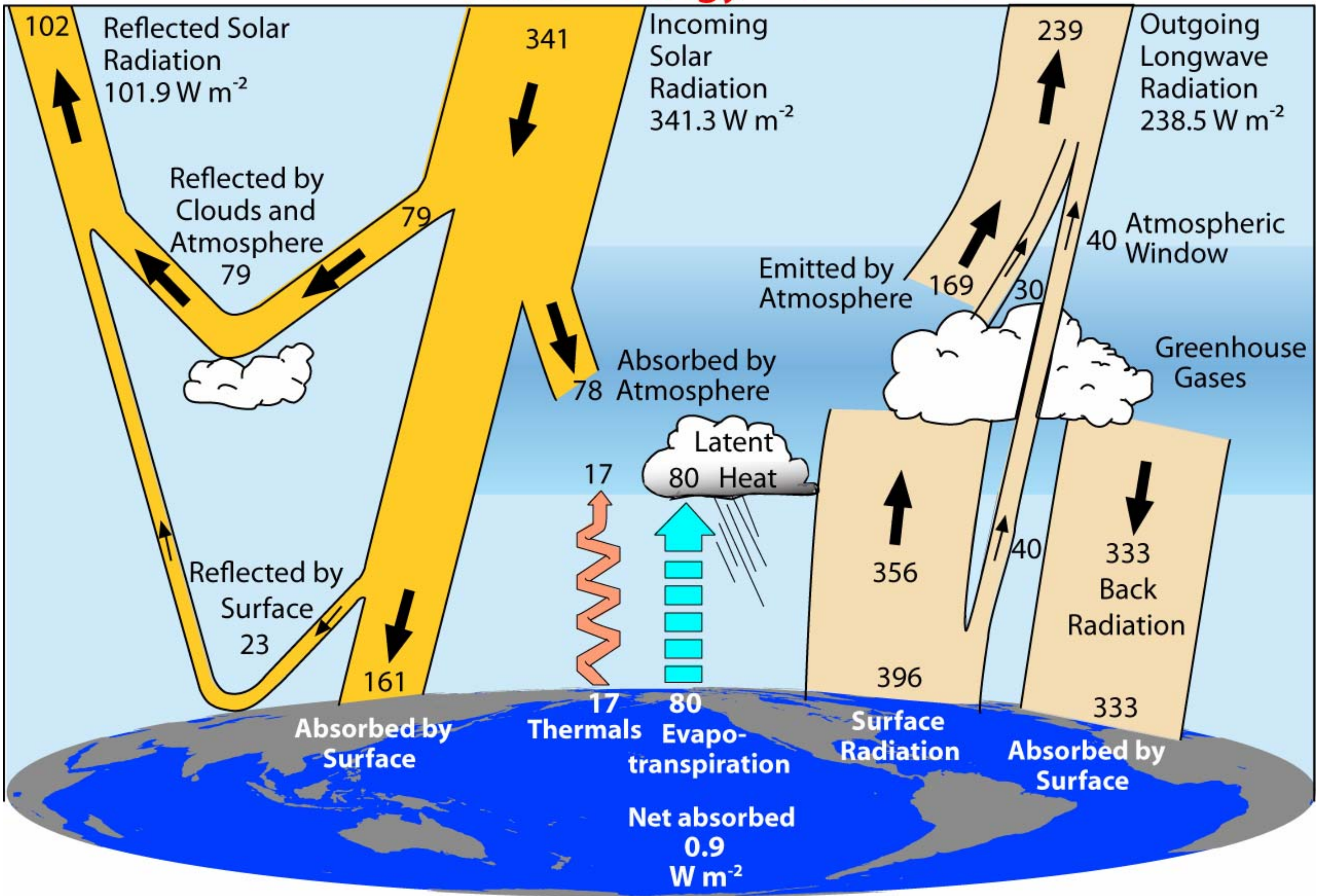
2000-2004 (CERES Period)

Global Energy Flows W m^{-2}



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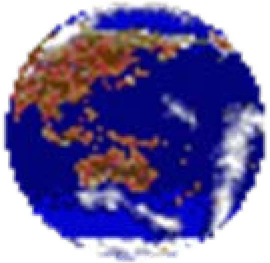
Conclusions

- We have a new estimate of observed global energy budget and land vs ocean domains
- A holistic view of the energy budget allows us to narrow estimates and highlight likely sources of errors.
- Low frequency variability in atmosphere and ocean is highly uncertain based on analyses
- We need to be able to do a full accounting of the energy storage and flows to determine what is happening to the planet and why the climate is changing.
- We can and must do better: but observations from space are in jeopardy, and in situ observations also need improvement
- We have used these to evaluate climate and weather models

NCAR



That's all folks!