Diagnosing the Earth's Energy Budget with Multiple Datasets and Closure Constraints

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NCAR

Energy on Earth: Background

Radiation is the dominant external influence on Earth.

Incoming solar radiation is unevenly distributed due to the geometry of the Earth-Sun system and Earth's rotation.

OLR is more spatially uniform than absorbed solar radiation (*ASR*) - *its gradients interact strongly with dynamics*.

ASR gradient is also influenced strongly by albedo - *determined to first order by cloud cover and surface properties.*

Energy on Earth: Motivations

What is the net TOA radiation (R_T)?

Where does the energy go?

How does the system manage the TOA imbalance? How does it get from where it enters the system to where it exits?

How much is stored, where, with what annual cycle?

How/where does energy leave the Earth?

What are the ocean->land transports and what balances exist over these regions?

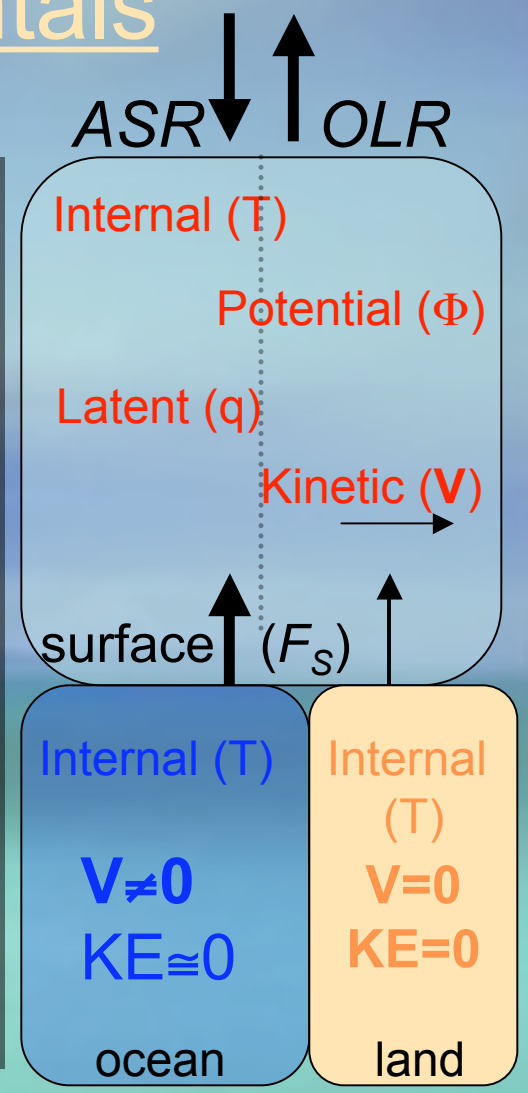
What are the uncertainties and where are they largest?

Energy on Earth: Fundamentals

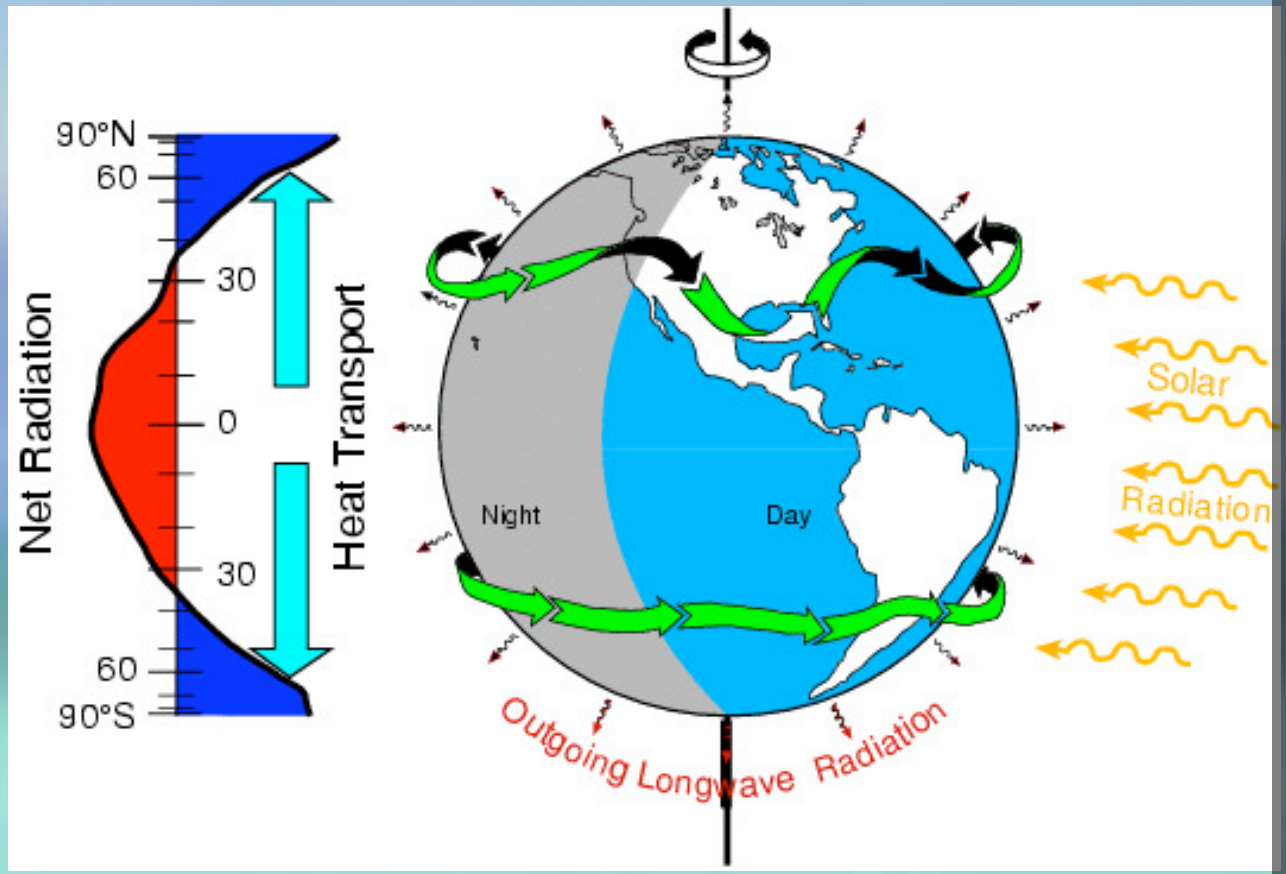
ASR is transformed into various forms moved around in various ways primarily by the atmosphere and oceans, stored and sequestered in the ocean, land, and ice components of the climate system, and ultimately radiated as *OLR*.

An equilibrium, *ASR*=*OLR*. The associated flows both drive and are modulated by the weather systems in the atmosphere, currents in the ocean, and thus fundamentally determine the climate.

And they can be perturbed with climate change.



Meridional Structure



Contrasts in the meridional distribution of radiation at TOA drive atmospheric and oceanic dynamics.

To first order the TOA budget in R_T is zonally symmetric.

Do the energy budgets of the ocean and atmosphere share this symmetry?

How do they partition R_T?

What relative roles do storage and divergence play in the annual cycle?

What form does ocean divergence take?

DATA: Energy Fluxes

- TOA (tuned)
  - ERBE and CERES retrievals
- Atmosphere (mass corrected)
  - NCEP/NCAR (NRA) and ERA(-40) Reanalyses
- Land (simulated)
  - Community Land Model
- Ocean
  - World Ocean Atlas 2005 (Levitus et al.)
  - Japanese Met Agency Ocean Analysis (Ishii et al.)
  - Global Ocean Data Assimilation System (NCEP)

Residual Analysis Methods

- Net surface flux is inferred from TOA and atmospheric budgets per:

$$F_S = \nabla \bullet \mathbf{F_A} - \partial A_E/\partial t - R_T$$

(over large scales, errors cancel)

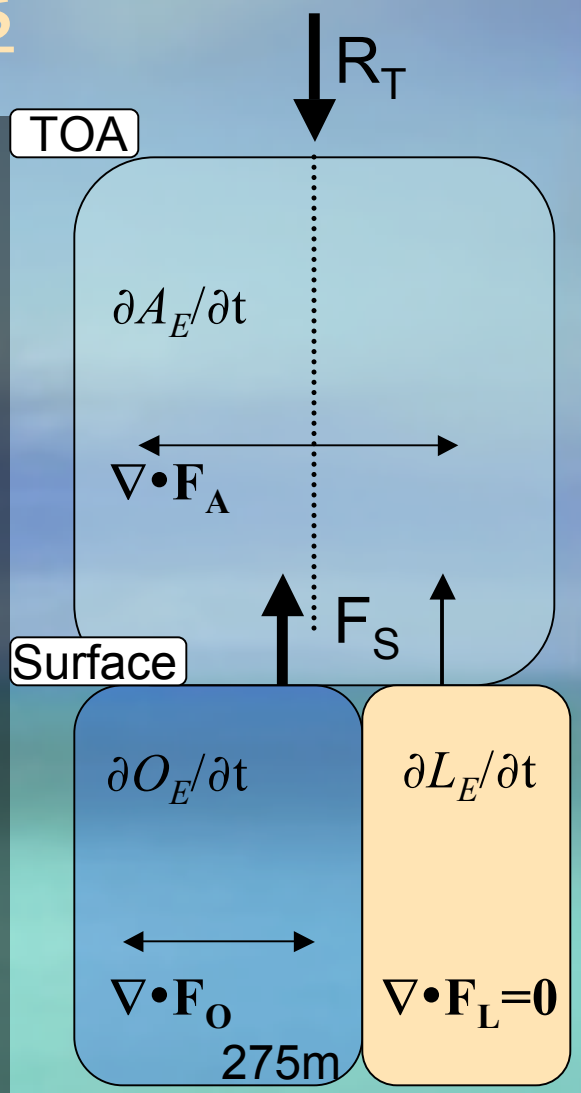
- Net ocean energy divergence can be inferred from residual of surface and ocean budgets per:

$$\nabla \bullet \mathbf{F_O} + F_S + \partial O_E/\partial t = 0$$

$$[O_E = \int T(z)\, C_w\, dz]$$

- Ocean to land energy transport can be calculated directly from reanalyses or inferred from satellite for annual means (as land tendency is small) per:

$$\overline{\mathbf{F_A}(ocean \rightarrow land)} = \overline{R_T(land)} + \overline{\frac{\partial A_E(land)}{\partial t}}$$



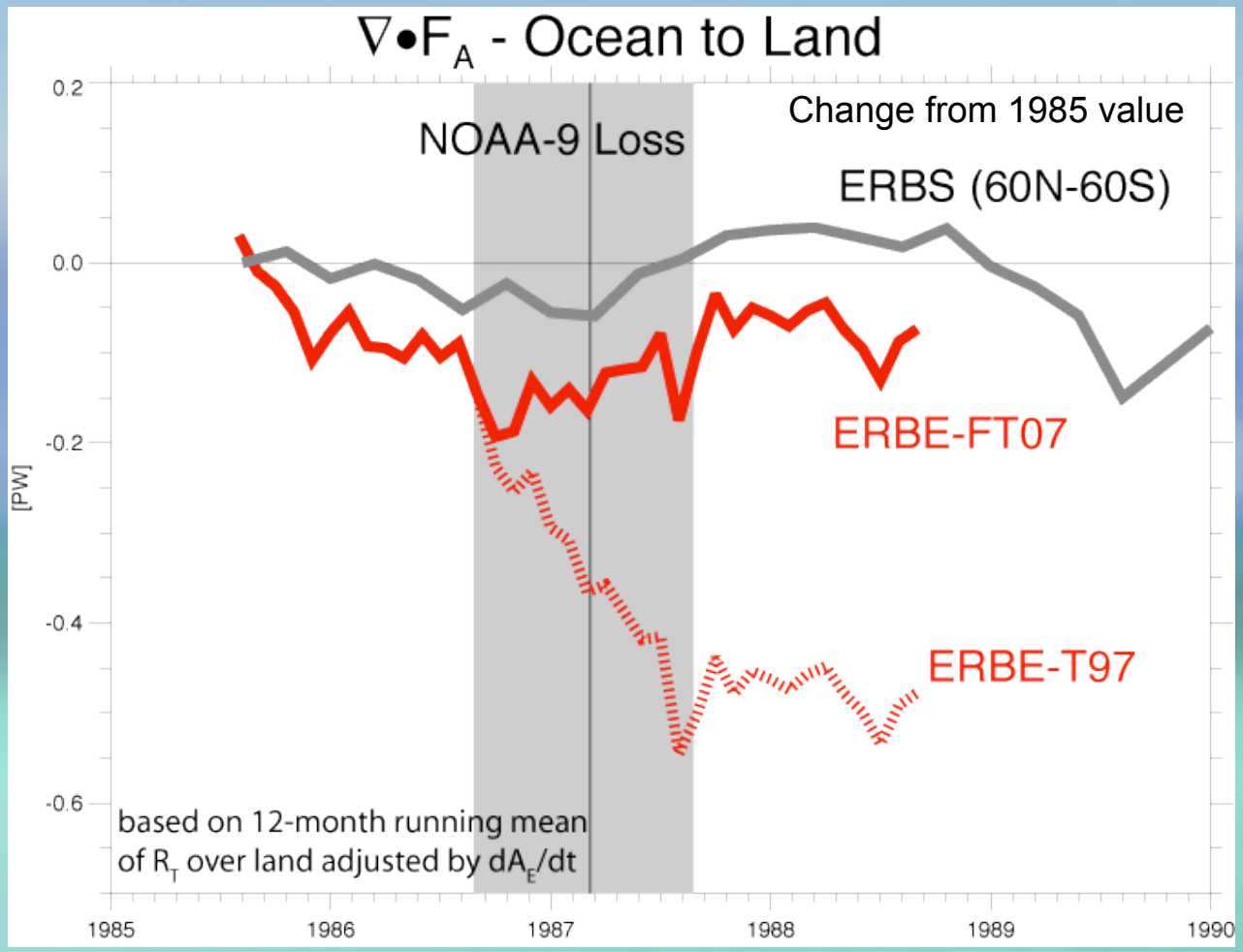
TOA Fluxes

- ERBE (Feb 1985 - Apr 1989)
  - 3 satellite configuration with 2 polar orbiting satellites and ERBS with a 72-day precessing orbit covering 60°N-60°S
  - Failure of NOAA-9 (afternoon crossing) in Feb 1987 left only a morning orbiter and imparted significant discontinuities to the ERBE fluxes
- CERES (Mar 2000-present)
  - Terra: single polar orbiting satellite supplemented with Aqua in Jul 2002 - here we use only the FM1 and FM2 retrievals. [TOASRB MODIS Edition2D Rev1]

ERBE Tuning

- Unadjusted, ERBE fields depict global mean R_T of several W m^{-2} which is unrealistic given $\partial O_E/\partial t$ (~0.0 PW, Levitus 2005)
- In Trenberth (1997) adjustments to albedo were made to address this imbalance and the discontinuity in *OLR* and R_T due to the loss of NOAA-9.
- But… we now find that *OLR* adjustment must distinguish between land and ocean due to their distinct diurnal cycles…
- We use ERBS as a guide.

ERBE Tuning



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

This also has the beneficial effect of yielding a more consistent OLR record with ERBS.

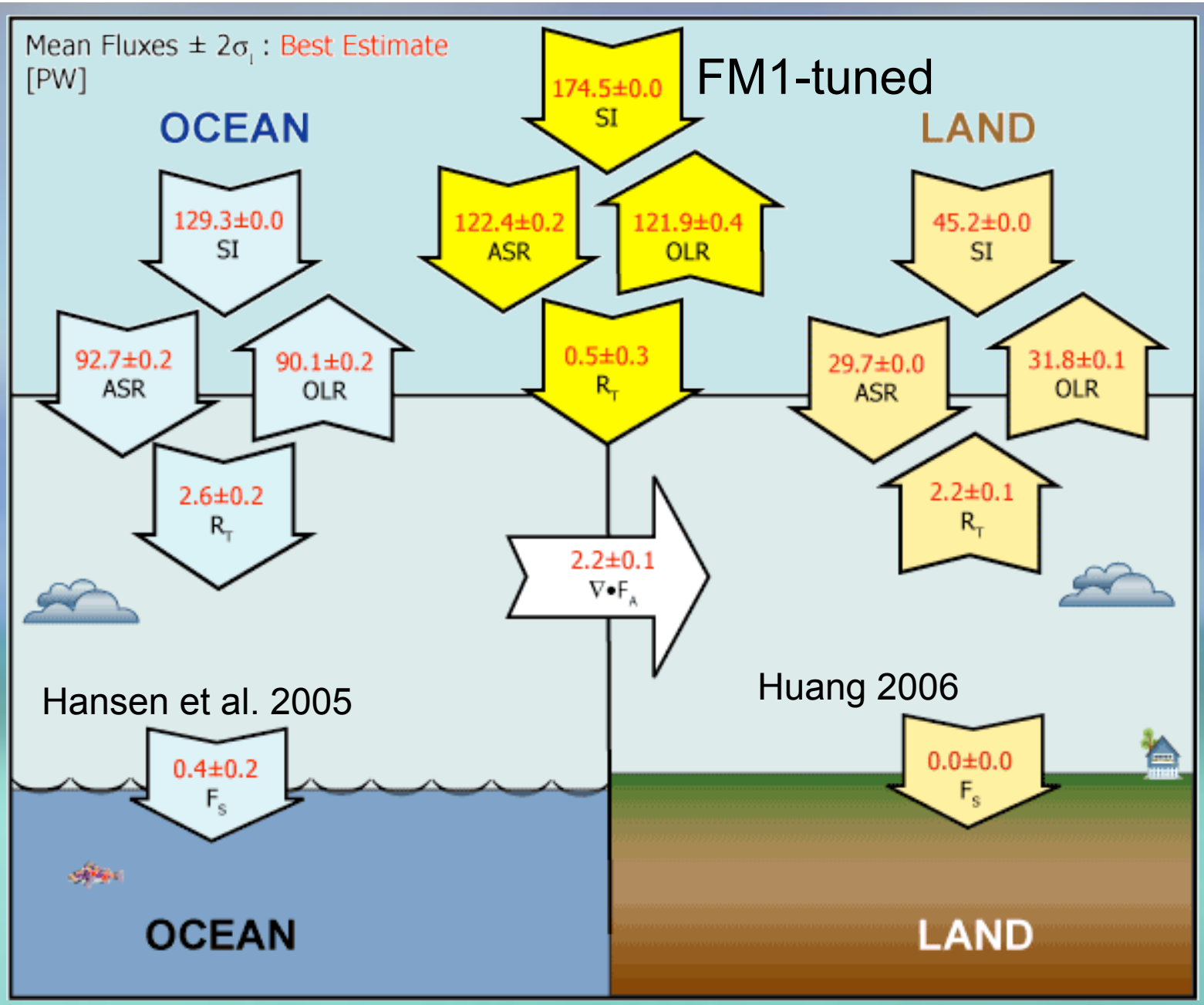
CERES Tuning

- Unadjusted, CERES fields depict a net TOA flux of ~6.4 W m^{-2} which is unrealistic given $\partial O_E/\partial t$ during CERES ~0.5 PW (e.g. Willis et al. 2003).

- 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).

Global R_T error budget: Wielicki et al. (2006)

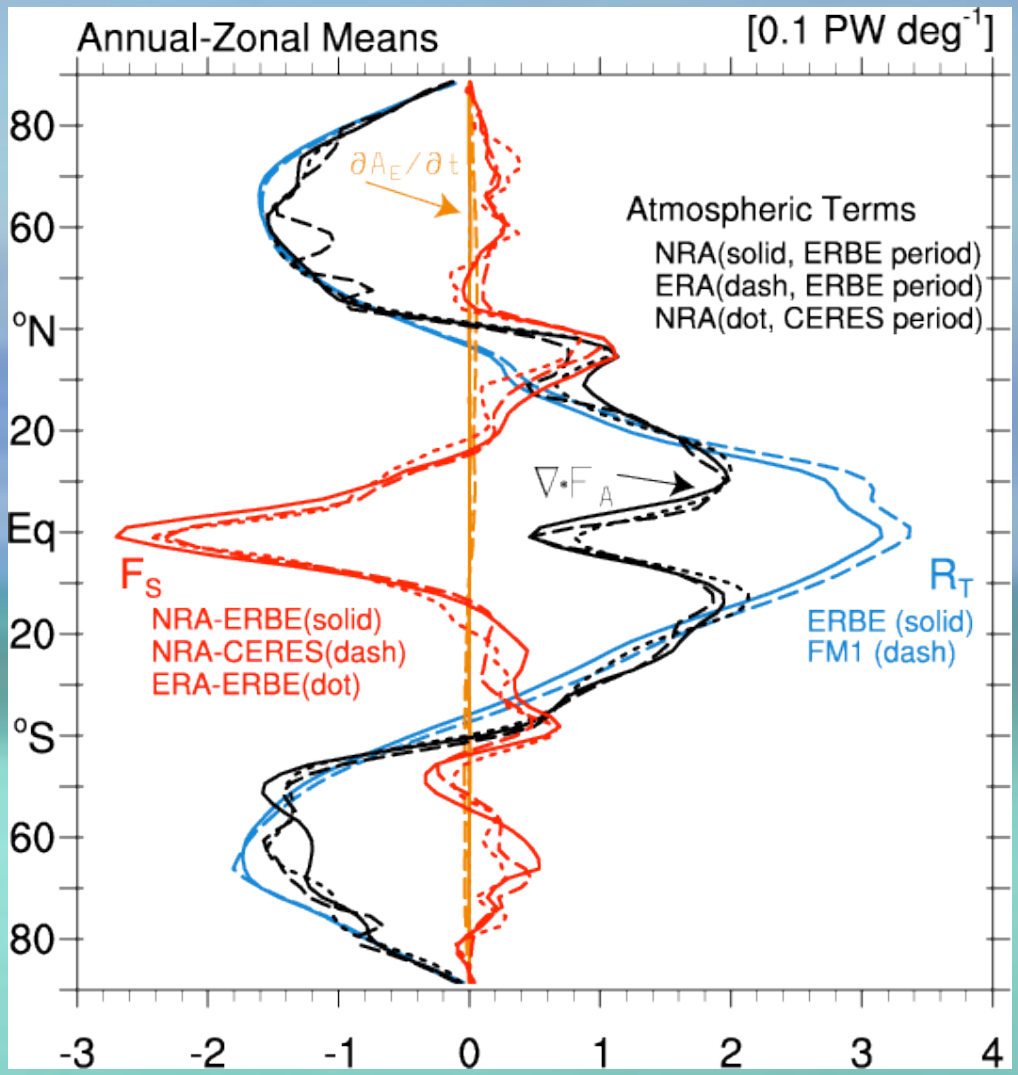
Error Source (W m^{-2})	SW	LW	Net
Total Solar Irradiance (1361 vs 1365)	+1.0	0.0	+1.0
Absolute Calibration	1.0	1.0	2.0
Spectral Correction	0.5	0.3	0.8
Spatial Sampling	<0.1	<0.1	<0.1
Angle Sampling	+0.2	-0.1	+0.1
Time Sampling (diurnal)	<0.2	<0.2	<0.2
Reference Altitude (20 km)	0.1	0.2	0.3
Twilight SW 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



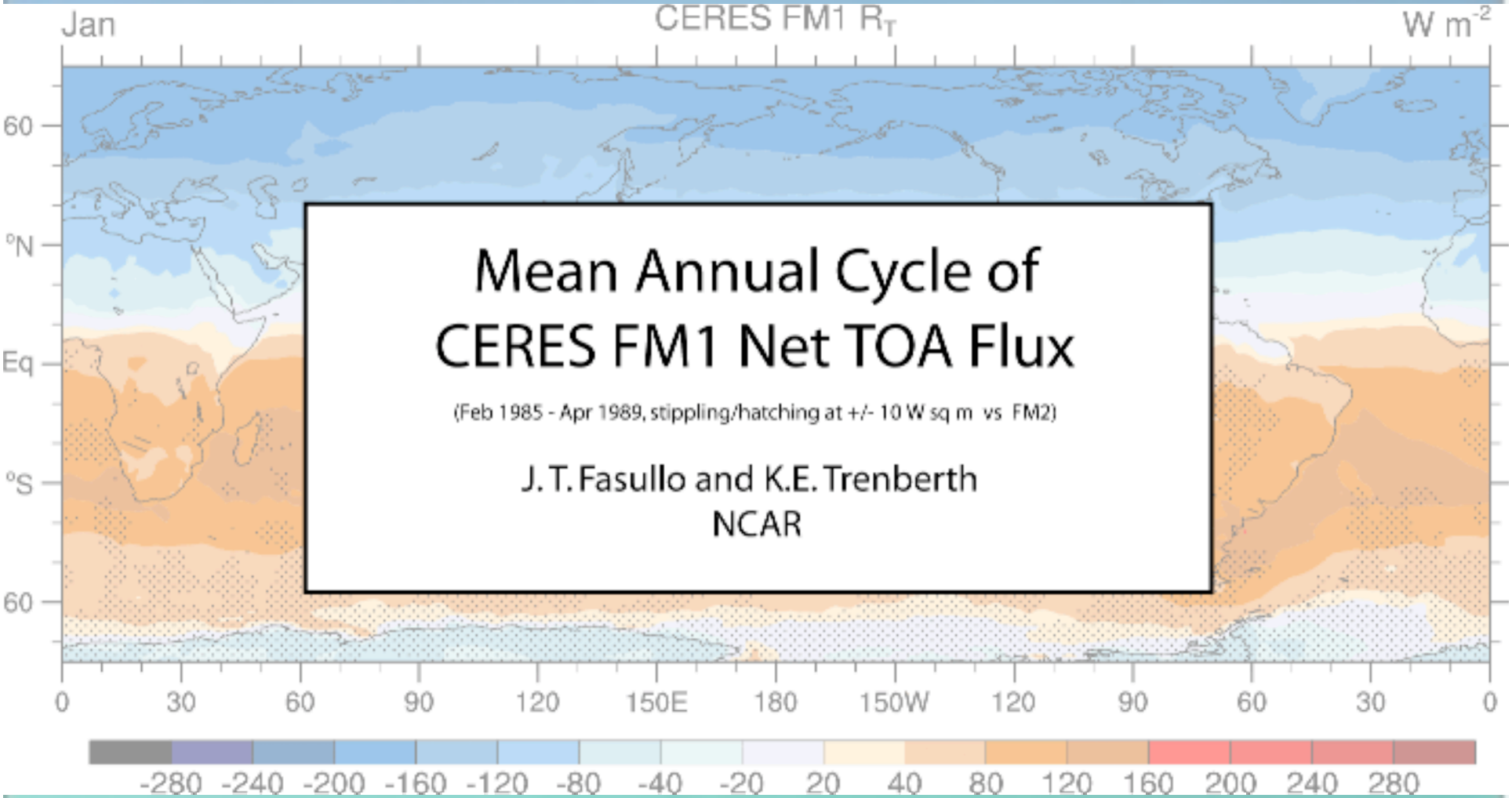
CERES period March 2000 to May 2004

Zonal-Annual Mean

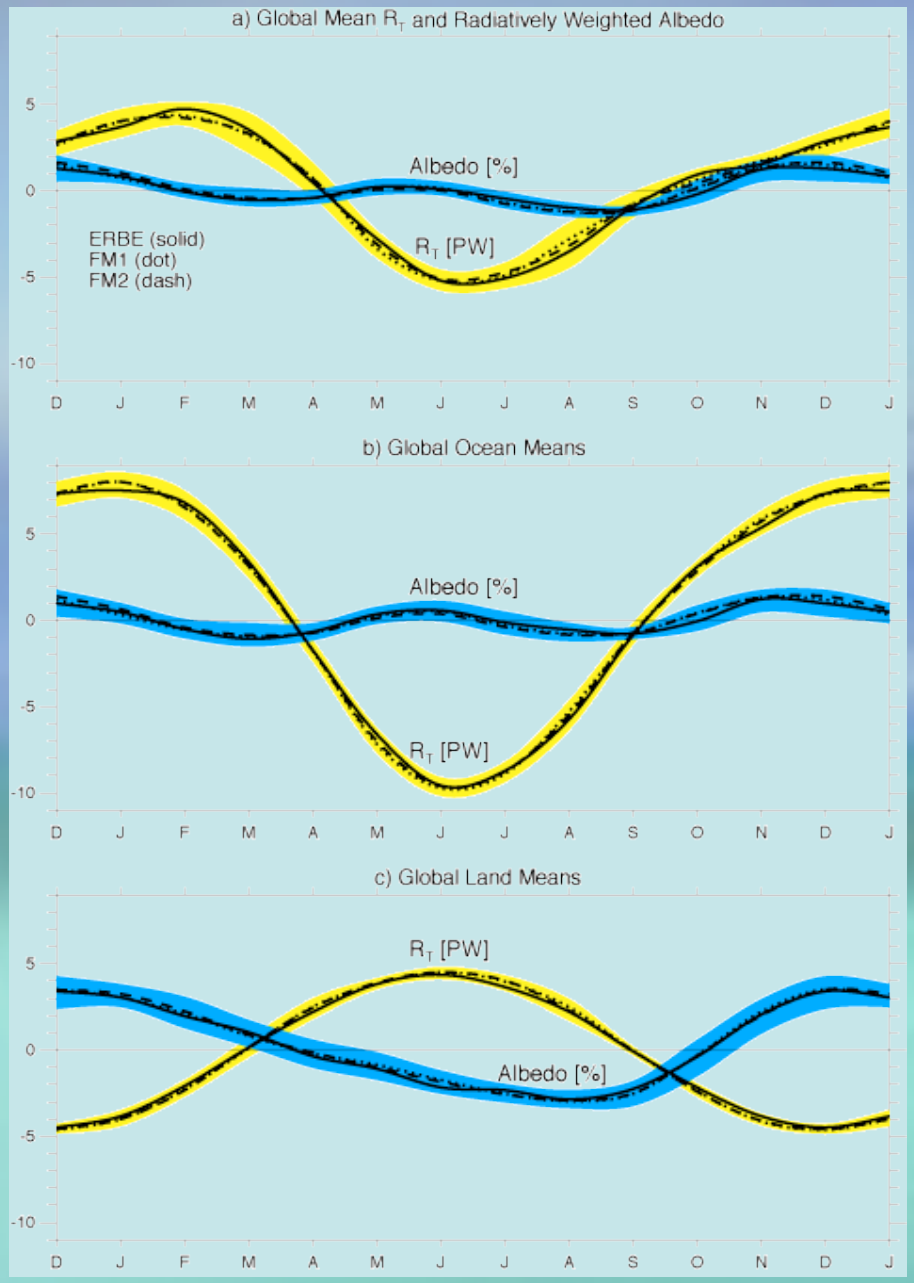
- R_T matches our idealized view - Large ERBE-CERES differences in the Tropics (Wong et al. 2006)
- F_S (ocean) balances R_T only in the deep Tropics. It is the atmosphere that mainly balances R_T poleward of 10°
- $R_T \sim \nabla \bullet \mathbf{F}_A$ poleward of 40° where mean ocean transport is very small



Annual Cycle of R_T (FM1 vs FM2)



Mean annual cycles of albedo and R_T



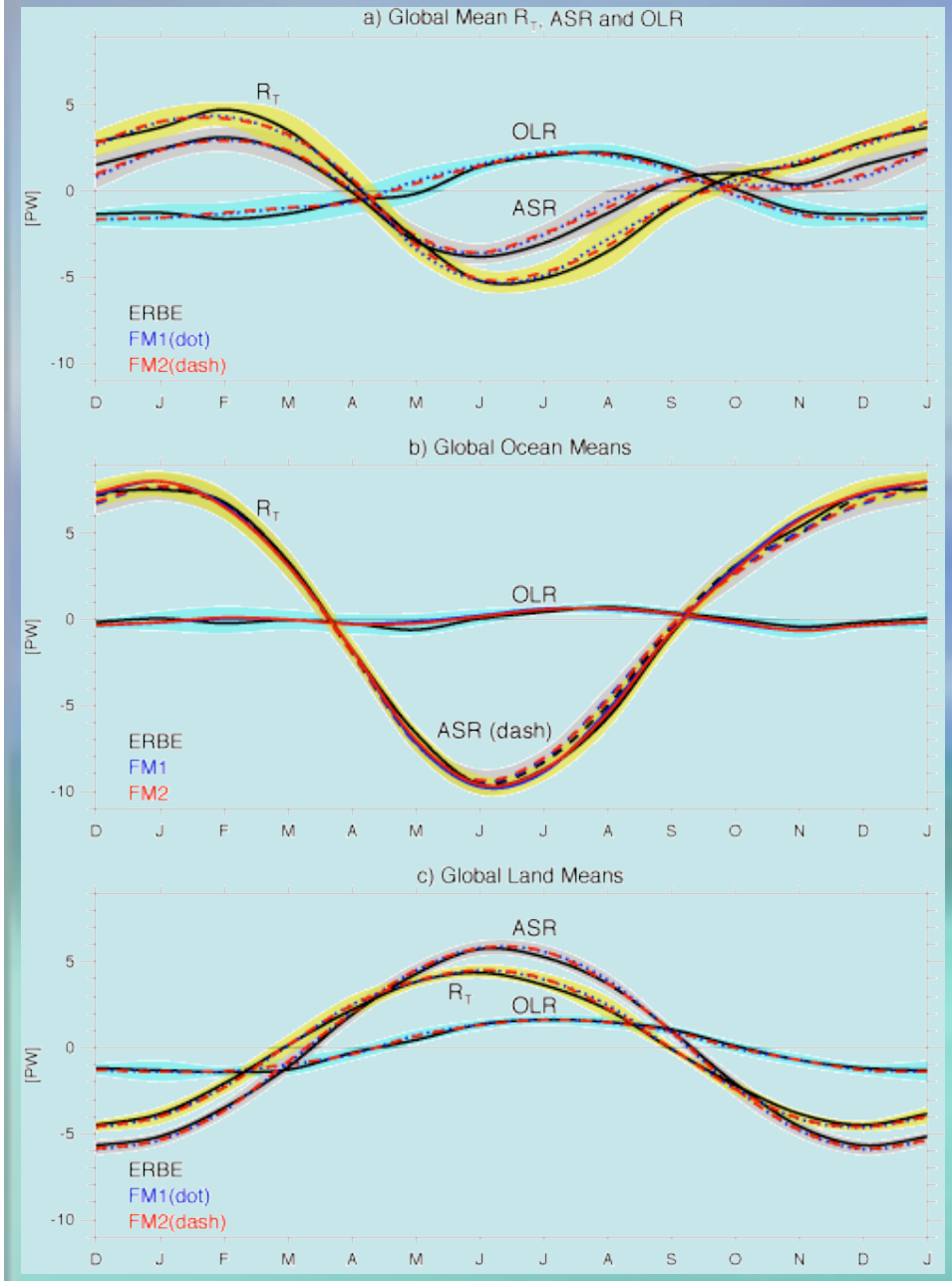
Global

Global-ocean

Global-land

where shading is $\pm 2\sigma$

ASR, OLR, and R_T



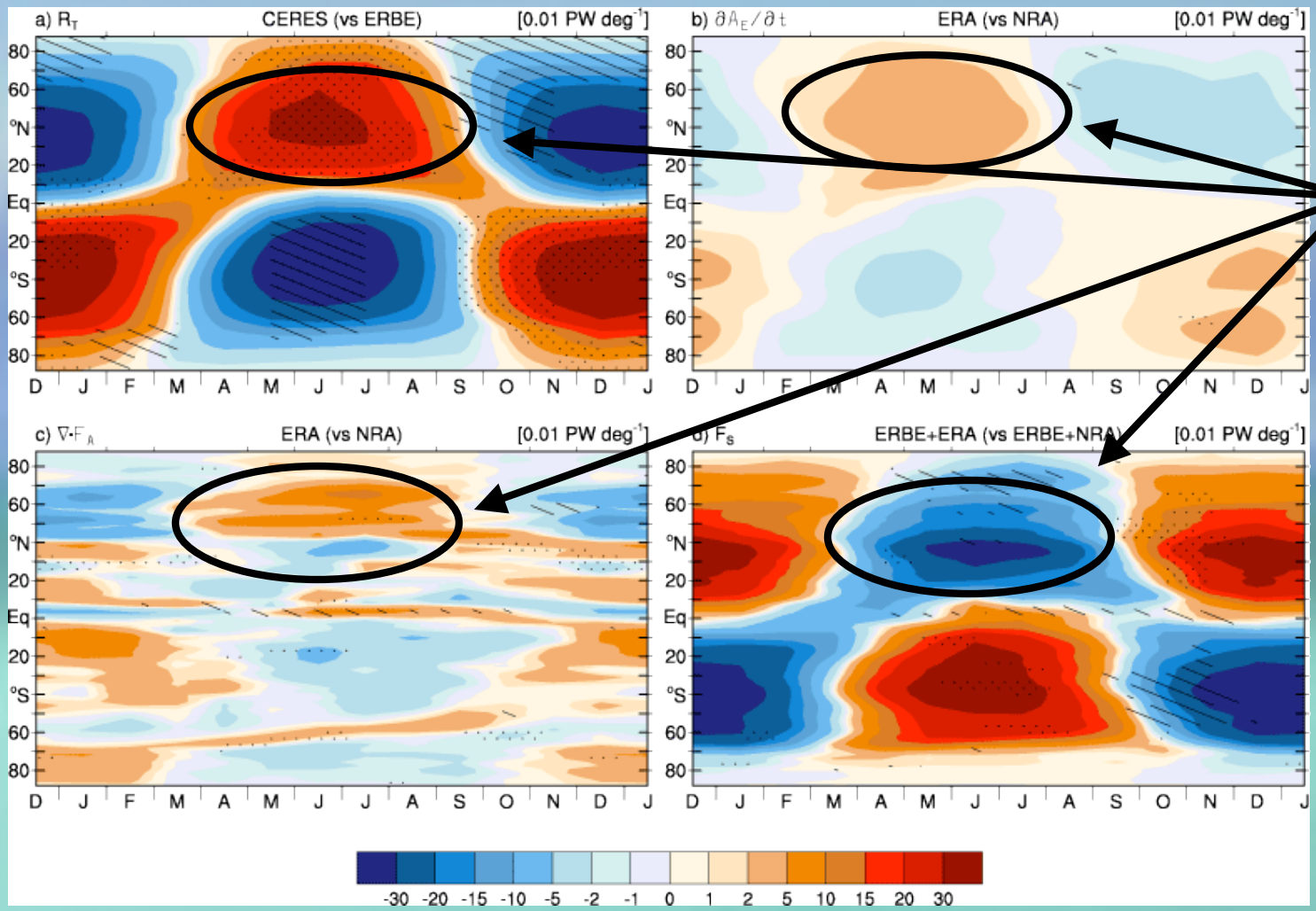
Global

Global-ocean

Global-land

where shading is $\pm 2\sigma$

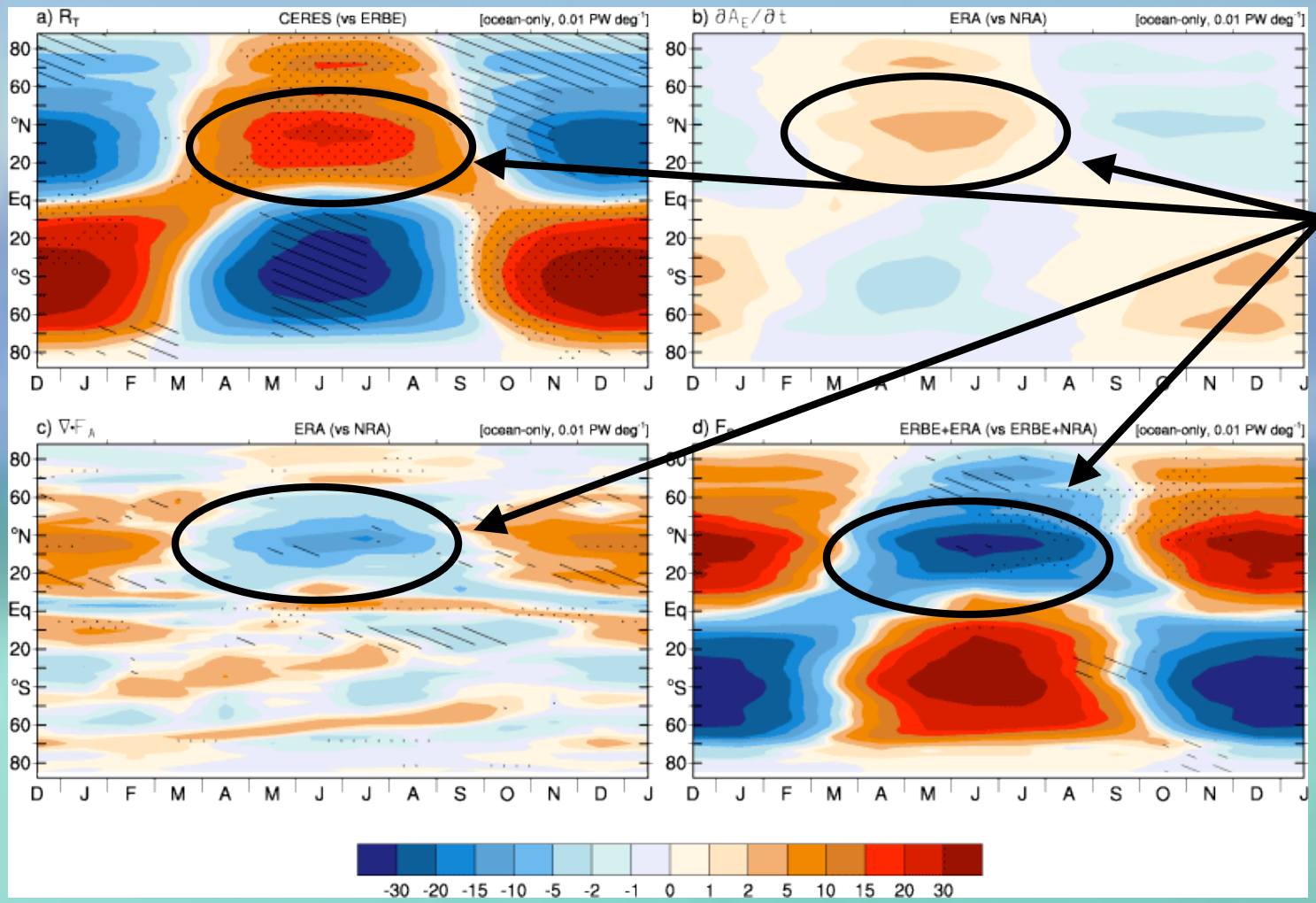
Zonal Mean Budgets and Balances: Global



First order balance is between R_T and F_S.

Globally, the atmosphere plays the role of moderating the impact of R_T on F_S.

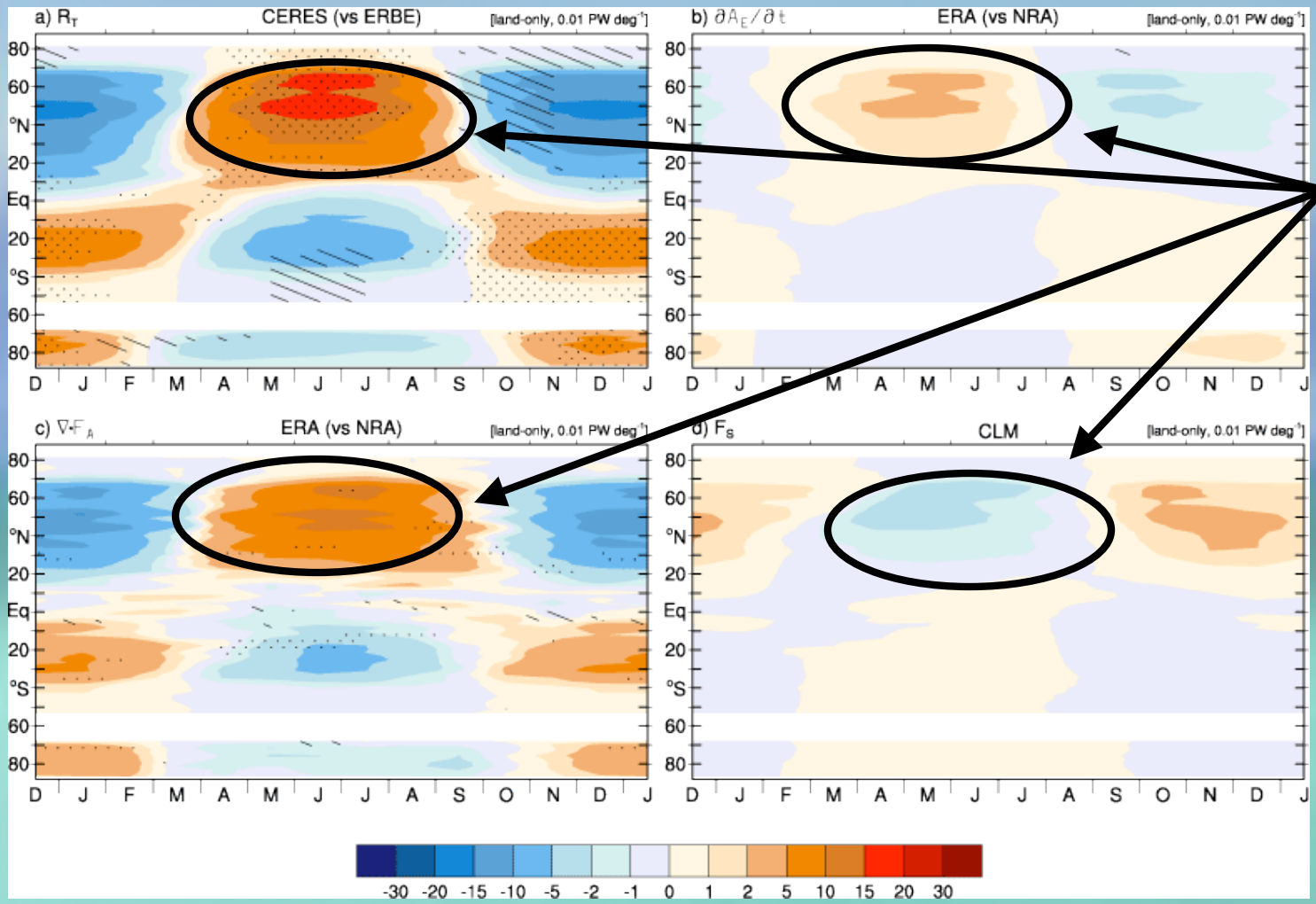
Zonal Mean Budgets and Balances: Ocean



Balance over ocean is again between R_T and F_S.

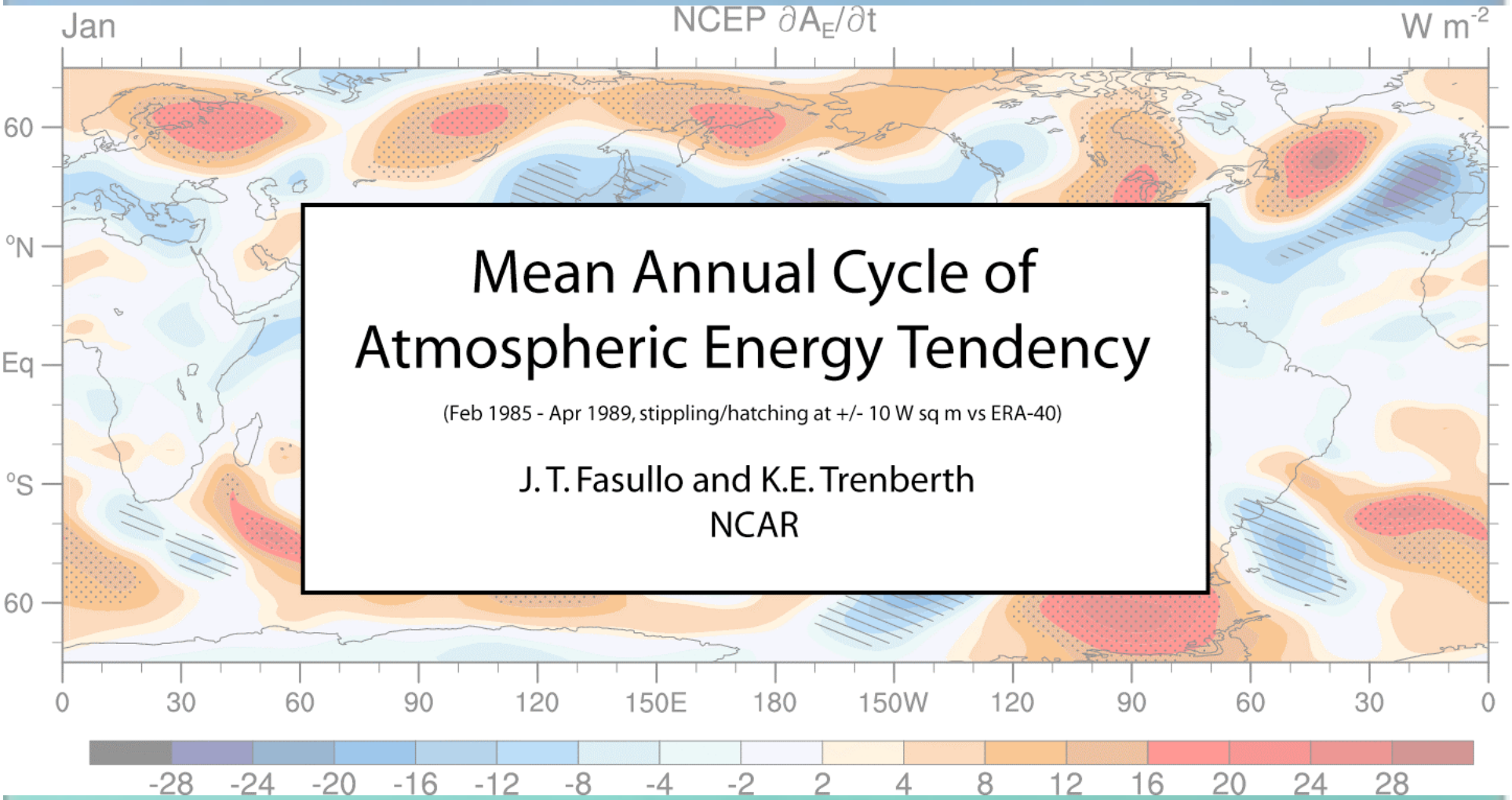
…but…the atmosphere's impact on F_S is mixed.

Zonal Mean Budgets and Balances: Land



Balance over land is between R_T and $\nabla \bullet \mathbf{F_A}$, not F_S, which is small.

Annual Cycle of Atmospheric Tendency



Mean Annual Cycle of Atmospheric Energy Tendency

(Feb 1985 - Apr 1989, stippling/hatching at +/- 10 W sq m vs ERA-40)

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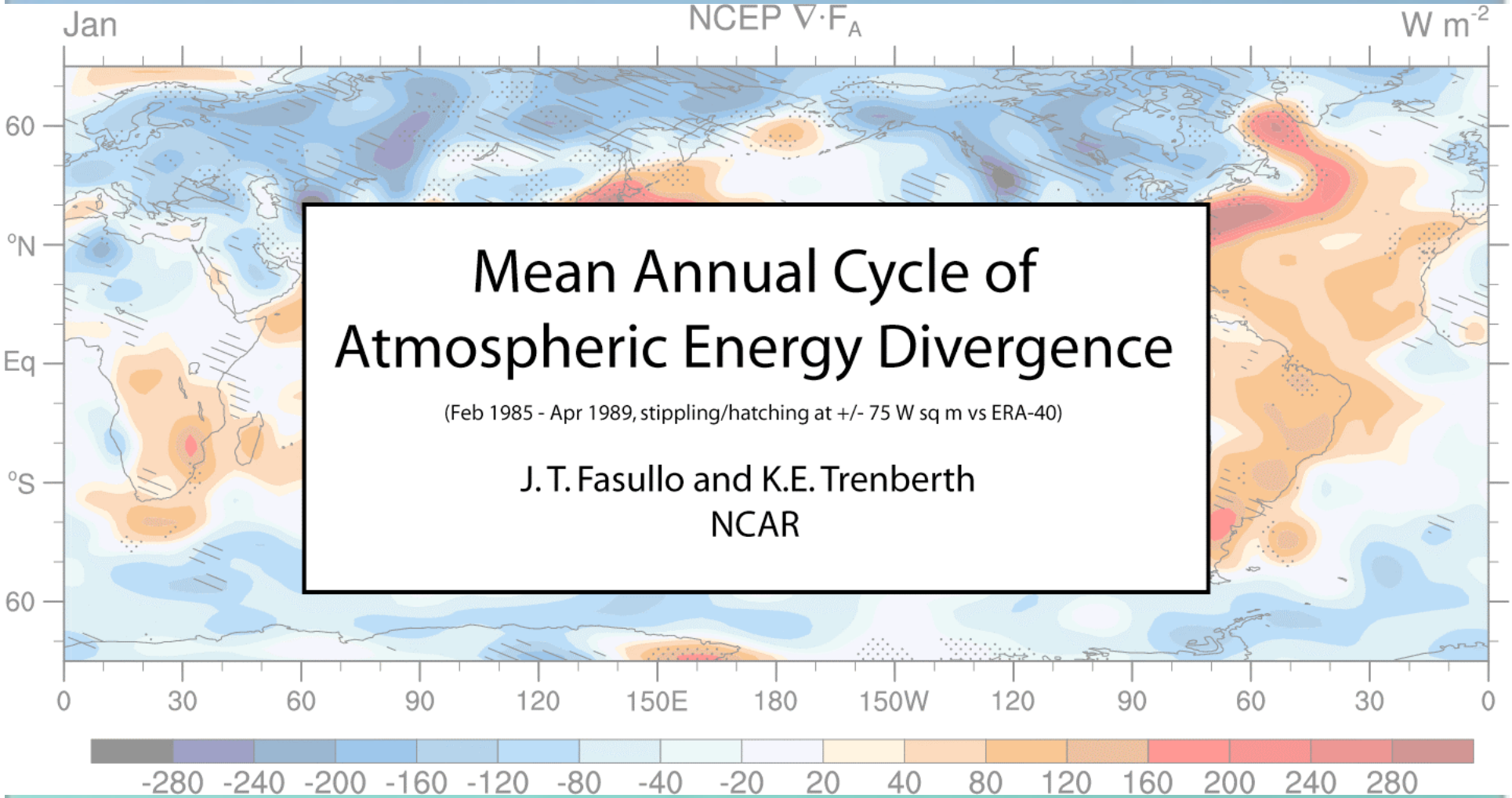
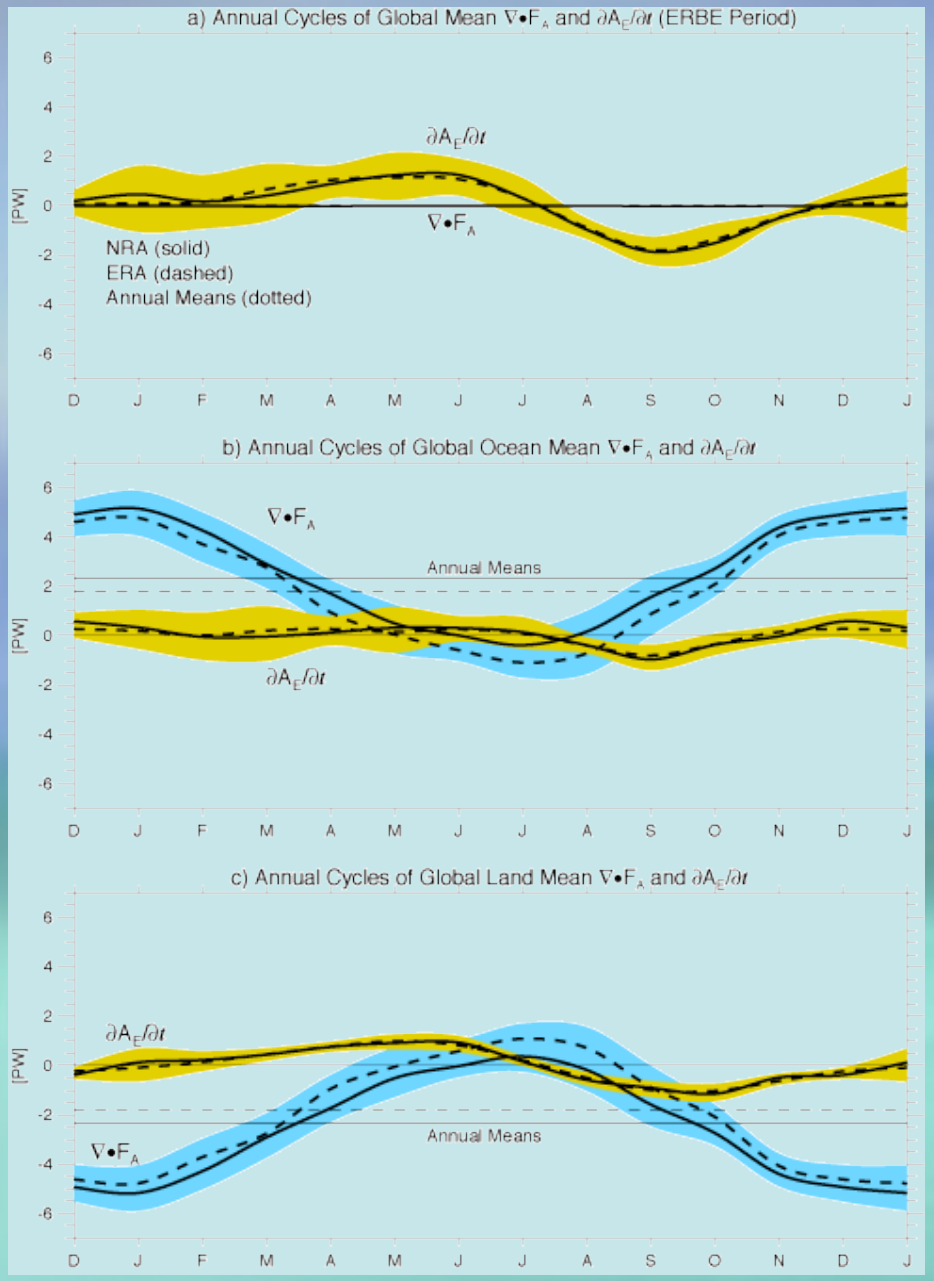
Annual Cycle of Atmospheric Divergence



$\nabla \bullet F_A$ and $\partial A_E/\partial t$



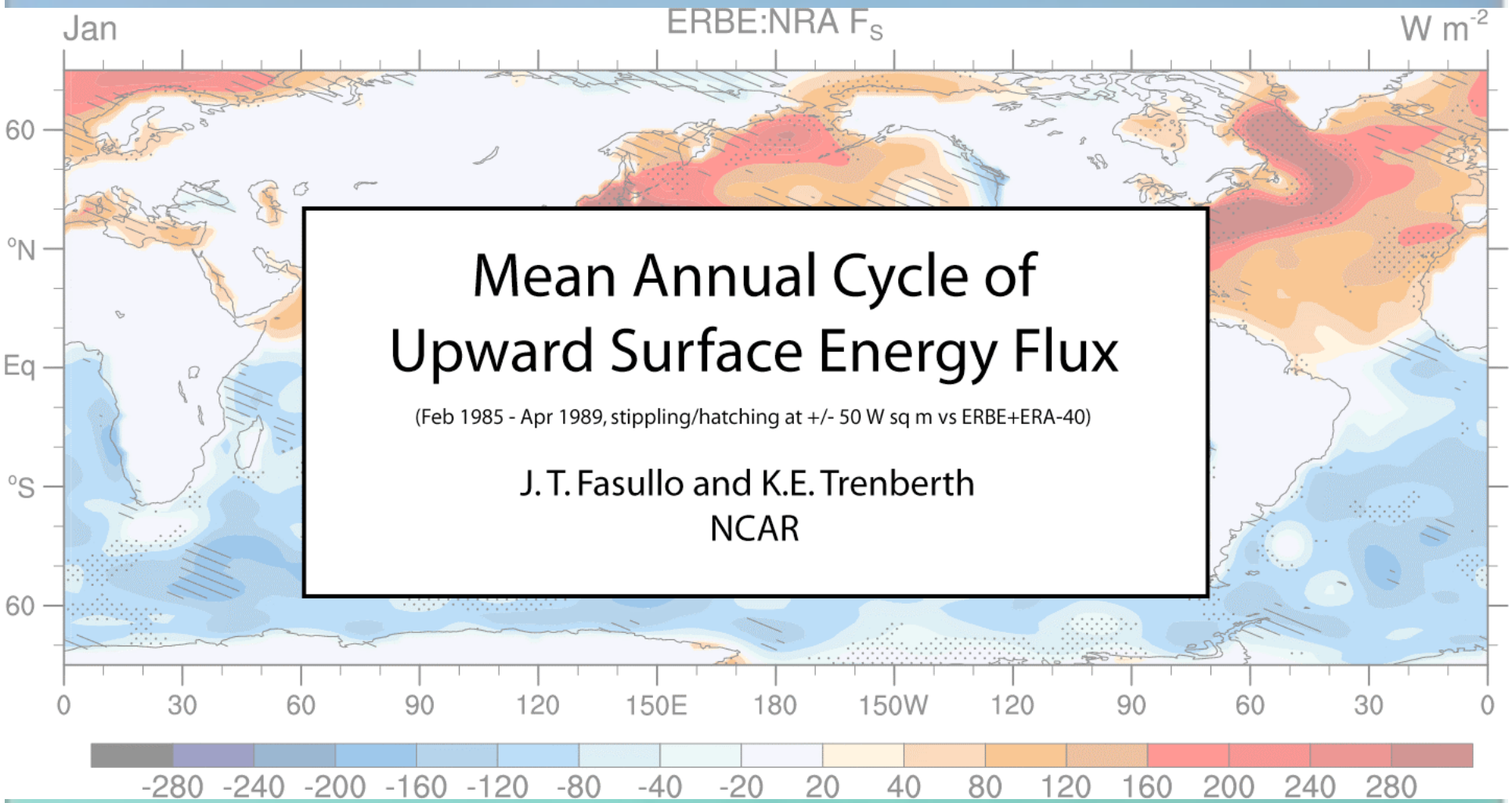
Global

Global-ocean

Global-land

where shading is $\pm 2\sigma$

Annual Cycle of upward surface flux (F_S)



Mean Annual Cycle of Upward Surface Energy Flux

(Feb 1985 - Apr 1989, stippling/hatching at +/- 50 W sq m vs ERBE+ERA-40)

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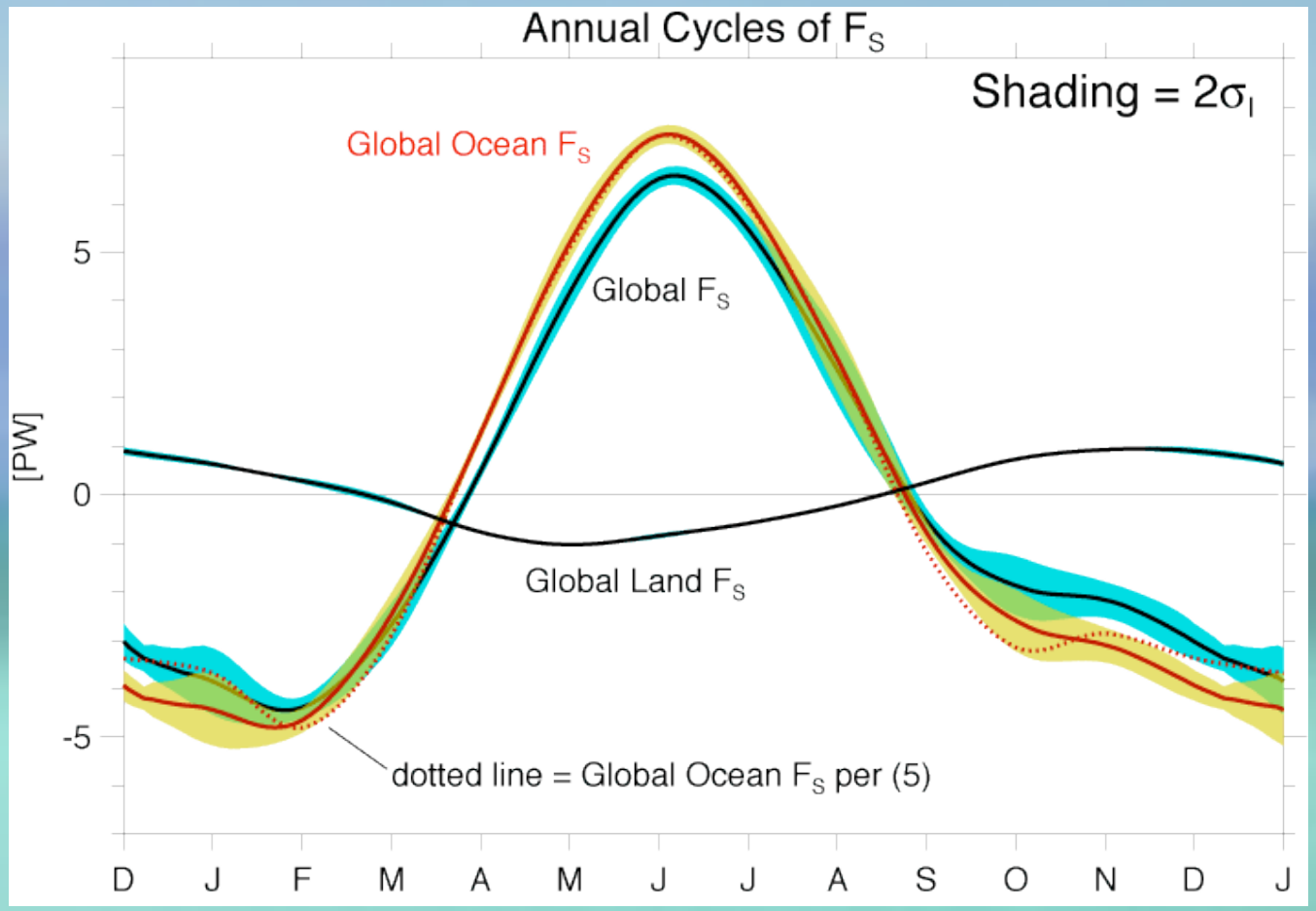
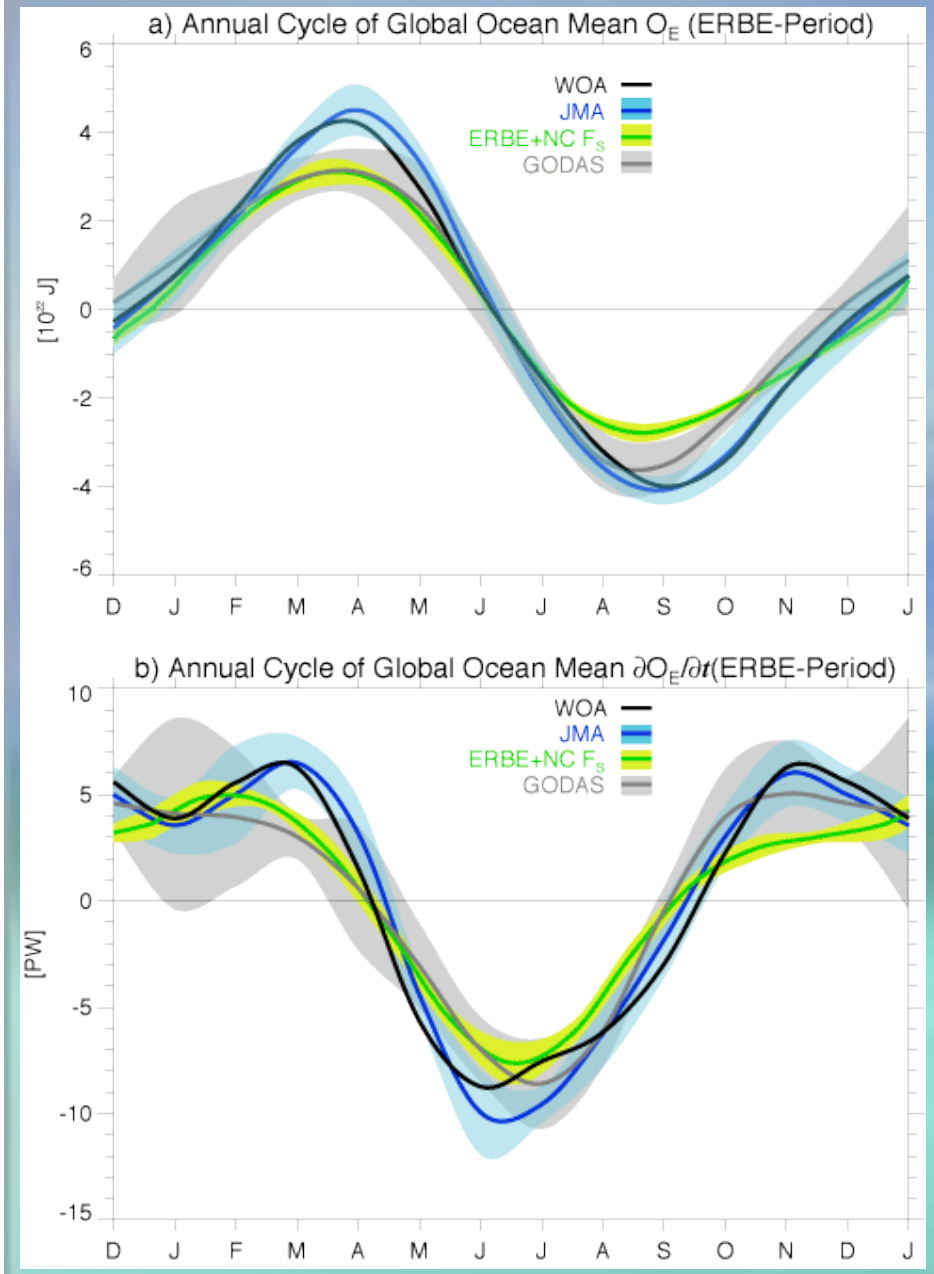
Annual cycle of F_S



F_S over land (here from CLM) varies little from year to year.

The presence of land in the NH augments the annual cycle of R_T (via OLR) and F_S over ocean (via ocean->land transport).

O_E and dO_E/dt



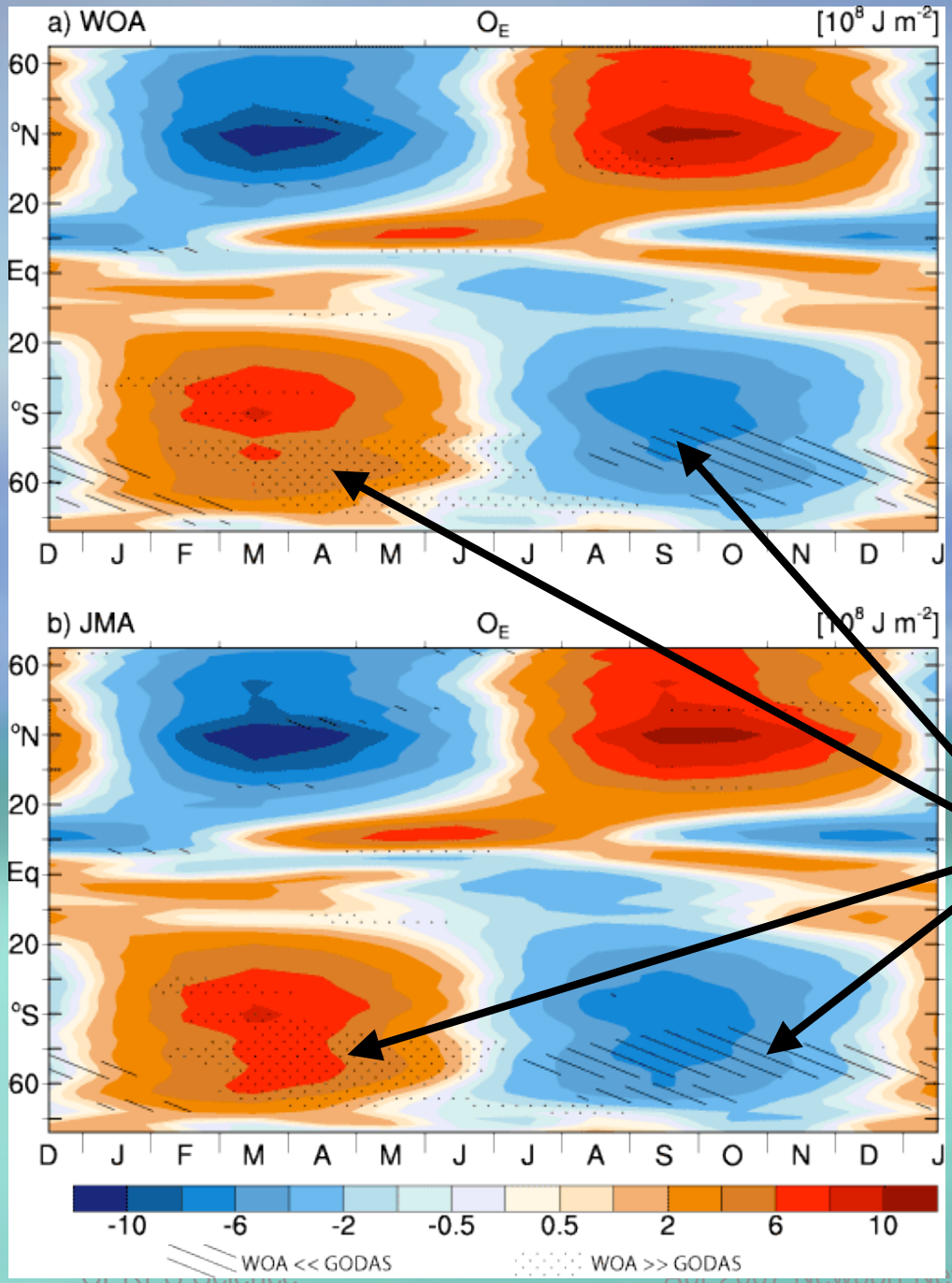
WOA,GODAS, JMA, and F_S

F_S has been integrated in time to give O_E' (spread includes ERA estimate)

O_E timeseries have been differenced to provide dO_E/dt

In situ data show an excessive annual cycle.

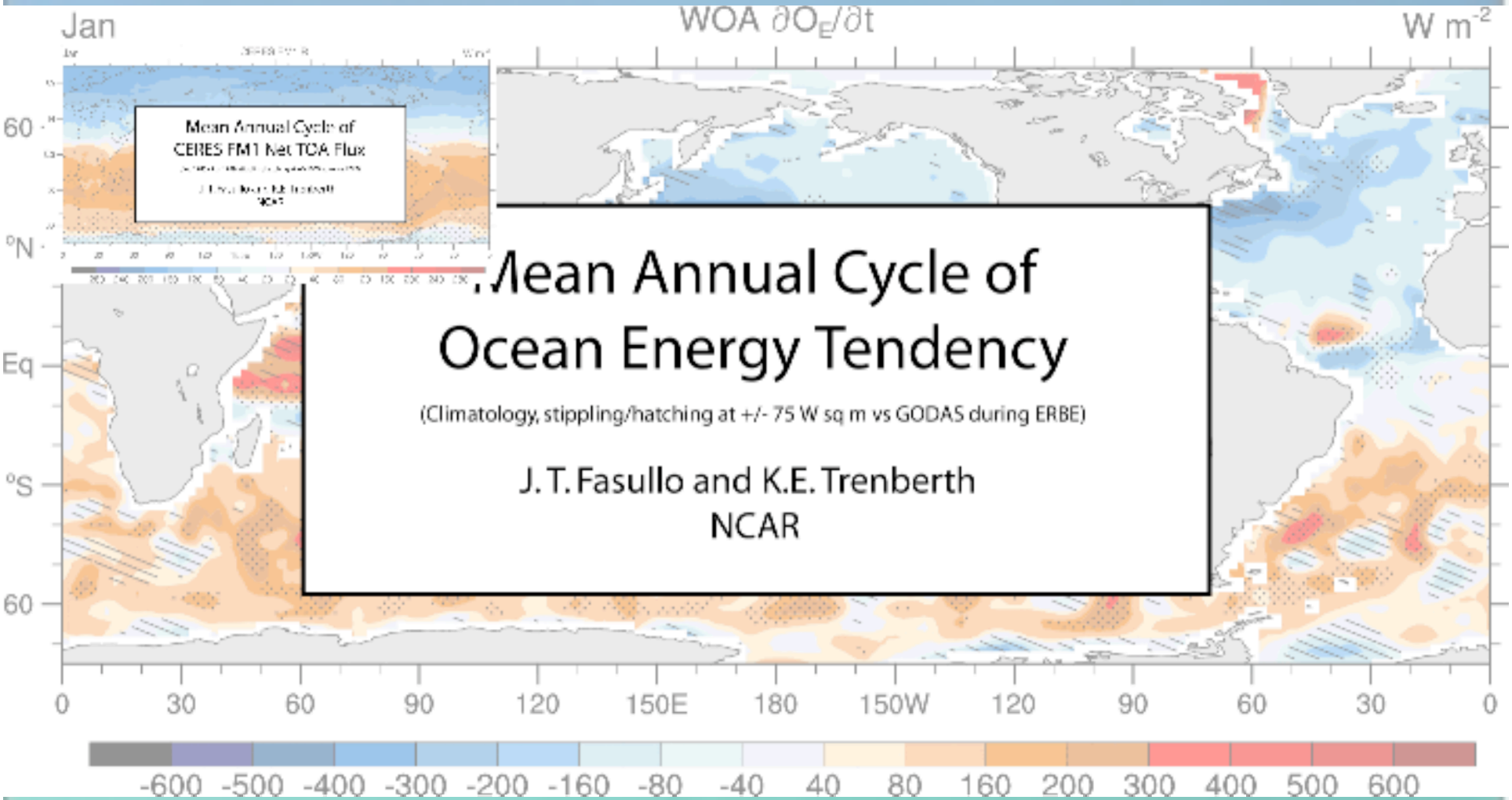
Zonal Mean O_E



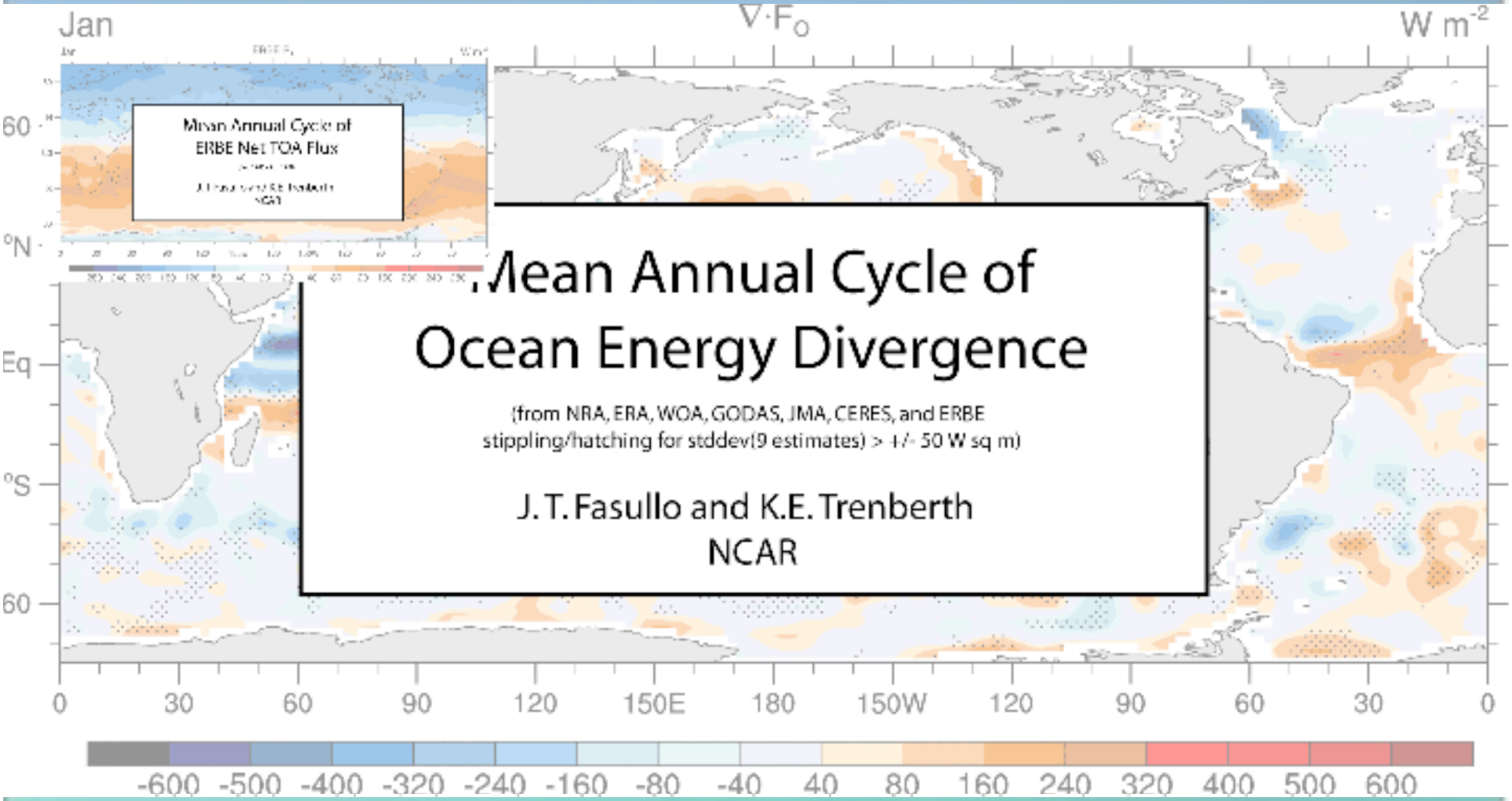
Departures from annual mean

Differences from GODAS exceeding ±2σ over southern oceans - regions where few obs exist

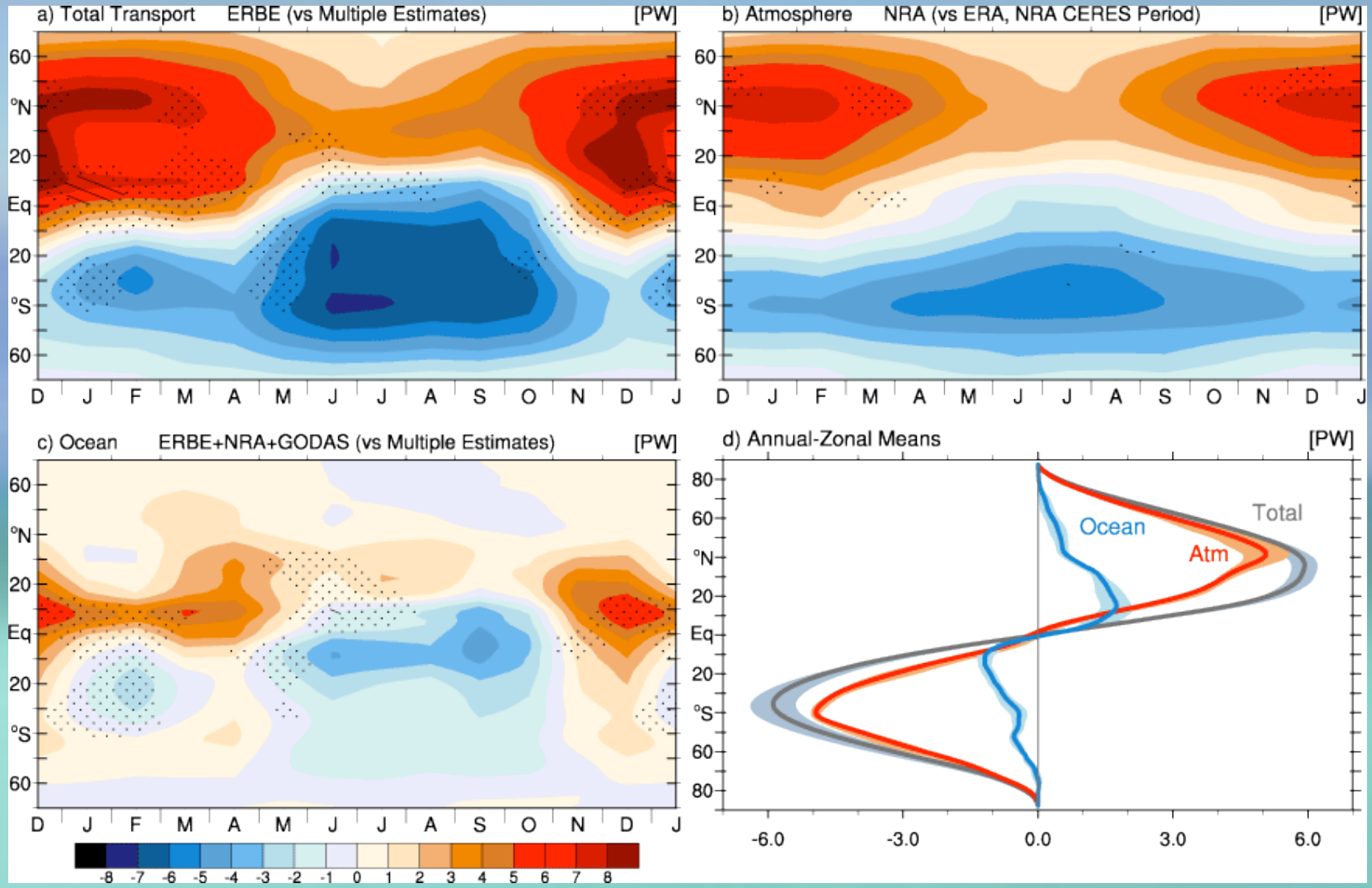
Annual Cycle of $\partial O_E/\partial t$

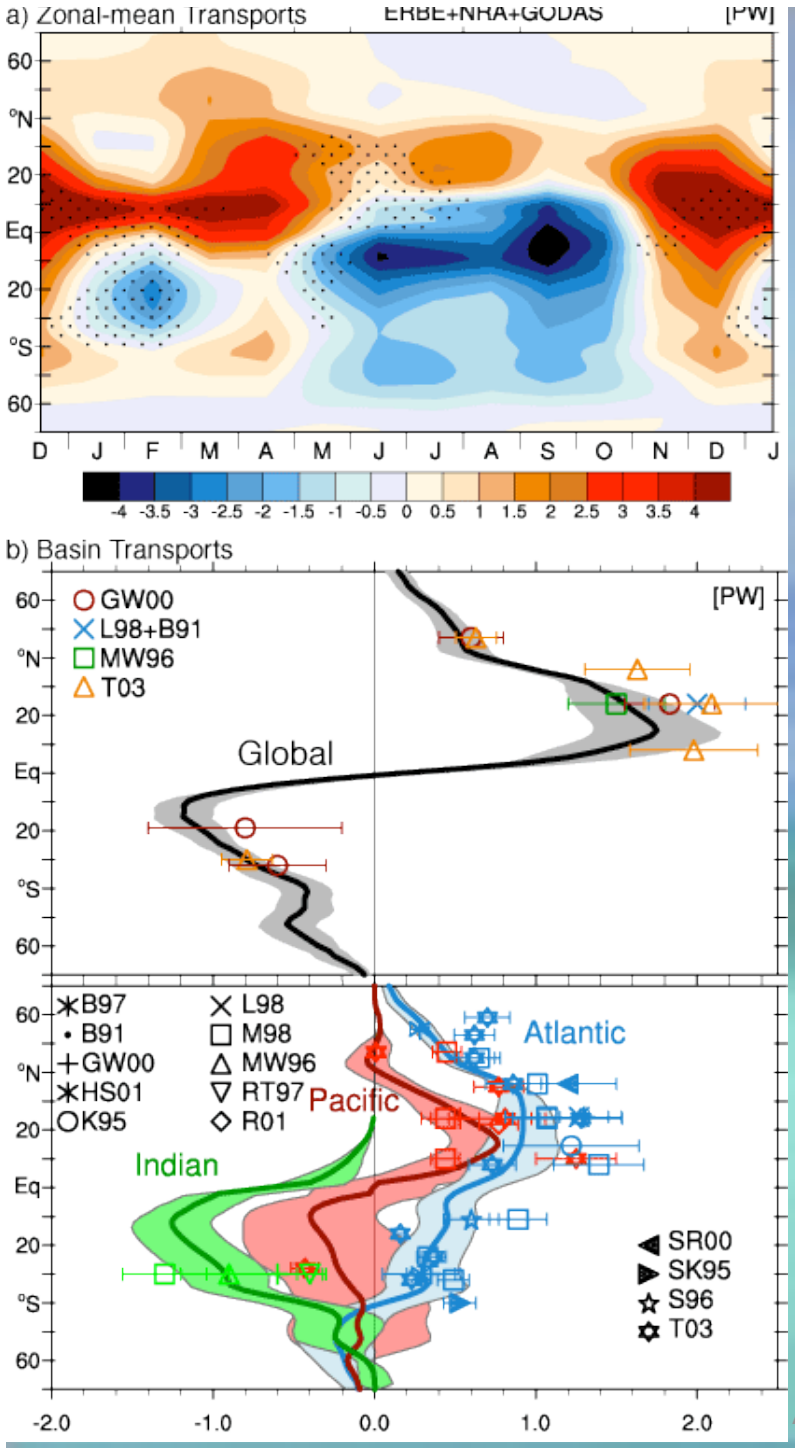


Annual Cycle of $\nabla \bullet F_O$



Poleward Transports



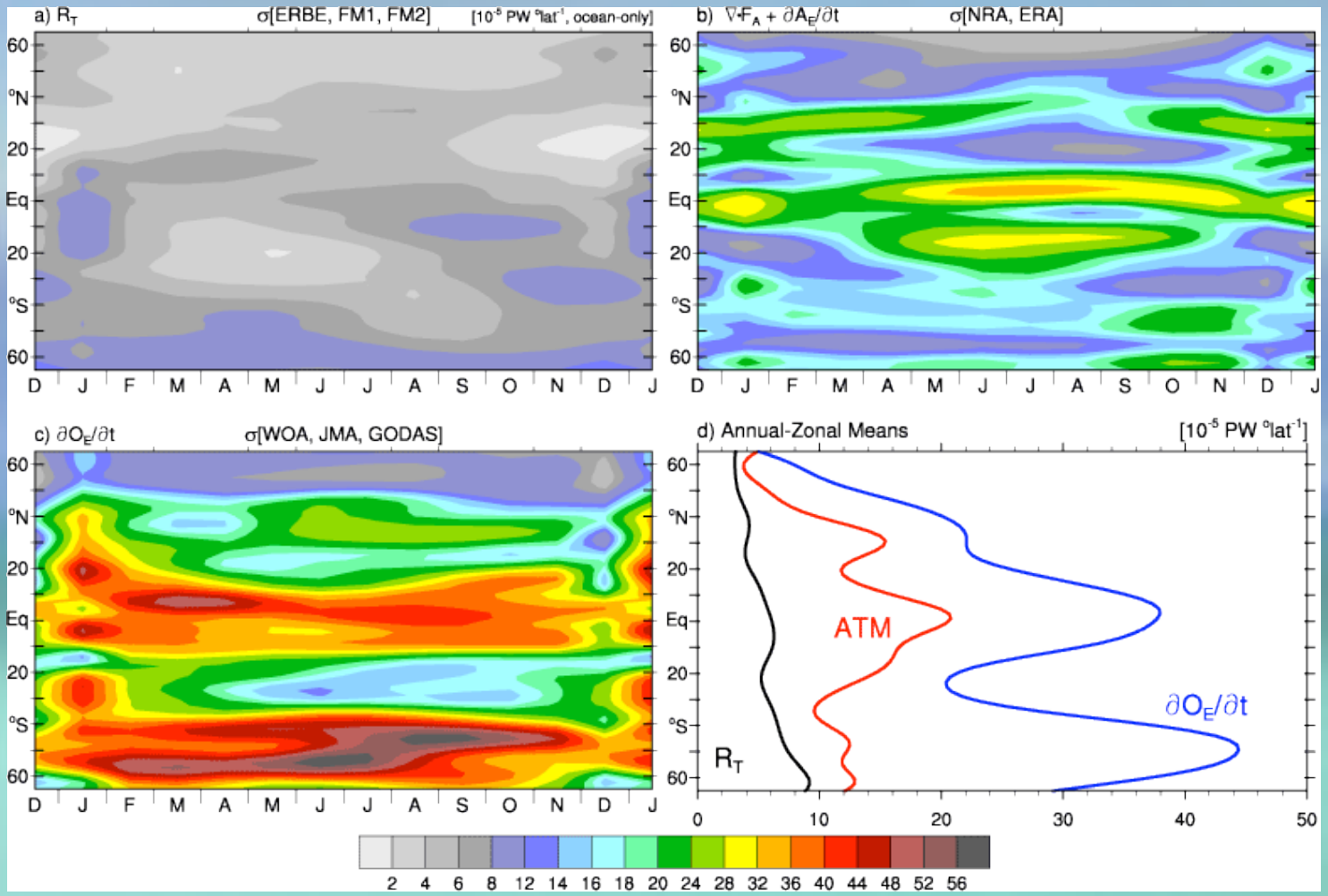


Ocean Transports

- Annual cycle
- Strongest in winter
- Limited in meridional extent
- >> annual mean

- Global Annual mean values are in close agreement with observations-in the Atlantic are somewhat larger than in our estimates - not clear which is correct - it is clear that some of the obs are wrong

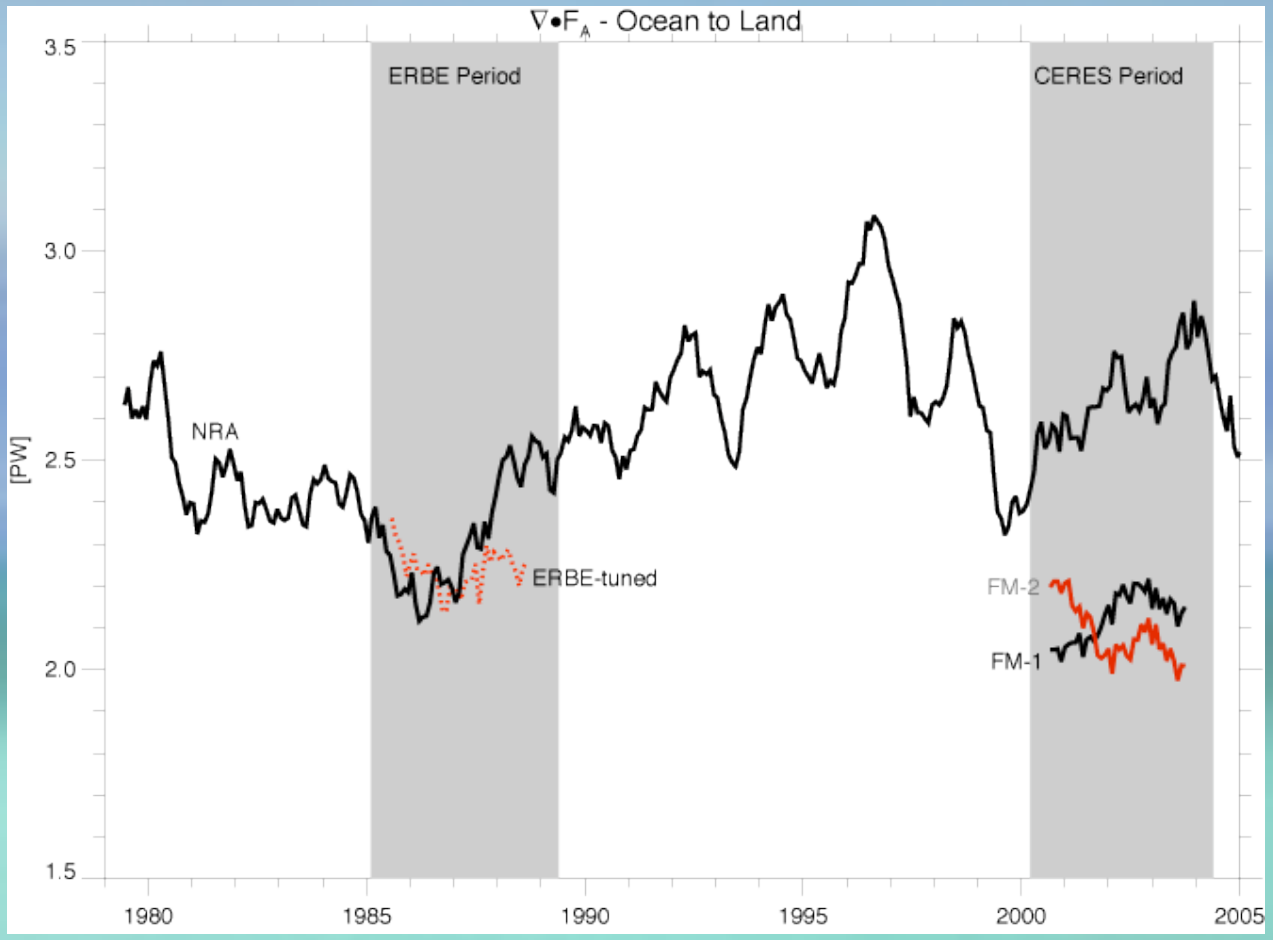
Sources of Error in $\nabla \bullet F_O$



Each caption is the zonal mean standard deviation among the estimates.

Tropical and southern hemisphere changes in energy content dominate.

Net ocean to land energy transport



12-month running means for ERBE and CERES R_T over land with NRA $\partial A_E/\partial t$

Conclusions (1)

The mean and annual cycle of the budgets have been quantified for both the ERBE and CERES periods.

Uncertainties associated with the limited span of observations have been estimated. The annual cycle is larger than the uncertainty in most terms.

The distinct natures of the balances between R_T, $\partial A_E/\partial t$, and $\nabla \bullet F_A$ for land and ocean regions are identified.

Compared with inferences from F_S, the annual cycle of $\partial O_E/\partial t$ based on *in situ* data is excessive. GODAS suggests that the largest errors in WOA and JMA exist in the SH.

Conclusions (2)

An observational estimate of the mean and seasonal cycle of ocean energy divergence has been presented.

Estimates of the poleward energy transport in the atmosphere and ocean have been derived. These estimates represent substantial refinement to previous estimates and are more in line with WOCE estimates.

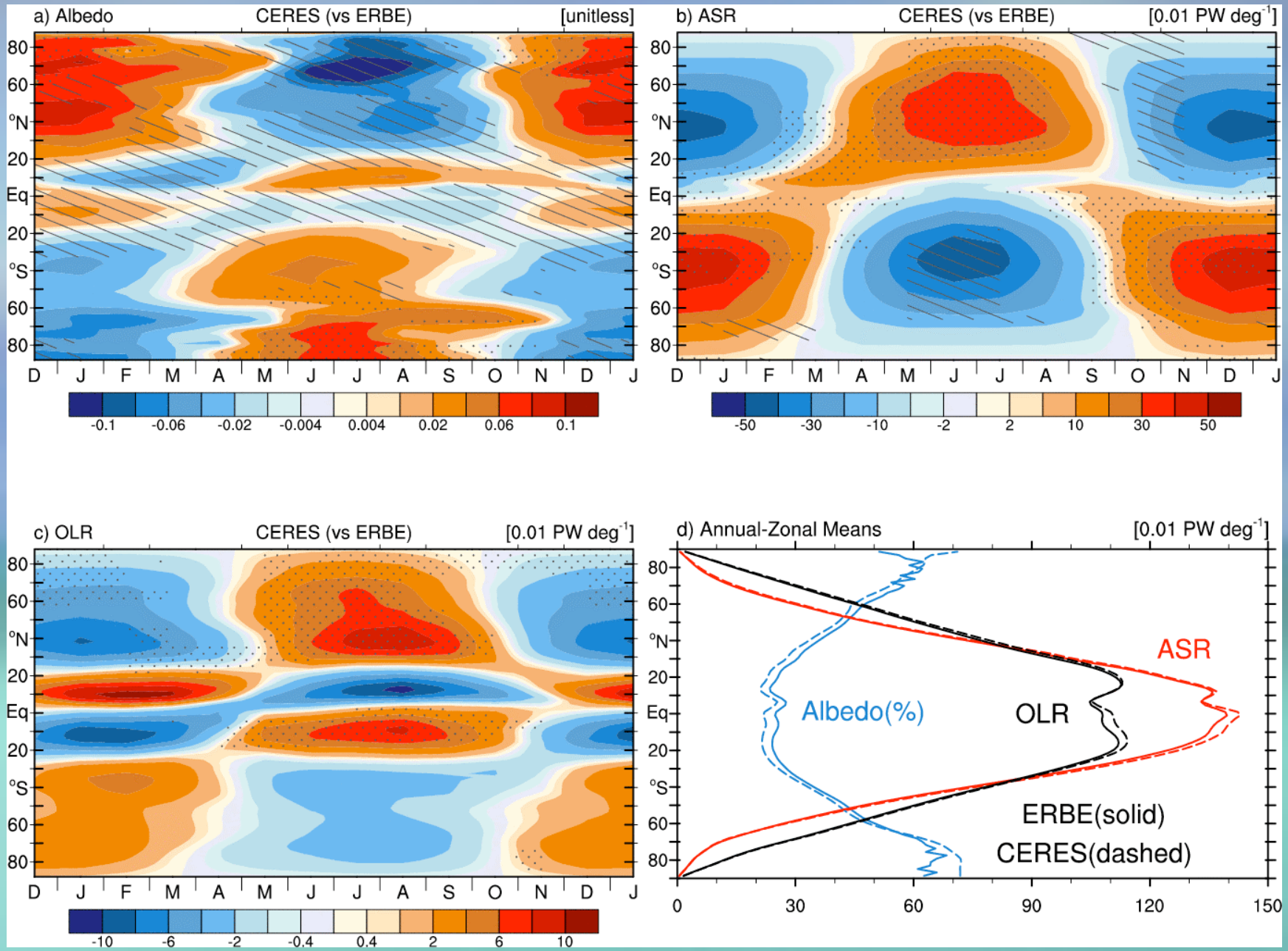
An uncertainty analysis suggests that ocean temperature estimates exist as the largest uncertainty in the divergence calculation and for the energy budget as a whole.

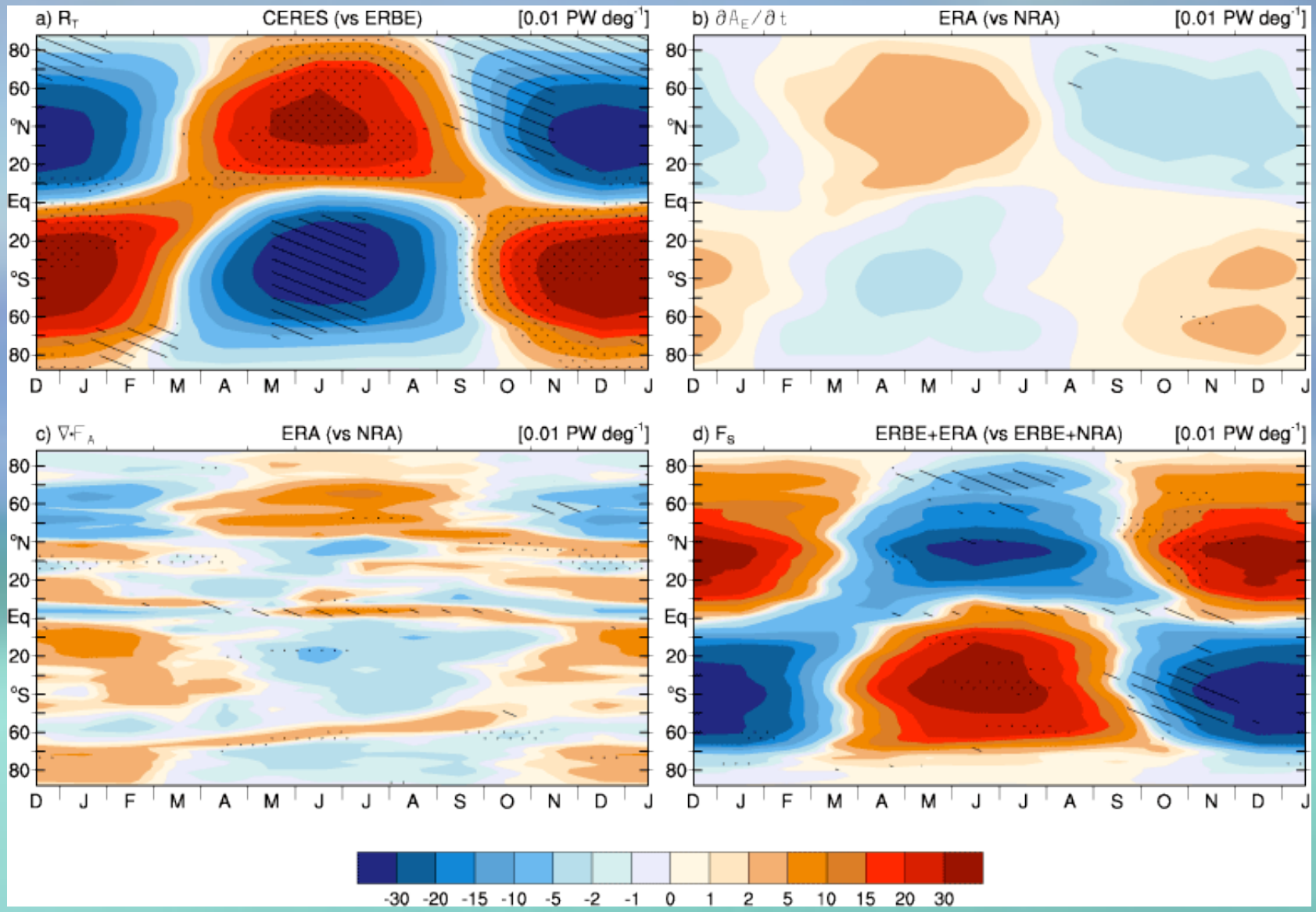
Moreover, issues for broadening this analysis to interannual timescales are raised.

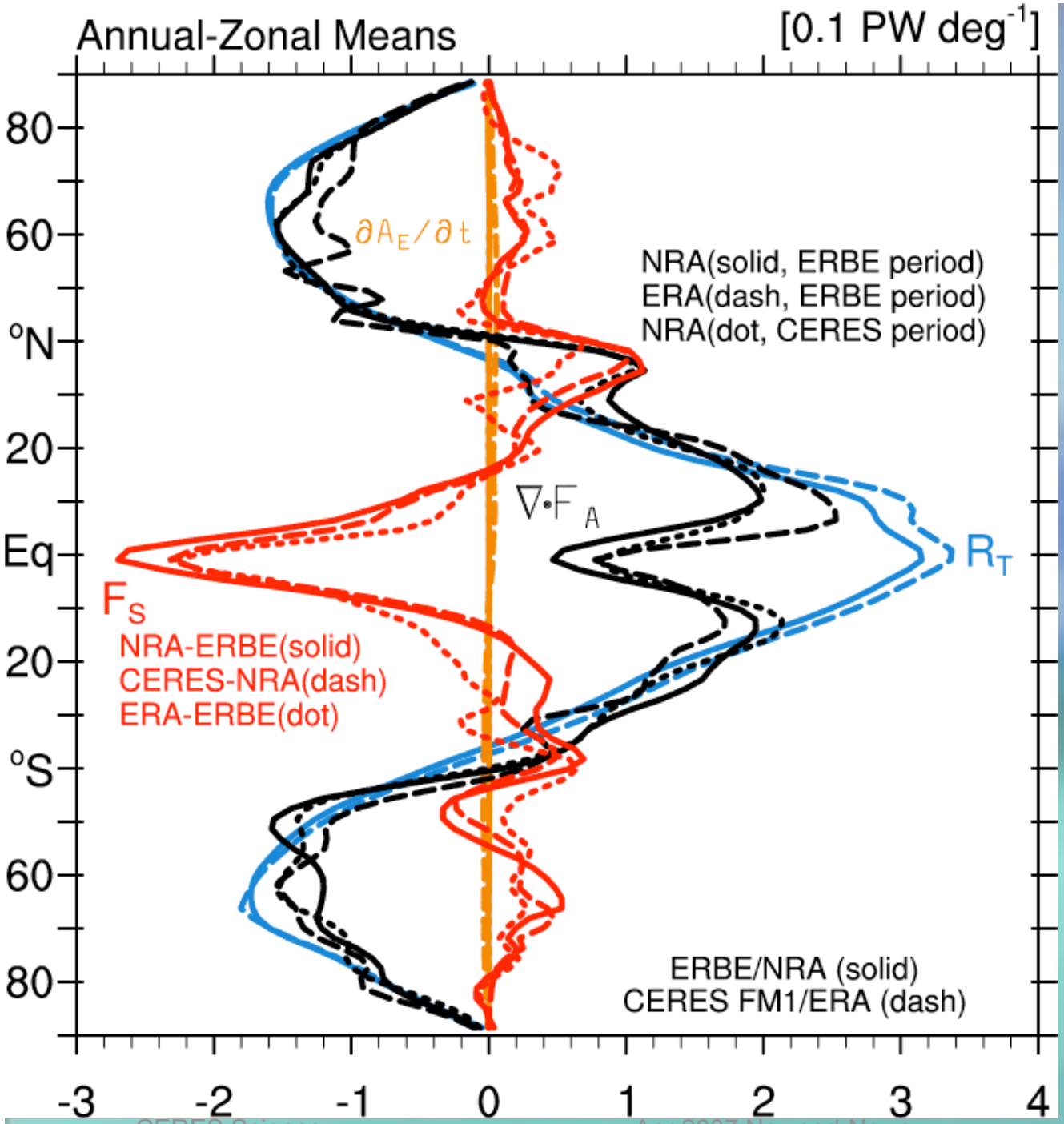
Future Work

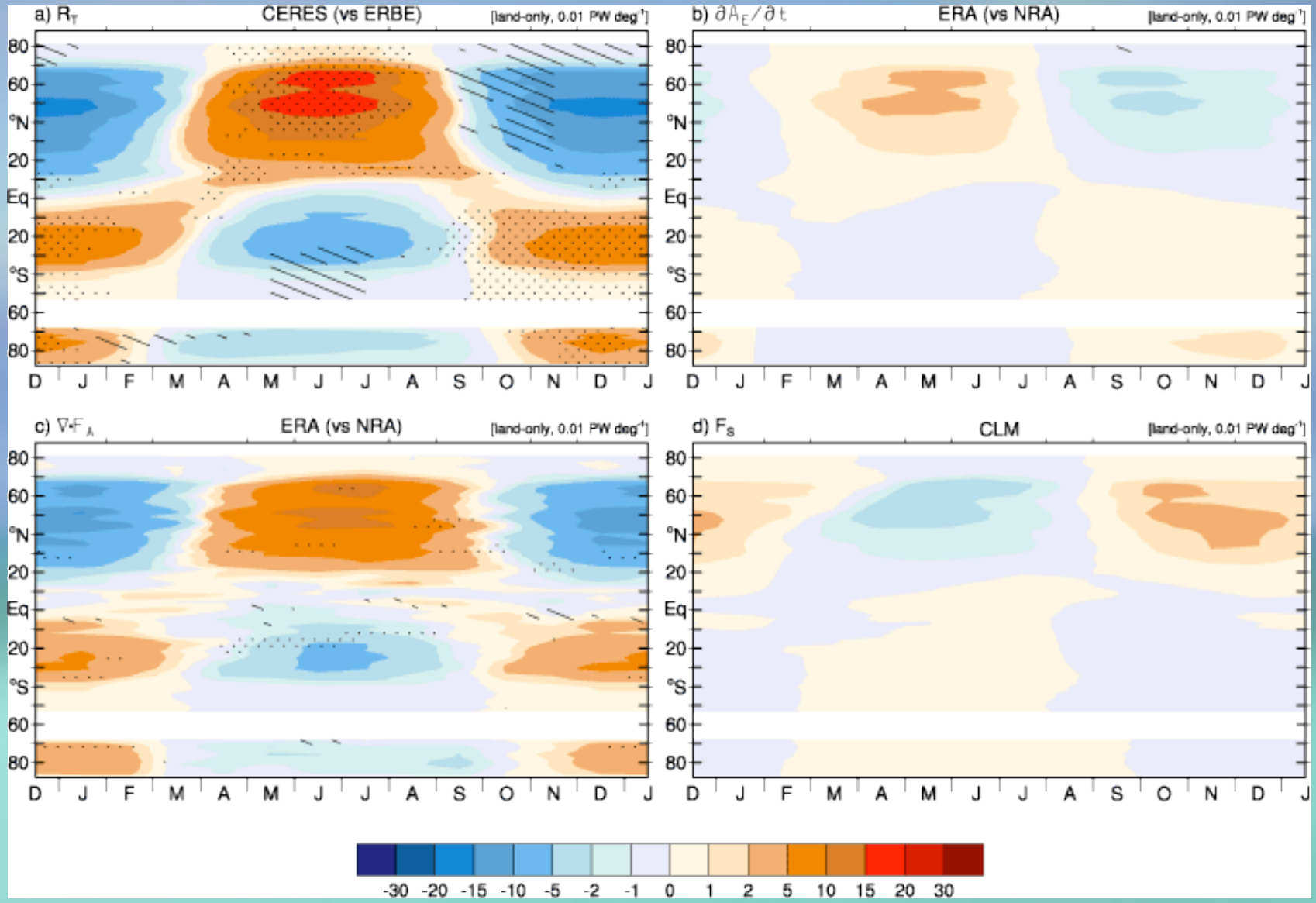
- Use these results as a baseline for model evaluation (IPCC AR4 simulations)
- Eagerly awaiting TOASRB Edition 3 for improvements to the current analysis

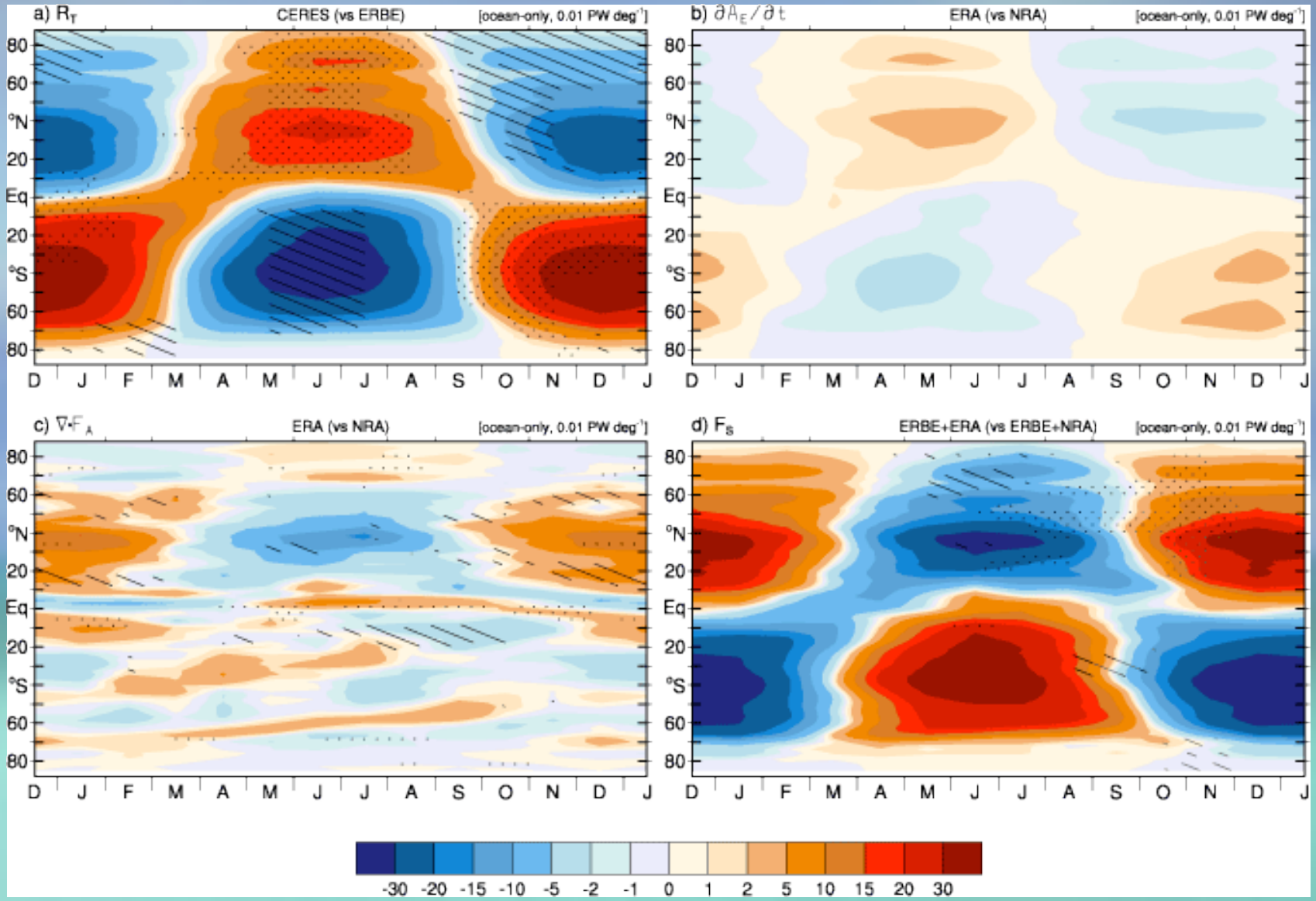
The End

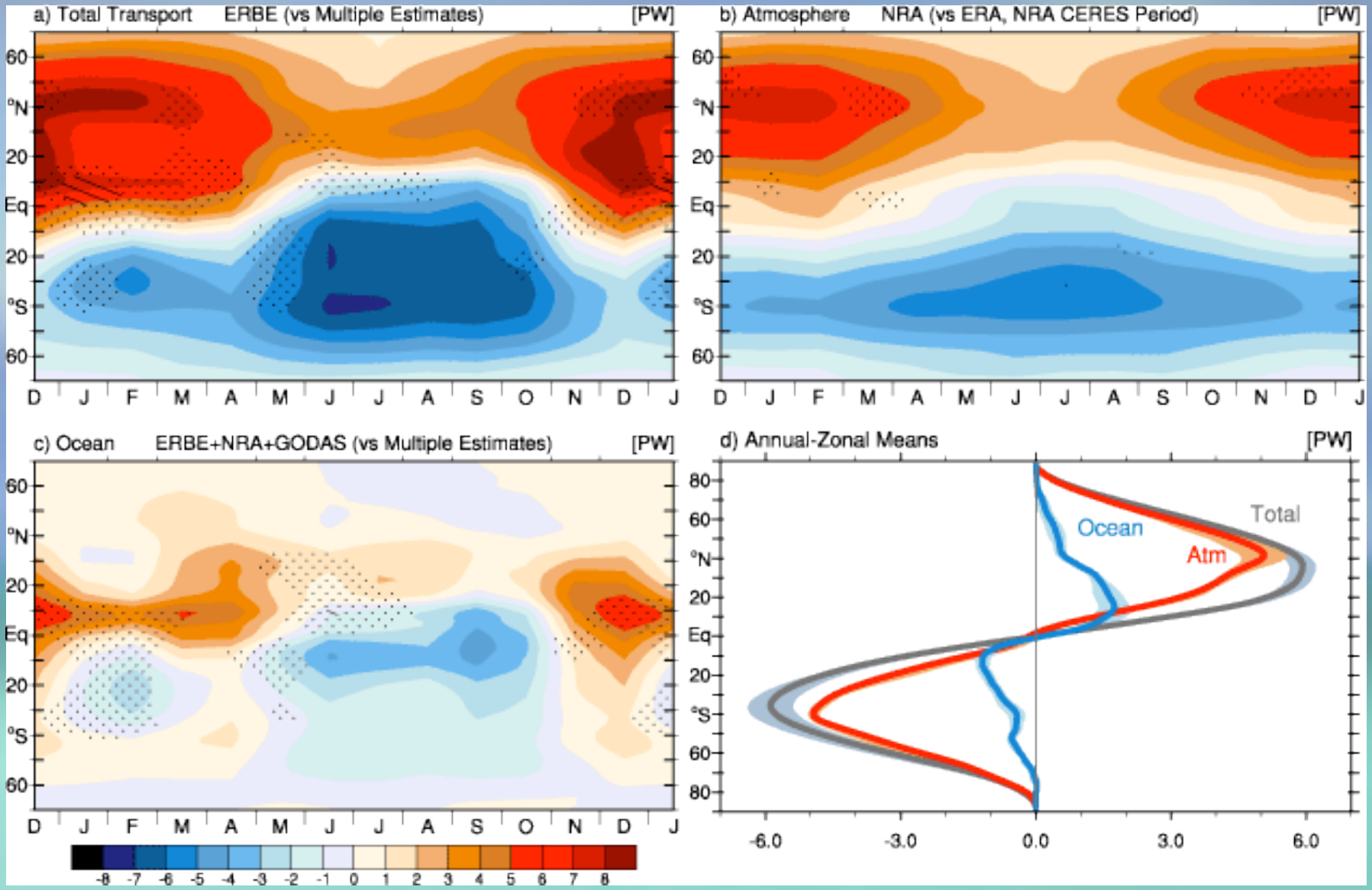

a) Albedo
CERES (vs ERBE)
[unitless]
b) ASR
CERES (vs ERBE)
[0.01 PW deg-1]
c) OLR
CERES (vs ERBE)
[0.01 PW deg-1]
d) Annual-Zonal Means
[0.01 PW deg-1]
80
60
°N
20
Eq
20
°S
60
80
D J F M A M J J A S O N D J
-0.1 -0.06 -0.02 -0.004 0.004 0.02 0.06 0.1
-50 -30 -10 -2 2 10 30 50
-10 -6 -2 -0.4 0.4 2 6 10
ASR
Albedo(%)
OLR
ERBE(solid)
CERES(dashed)
0 30 60 90 120 150


a) R_T
CERES (vs ERBE)
[0.01 PW deg^{-1}]
b) $\partial A_E/\partial t$
ERA (vs NRA)
[0.01 PW deg^{-1}]
c) $\nabla \cdot F_A$
ERA (vs NRA)
[0.01 PW deg^{-1}]
d) F_S
ERBE+ERA (vs ERBE+NRA)
[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


Annual-Zonal Means
[0.1 PW deg-1]
80
60
°N
20
Eq
20
°S
60
80
-3
-2
-1
0
1
2
3
4
∂A_E/∂t
NRA(solid, ERBE period)
ERA(dash, ERBE period)
NRA(dot, CERES period)
∇•F_A
R_T
F_S
NRA-ERBE(solid)
CERES-NRA(dash)
ERA-ERBE(dot)
ERBE/NRA (solid)
CERES FM1/ERA (dash)


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


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


a) Total Transport ERBE (vs Multiple Estimates) [PW]
b) Atmosphere NRA (vs ERA, NRA CERES Period) [PW]
c) Ocean ERBE+NRA+GODAS (vs Multiple Estimates) [PW]
d) Annual-Zonal Means [PW]
60 °N 20 Eq 20 °S 60
D J F M A M J J A S O N D J
-8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8
80 60 °N 20 Eq 20 °S 60 80
-6.0 -3.0 0.0 3.0 6.0
Total
Ocean
Atm

Appendix

- ERBE Adjustments continued

Original Adjustment

OLR'->OLR-2.6 W m^{-2}, albedo uniformly increased so that R_T=0

Additional Adjustments

OLR over land is adjusted by +0.35 W m^{-2} (rather than decreased) and OLR over ocean is kept at its original -2.6 W m^{-2} adjustment

These adjustments:

1) provide continuity in the ocean->land transport of energy across the NOAA-9 failure.

2) provide consistency with ERBS trend in OLR from 60oN to 60°S across the NOAA-9 failure.

Albedo adjustments are then employed to yield zero annual mean R_T across the full ERBE period.

Equations

$$ASR - OLR + F_S + \nabla \bullet \mathbf{F_A} - \frac{\partial A_E}{\partial t} = 0$$

TOA Budget

$$\mathbf{F_A} = \frac{1}{g}\int_0^{p_s} \mathbf{v}(c_p T + \Phi + k + Lq)dp$$

Atmospheric Energy Flux

$$A_E = \frac{1}{g}\int_0^{p_s} (c_p T + \Phi_s + k + Lq)dp.$$

Atmospheric Energy
MSE=(DSE+Lq)

Abstract 1

- The mean and annual cycle of energy flowing into the climate system and its storage, release, and transport in the atmosphere, ocean, and land surface are estimated with recent observations. An emphasis is placed on establishing internally consistent quantitative estimates with a full discussion and assessment of uncertainty. At the top-of-atmosphere (TOA), adjusted Earth Radiation Budget Experiment (ERBE) and Clouds and the Earth's Radiant Energy System (CERES) satellite retrievals are used, while in the atmosphere National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) and European Centre for Medium Range Weather Forecasts (ECMWF) reanalysis (ERA-40) estimates are used. The net upward surface flux (F_S) over ocean is derived from the residual of TOA and atmospheric budgets, and is compared with direct calculations of ocean heat content (O_E) and its tendency ($\delta O_E/\delta t$) from several ocean temperature datasets. Over land F_S from a stand-alone simulation of the Community Land Model forced by observed fields is used. A comprehensive depiction of the budget based on ERBE fluxes from 1985 to 1989 and CERES fluxes from 2000 to 2004 is constructed that matches best estimates of the global, global-ocean, and global-land imbalances. In addition, the annual cycle of the energy budget during both periods is examined and compared with $\delta O_E/\delta t$.

- The near balance between net TOA radiation (R_T) and F_S over ocean and thus with O_E, and between R_T and atmospheric total energy divergence over land, are documented both in the mean and for the annual cycle. However, there is an annual mean transport of energy by the atmosphere from ocean to land regions of 2.2±0.1 PW (10^{15} watts) primarily in the northern winter when the transport exceeds 5 PW. The global albedo is dominated by a semiannual cycle over the oceans, but combines with the large annual cycle in solar insolation to produce a peak in absorbed and net radiation in February, somewhat after the perihelion, and with the net radiation 4.3 PW higher than the annual mean, as it is enhanced by the annual cycle of outgoing long-wave radiation that is dominated by land regions. *In situ* estimates of the annual variation of O_E are found to be unrealistically large. The analysis herein thus establishes a basis for further regional investigation of the energy budget in a companion manuscript and for subsequent model evaluation. Challenges in diagnosing interannual variability in the energy budget and its relationship to climate change are identified in the context of the episodic and inconsistent nature of observations.

Abstract 2

- Meridional structure of the annual cycle and mean energy budget of the climate system is evaluated with an internally consistent global observational record that best matches available estimates of the global, global-land, and global-ocean imbalances, with full discussion and assessment of uncertainty. The annual cycle and net meridional energy transports by the atmosphere and ocean are also estimated. At the top-of-atmosphere (TOA), Earth Radiation Budget Experiment (ERBE) and Clouds and Earth's Radiant Energy System (CERES) satellite retrievals are used along with two global reanalysis datasets for the atmosphere. Several ocean temperature datasets are also used to assess changes in ocean heat content (O_E) and their relationship to the net upward surface flux (F_S) over ocean, which is derived from the residual of TOA and atmospheric energy budgets. The surface flux over land from a stand-alone simulation of the Community Land Model forced by observed fields is also used, and the contrasting characteristics of the budget over land and ocean regions are identified.

- In the extratropics, absorbed solar radiation (*ASR*) achieves a maximum in summer with peak values near the solstices. Outgoing longwave radiation (*OLR*) maxima also occur in summer but lag *ASR* by 1 to 2 months, more consistent with temperature maxima over land. In the Tropics, however, *OLR* relates to high cloud variations and peaks late in the dry monsoon season, while the *OLR* minima in summer coincide with deep convection in the monsoon trough at the height of the rainy season. Most of the difference between the TOA radiation and atmospheric energy storage tendency is made up by a large heat flux into the ocean in summer and out of the ocean in winter. In the Northern Hemisphere, the transport of energy from ocean to land regions is substantial in winter, and modest in summer. In the Southern Hemisphere extratropics, land–ocean differences play only a small role and the main energy transport by the atmosphere and ocean is polewards. There is reasonably good agreement between F_S, as estimated as a residual from TOA radiation and atmospheric changes, with observed changes in O_E, except for south of 40ºS, where differences among several ocean datasets point to that region as the main source of errors in achieving an overall energy balance. The winter hemisphere atmospheric circulation is identified as the dominant contributor to poleward transports outside of the Tropics (6 to 7 PW), with summer transports being relatively weak (~3 PW) – slightly more in the Southern Hemisphere and slightly less in the Northern Hemisphere. Ocean transports outside of the Tropics are found to be small (<2 PW) for all months. Strong cross equatorial heat transports in the ocean of up to 5 PW exhibit a large annual cycle, but one that is in phase with poleward atmospheric transports of the winter hemisphere.

Abstract 3

- Monthly net upwards surface energy fluxes (F_S) over the oceans are computed as residuals of the total energy budget of the atmosphere using top-of-atmosphere (TOA) net radiation (R_T) and the complete energy budget tendency and divergence for the atmosphere ($\nabla \mathbf{F_A}$). The focus is on TOA radiation from Earth Radiation Budget Experiment (ERBE) (February 1985 to April 1989) and Clouds and the Earth Radiant Energy System (CERES) (March 2000 to May 2004) combined with results from two atmospheric reanalyses and three ocean datasets that enable a comprehensive estimate of uncertainties. An analysis of F_S departures from the annual mean and the implied annual cycle in "equivalent ocean energy content" is compared with directly observed ocean energy content (O_E) and tendency ($\delta O_E/\delta t$) to reveal the inferred annual cycle of divergence of ocean energy transport ($\nabla \mathbf{F_O}$). In the extratropics, F_S dominates changes in O_E although supplemented by ocean Ekman transports that enhance the annual cycle in O_E. In contrast, in the Tropics, and especially from about 5 to 15°N, ocean dynamics dominate O_E variations throughout the year in association with the annual cycle in surface wind stress and the North Equatorial Current, and F_S plays a smaller role in the upper ocean heat budget. An analysis of the regional characteristics of the first joint Empirical Orthogonal Function (EOF) of F_S, $\delta OE/\delta t$, and $\nabla \mathbf{F_O}$ is presented, and the largest sources of uncertainty are identified with ocean heat content estimates. The annual cycle of zonal mean global ocean transports is estimated from observations. Inferred annual mean ocean heat transports are somewhat lower than direct ocean estimates in the North Atlantic and thus for the zonal average global ocean, as there is reasonable agreement elsewhere. Although there are uncertainties in the atmospheric energy transports, there is not much scope for the ocean transports to be increased much as their sum is quite strongly constrained.