Salinity and the Global Ocean Water Cycle

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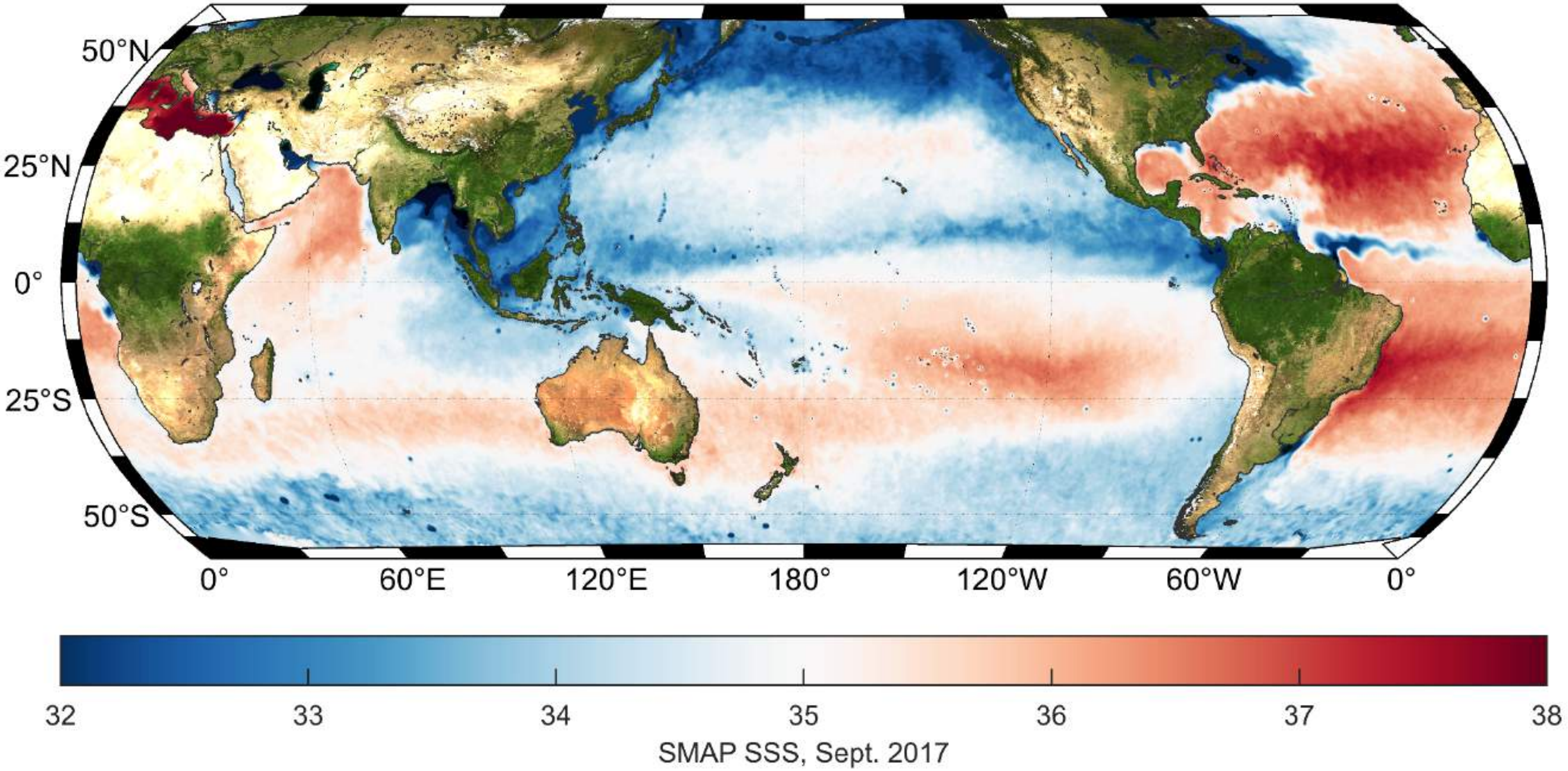
ECCO Summer School 2019
Friday Harbor, WA

Overview

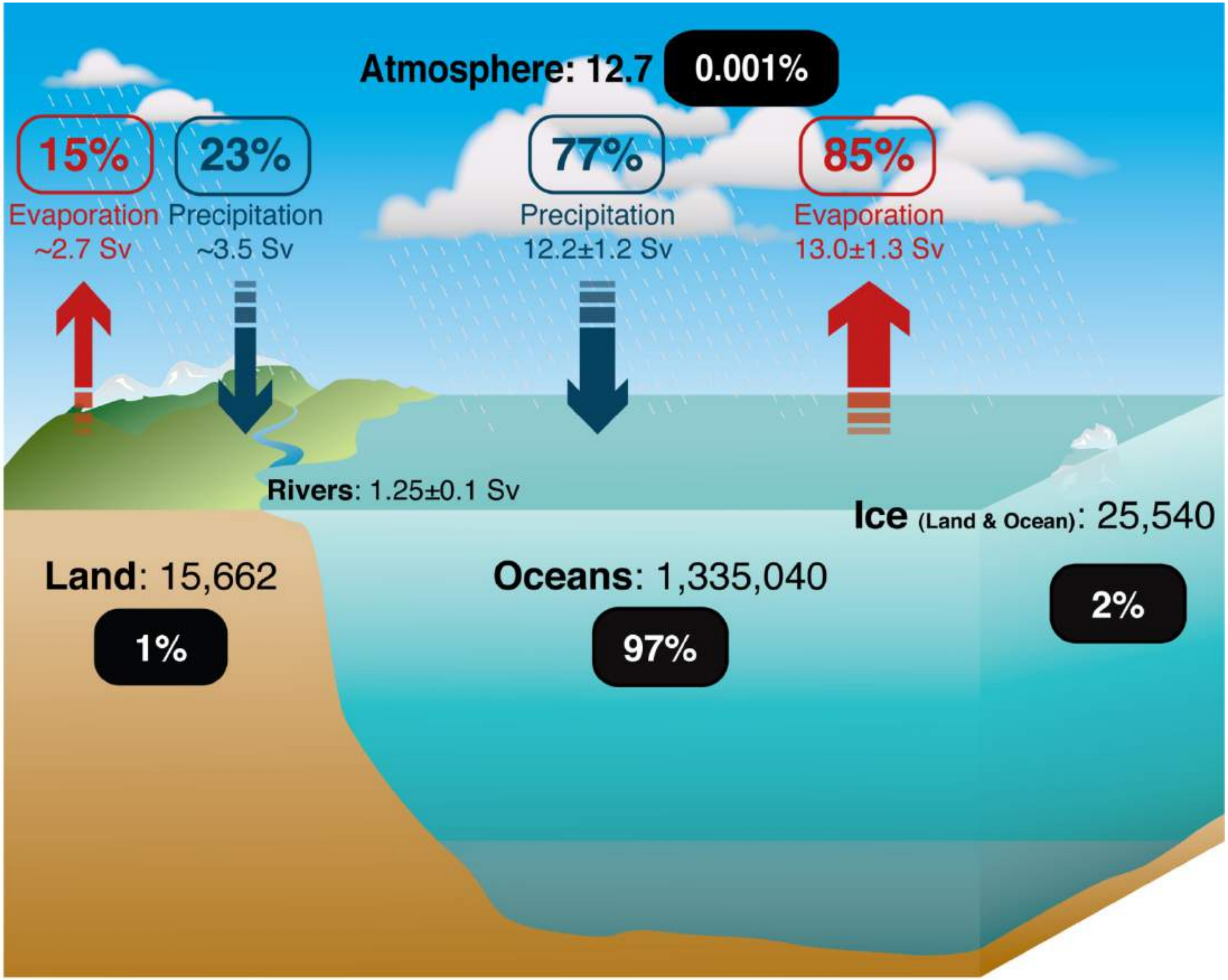
- The Global Ocean Freshwater Cycle
- Links to Salinity
- Changes in the Water Cycle and Salinity
- E-P-R, Recycling, and Implied Exports through E:P Ratios
- NASA Field Campaigns: Satellites and *In Situ* Measurements
- Conclusions

Global Salinity



- A Smapshot (pardon the pun) of Global Salinity during the SPURS-2 field campaign, September 2017.
- ITCZ, Amazon, BoB (end of monsoon). Also RFI/Land

The Global Water Cycle



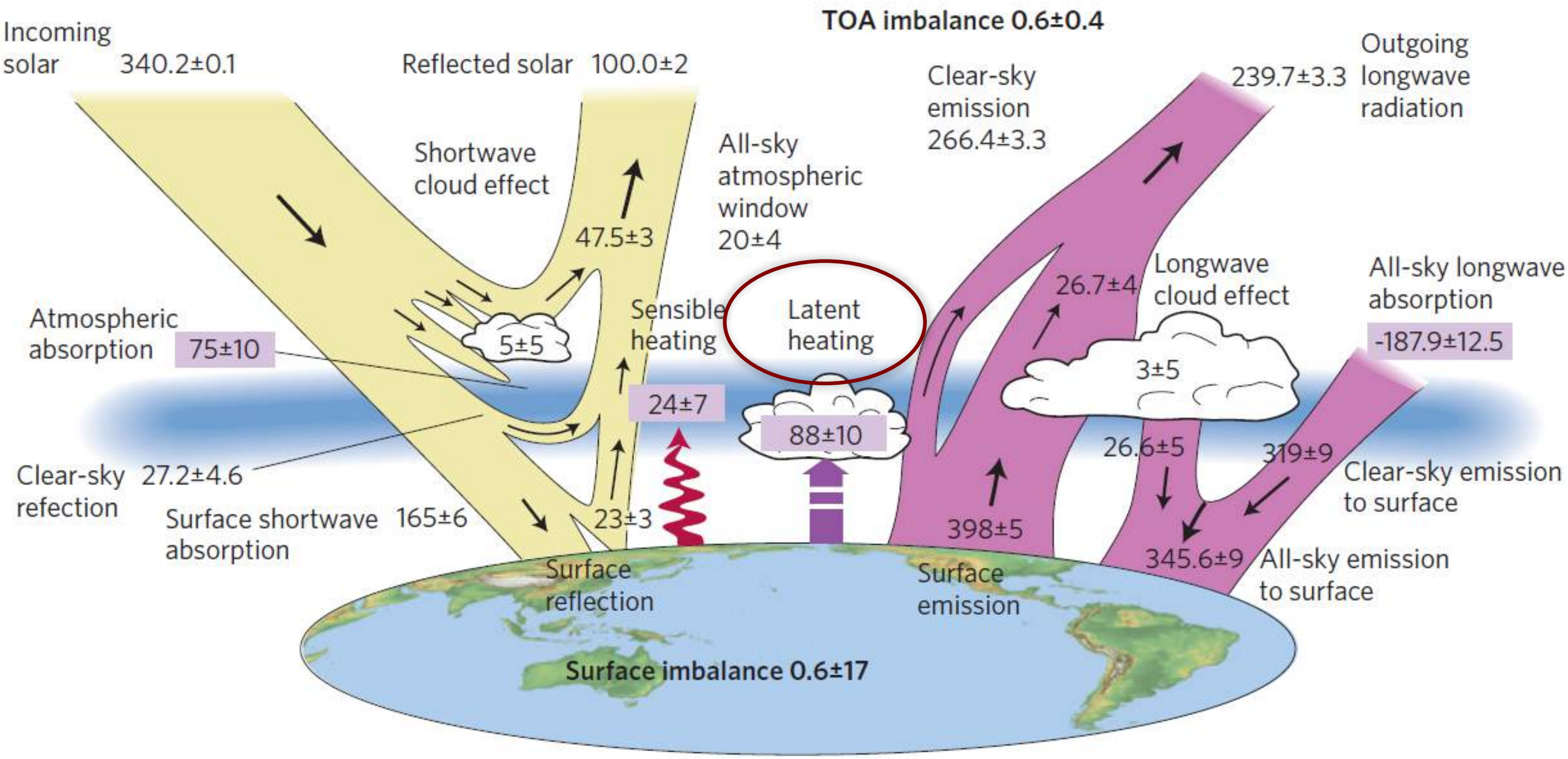
Reservoirs represented by solid boxes: 10^3 km^3, fluxes represented by arrows: Sverdrups (10^6 m^3 s^{-1})

Sources: Baumgartner & Reichel, 1975; Schmitt, 1995; Trenberth et al., 2007; Schanze et al., 2010; Steffen et al., 2010

- Oceans dominate fluxes and reservoirs
- Generally 'mis-represented'

I

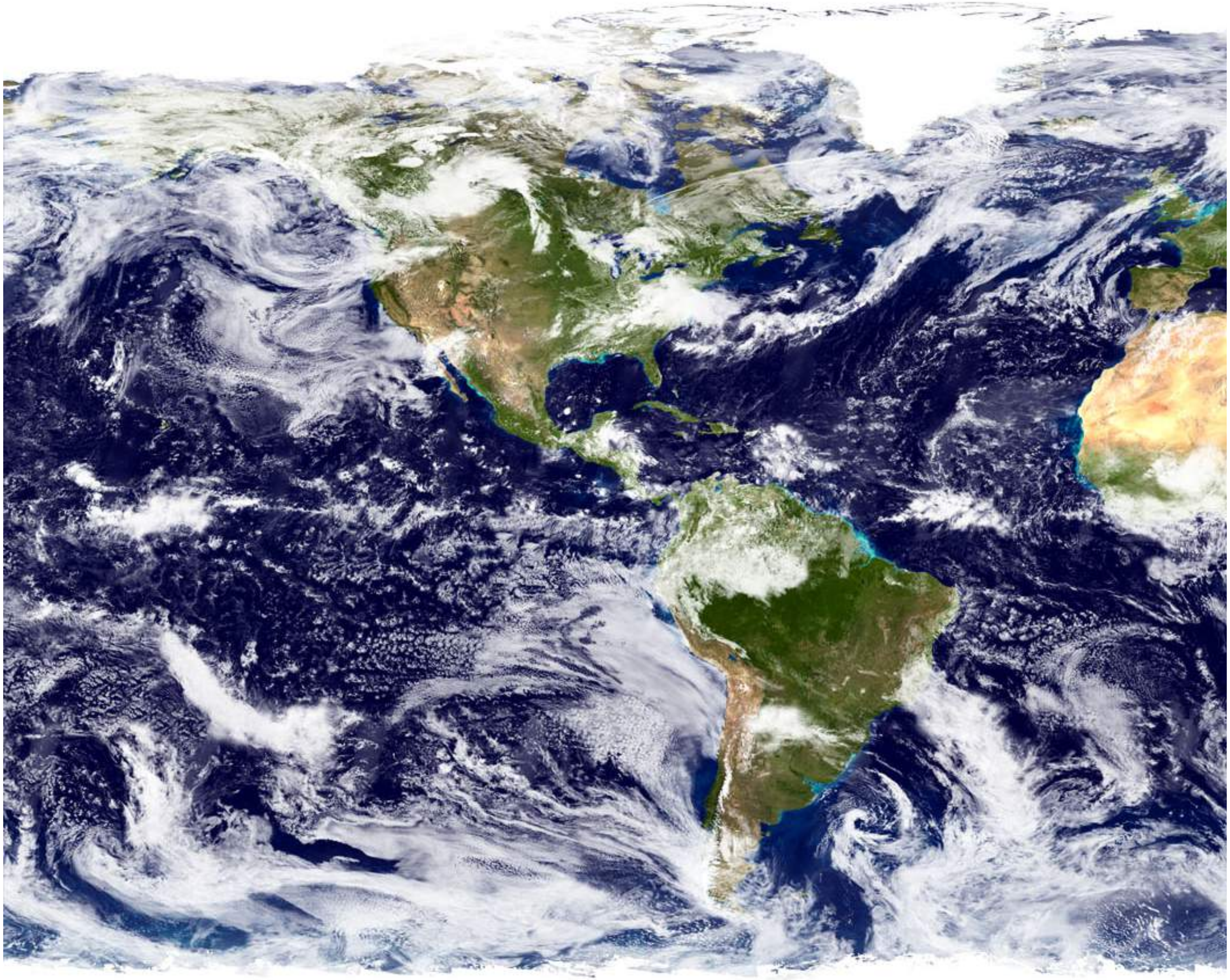
The Link to the Energy Balance



- Stephens et al, 2012: An update on Earth's energy balance in light of the latest global observations, Nature Geoscience, 5(10), 691-696

I

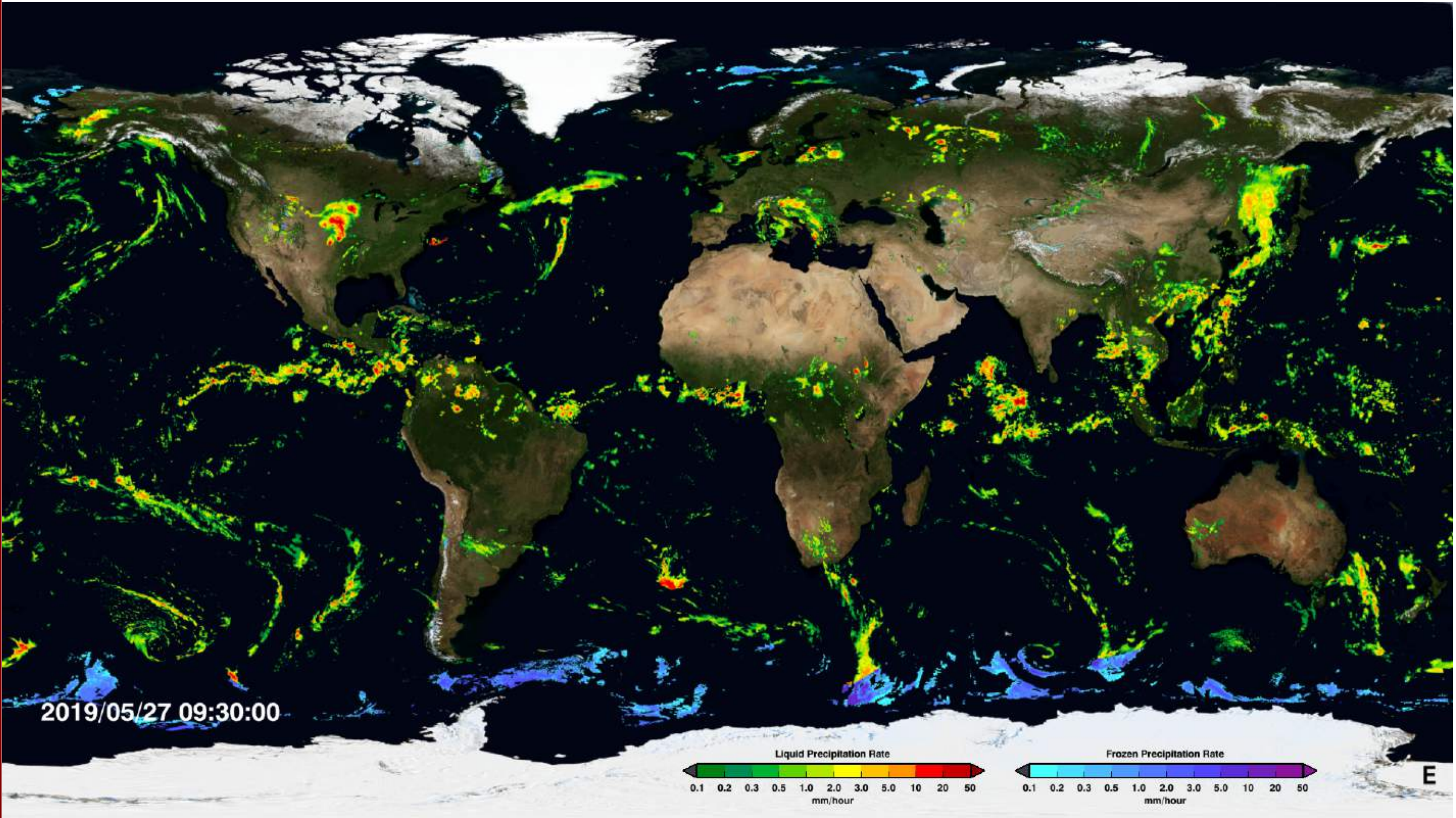
From Clouds…



- ITCZ clearly visible
- High latitudes
- Sub-tropical gyres almost cloud-free
- Source: Blue Marble NG

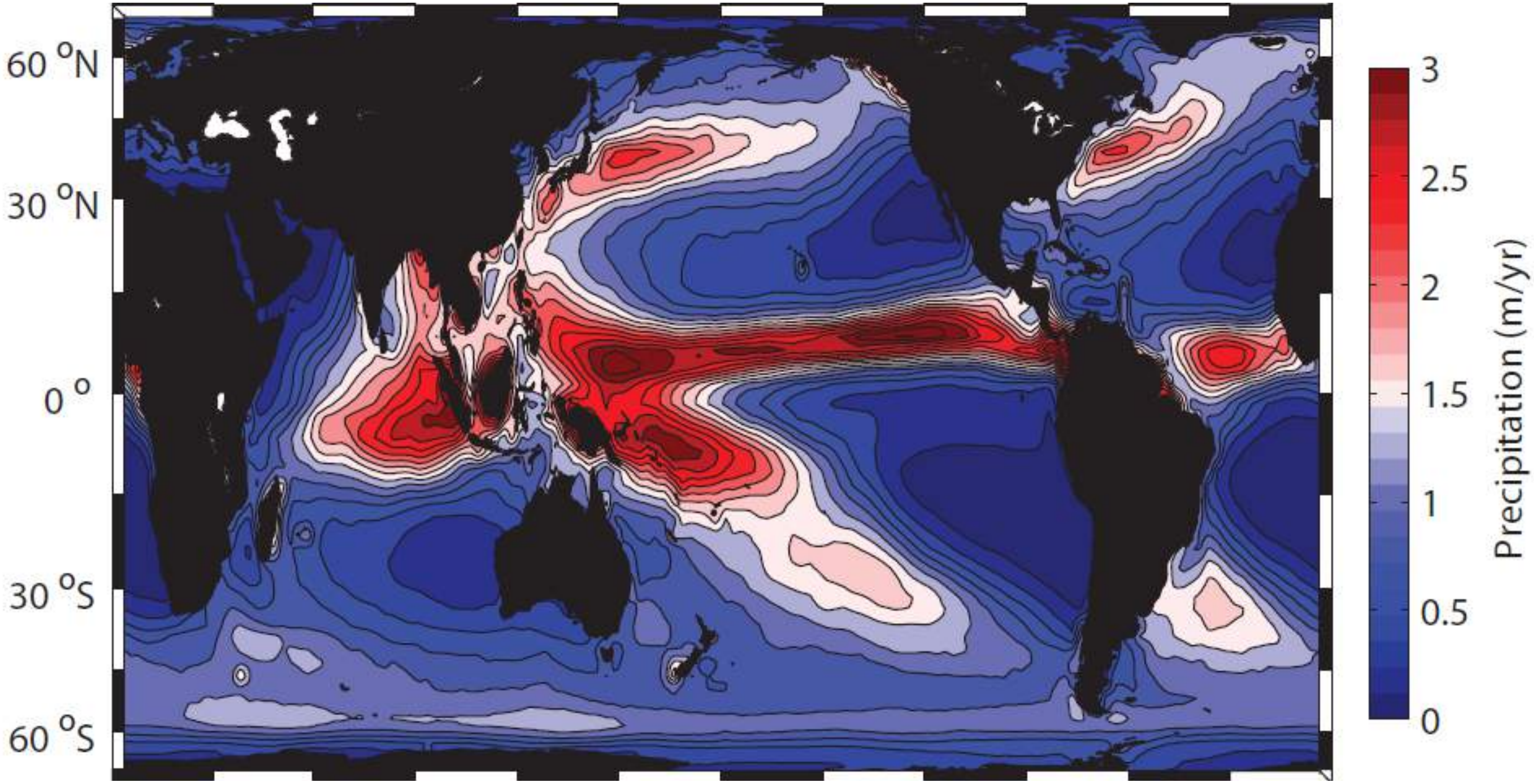
I

…to Rain



- IMERG Precipitation snapshot (half-hourly)

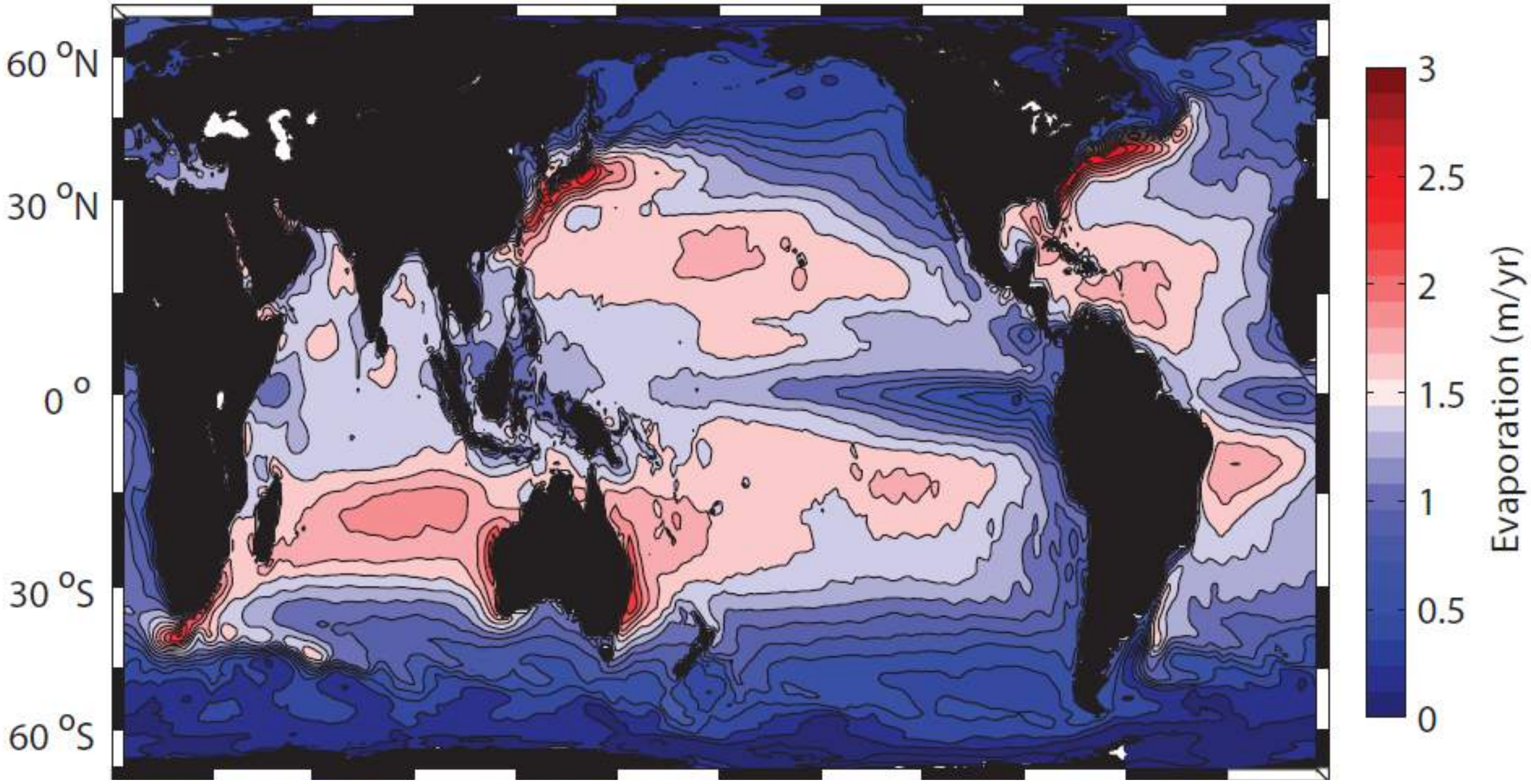
Mean Precipitation (1987-2006)



- From Schanze & Schmitt (2010), adjusted for E-P-R=0
- ITCZ, Kuroshio, Gulf Stream

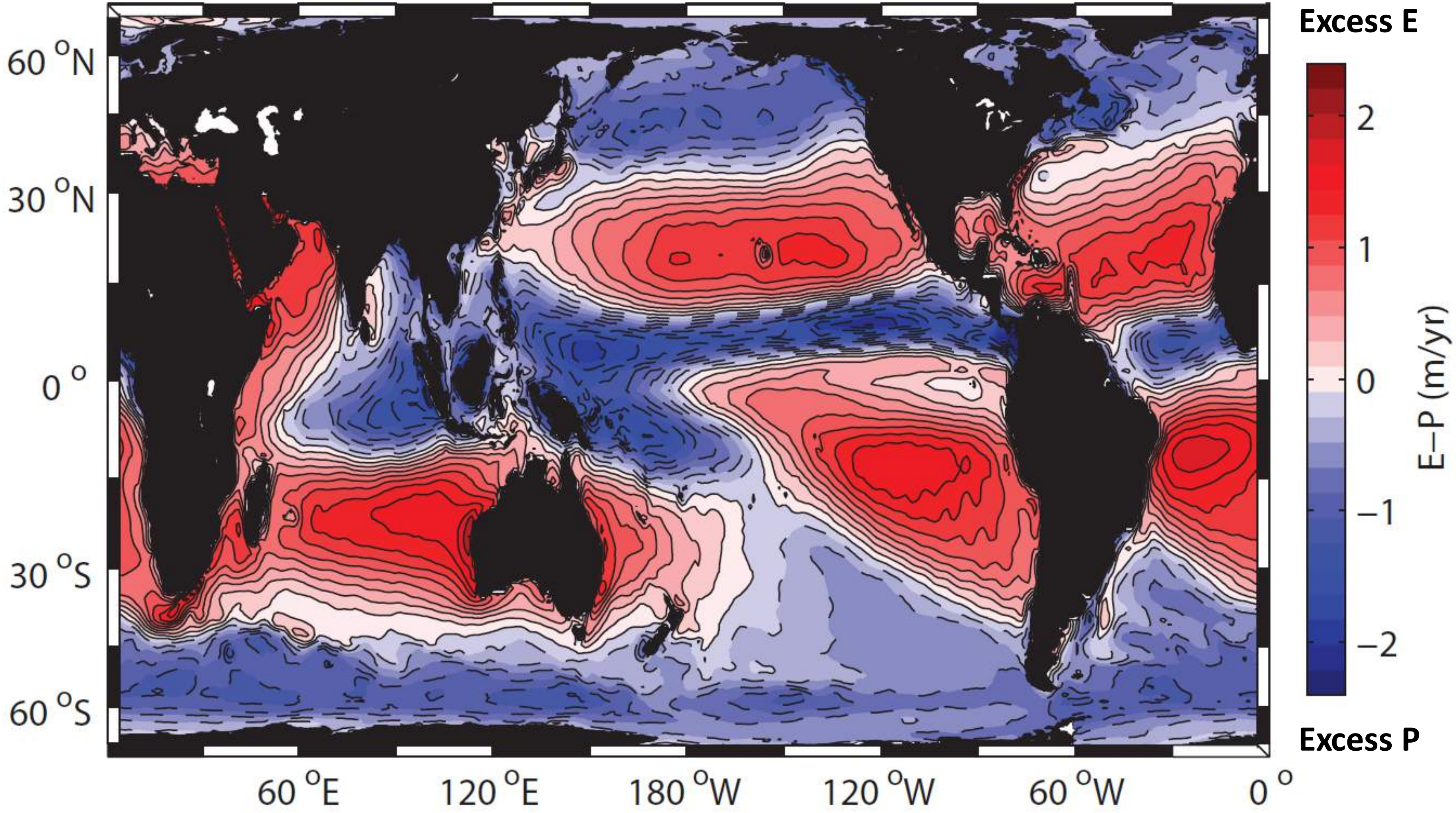
I

Mean Evaporation (1987-2006)



- OAFlux 3.1, From Schanze & Schmitt (2010), E-P-R=0 adjusted
- Peak in WBCs (recycling) & SSS maximum areas

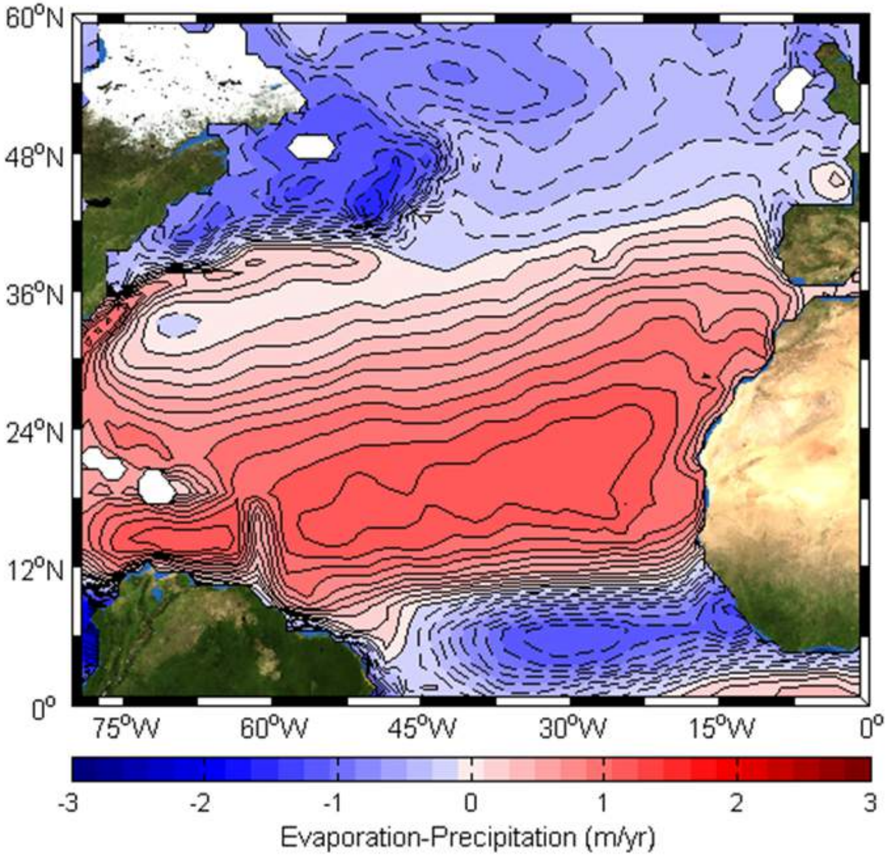
Mean E-P (1987-2006)

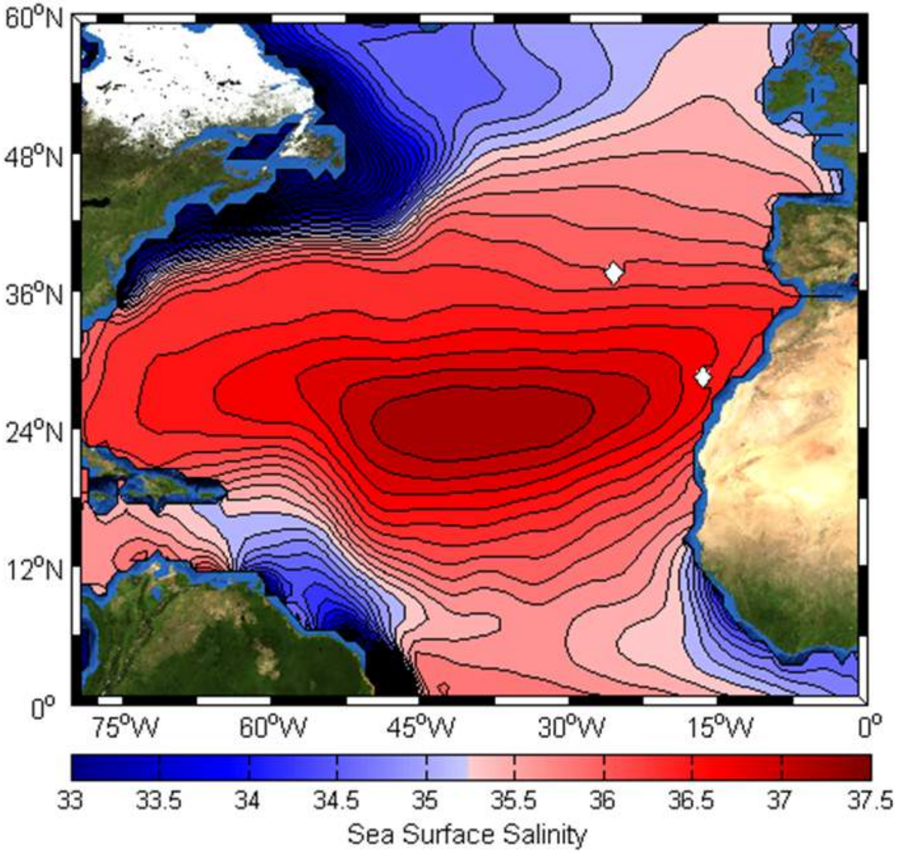


- From Schanze & Schmitt (2010), adjusted for E-P-R=0
- Advective effects visible

I

Salinity and Freshwater Flux

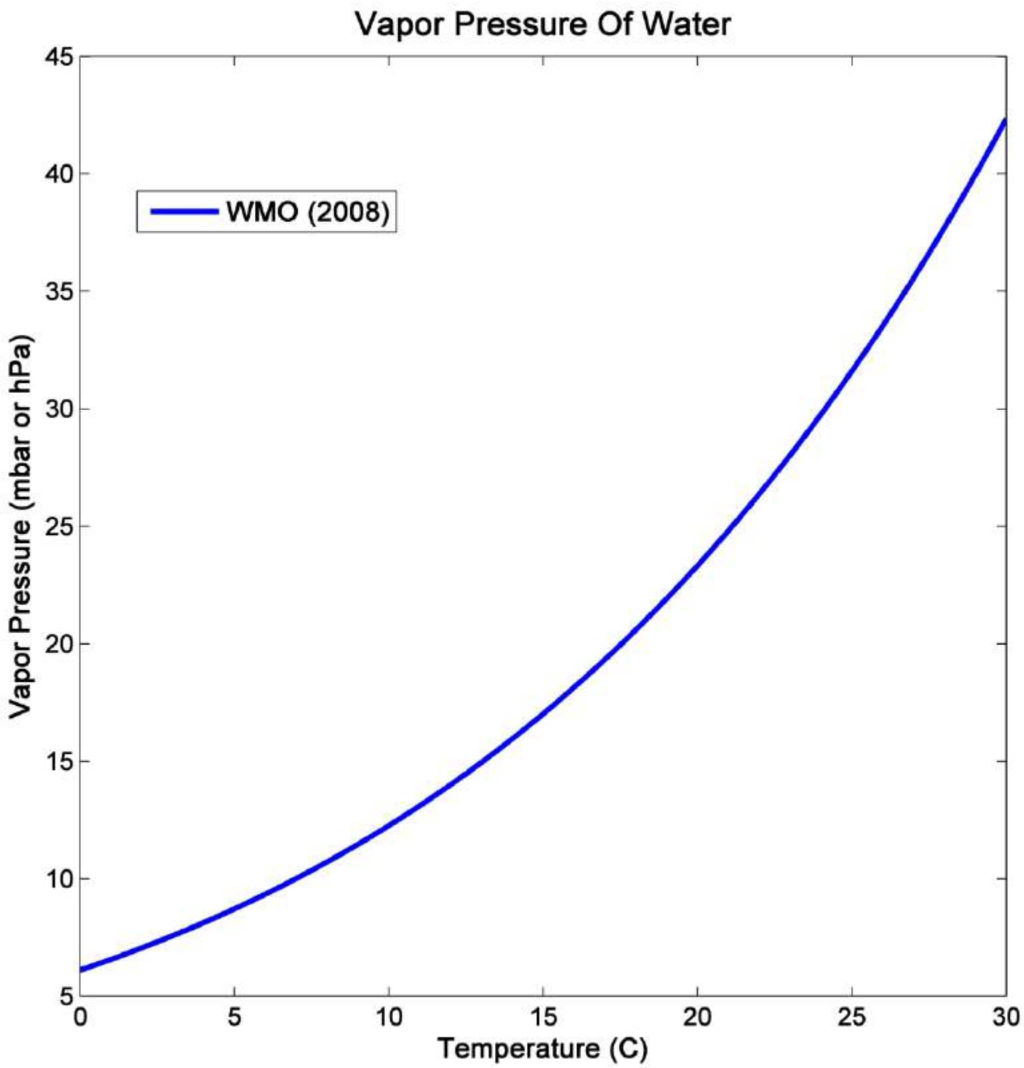




- North Atlantic E-P (left) and Aquarius Salinity (right) are highly correlated
- E-P=0 line right at vegetative index transition in Africa

II

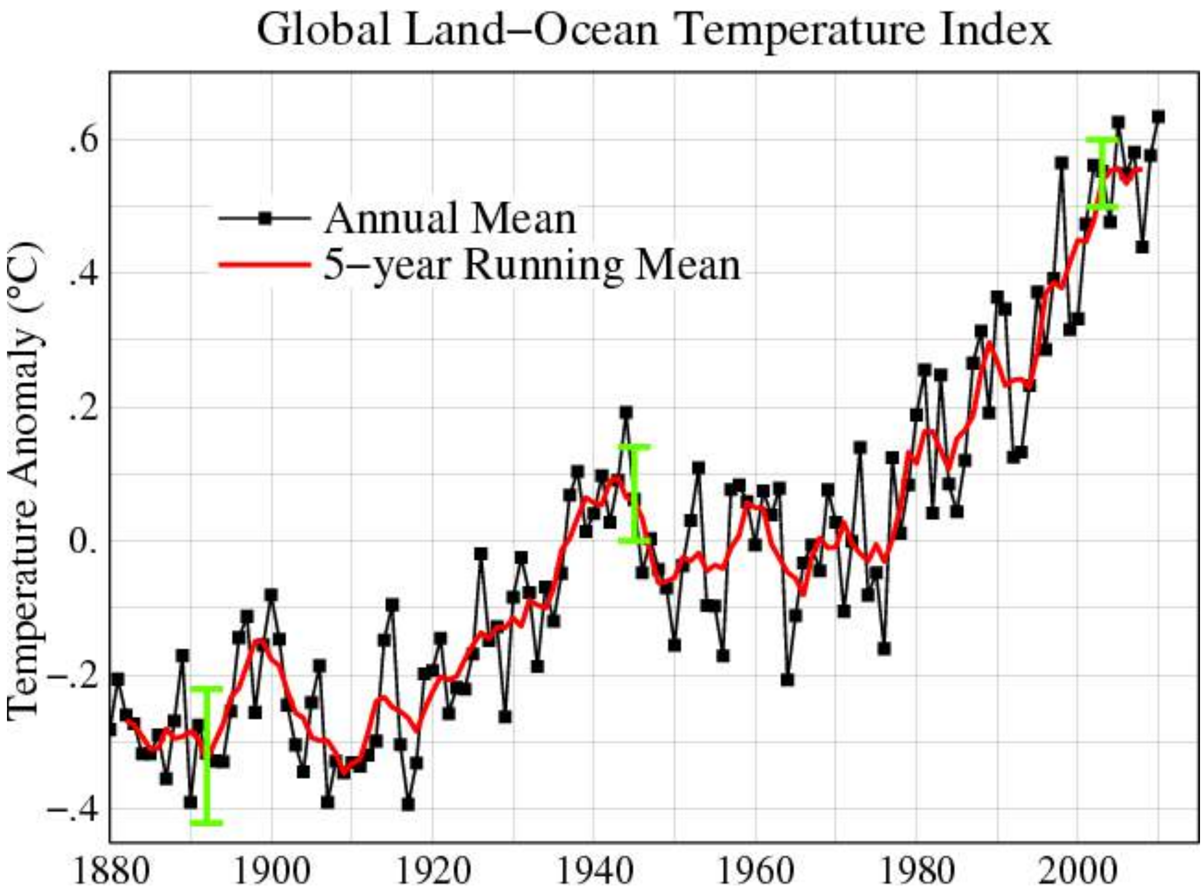
Clausius-Clapeyron



- Increased water holding capability in the atmosphere
- Implied amplification of water cycle with increasing global temperatures
- ~7.6%/K

II

Pattern Amplification

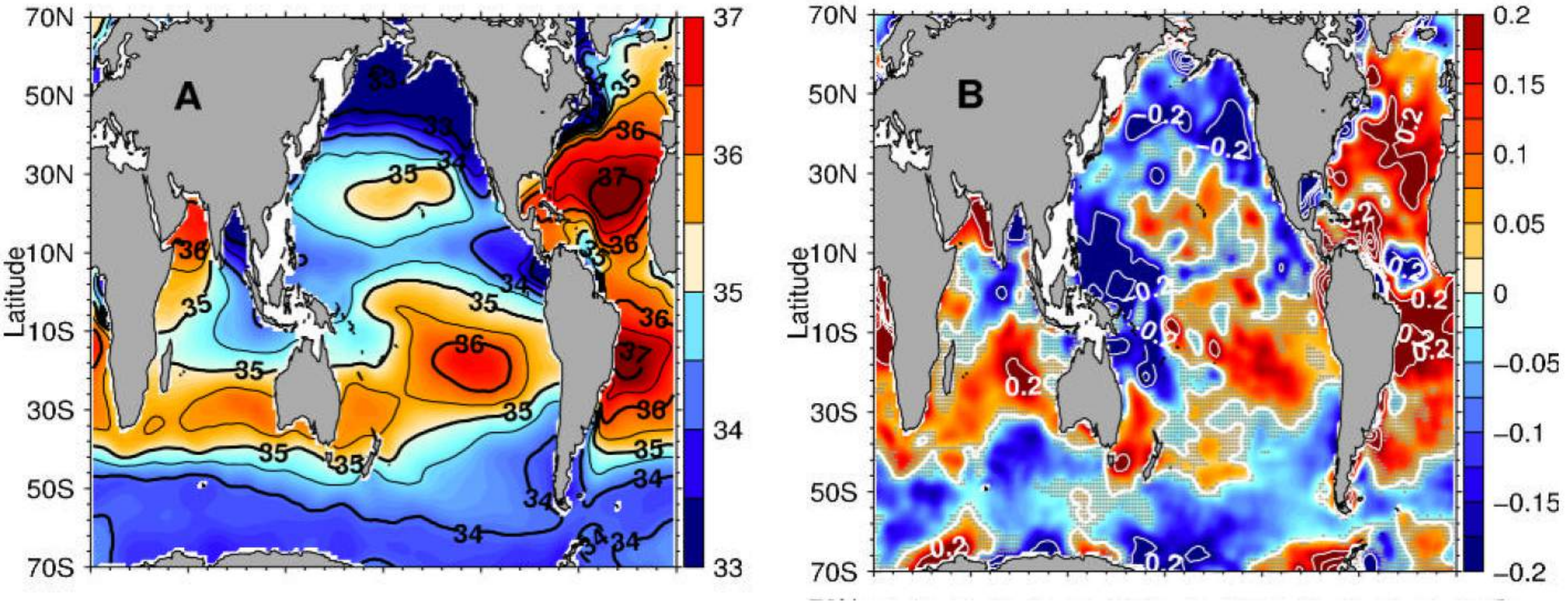


- ➢ temperatures are rising…
- ➢ Changes in SSS?

II

Pattern Amplification

- ➢Durack et al., 2010 (J. Clim) & 2012 (Science)
- ➢Salinity is hypersensitive to change in the water cycle



Mean SSS

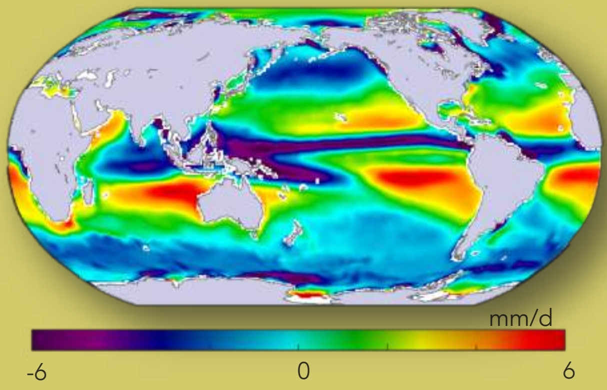
50-Year SSS Change

II

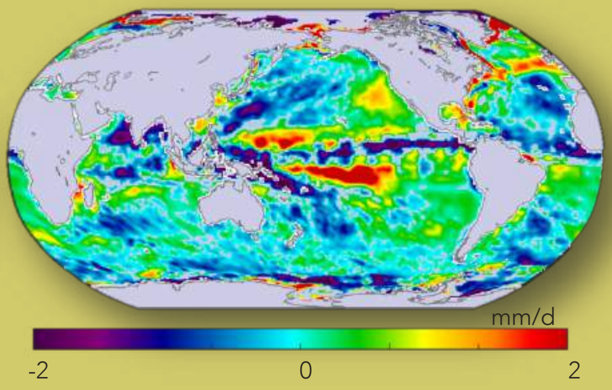
E-P Pattern Amplification in ECCO

(Slides: Nadya Vinogradova-Shiffer, NASA HQ)

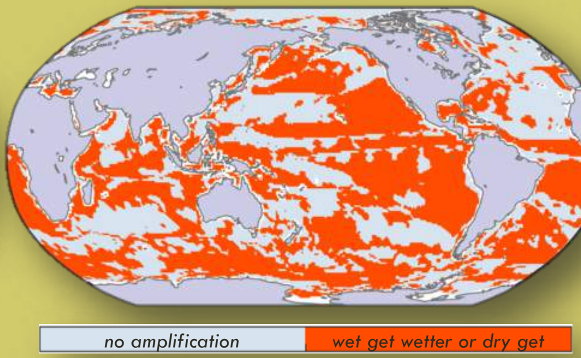
ANNUAL MEAN E-P

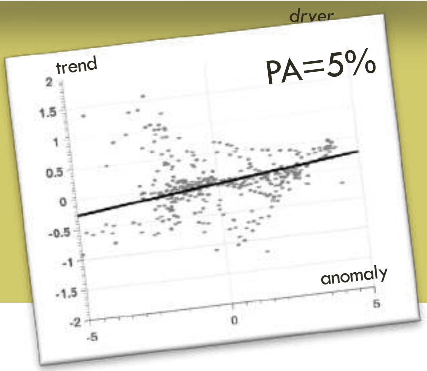


CHANGE IN E-P SINCE 1993



REGIONS OF AMPLIFICATION





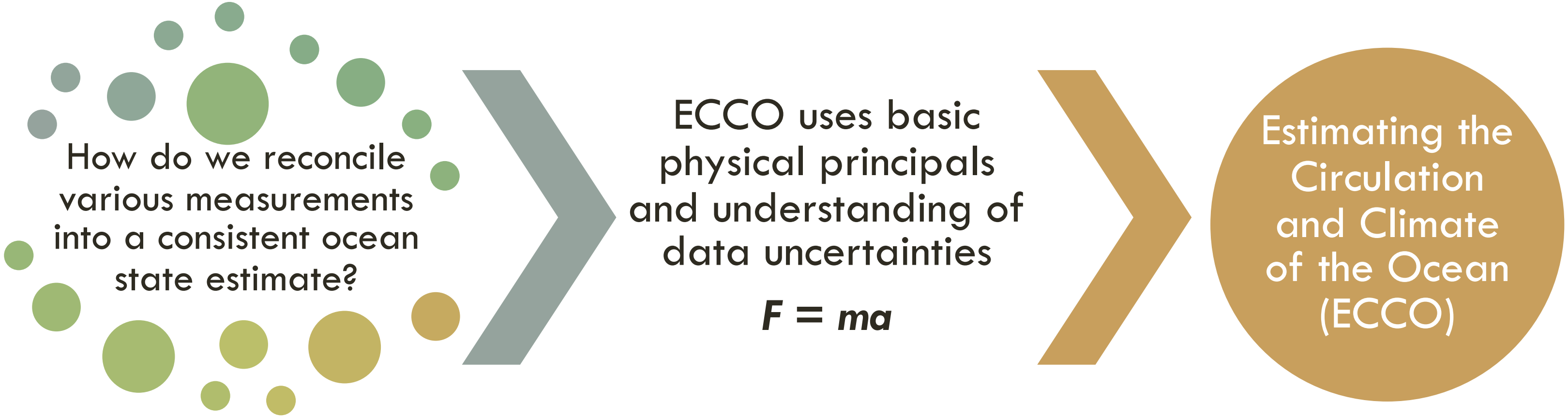
Vinogradova & Ponte, 2017, J. Climate

CONTEMPORARY CHANGES IN WATER CYCLE:

Average amplification ~5%* – consistent with Clausius-Clapeyron equation

*Equivalent 7.6% °C and 0.65 °C change

NASA's ECCO

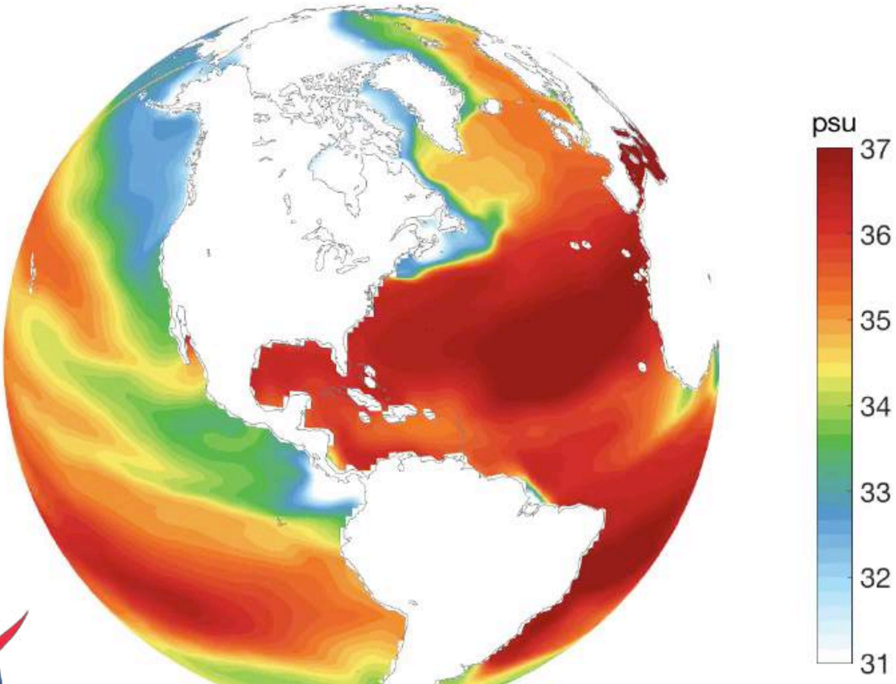


How do we reconcile various measurements into a consistent ocean state estimate?

ECCO uses basic physical principals and understanding of data uncertainties

F = ma

Estimating the Circulation and Climate of the Ocean (ECCO)


ECCO SSS - Jan1992

Example:	*multi-platform salinity estimate from ECCO*
ECCO website:	*ecco.jpl.nasa.gov*
ECCO in the cloud:	*Shiffer et al..2016;* *Vinogradova et al., 2017*

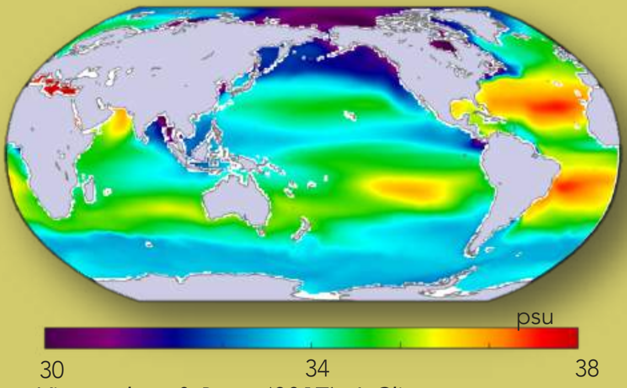
Slide: Nadya Vinogradova-Shiffer

II

SSS Pattern Amplification in ECCO

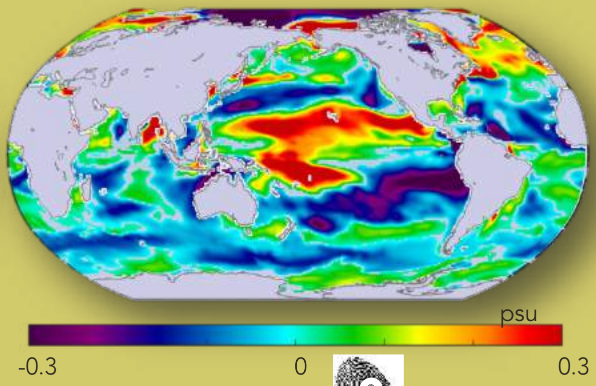
(Slide: Nadya Vinogradova-Shiffer, NASA HQ)

ANNUAL MEAN SALINITY

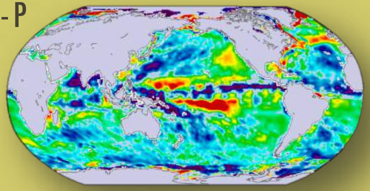


Vinogradova & Ponte (2017), J. Climate

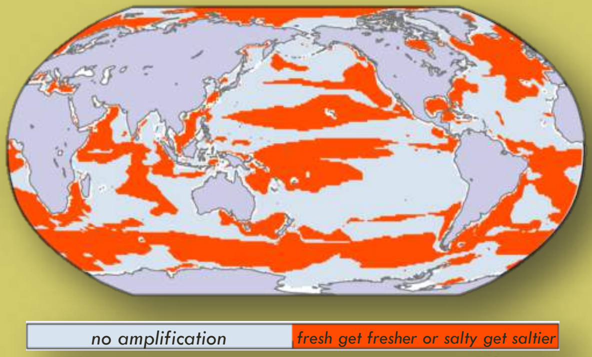
CHANGE IN SALINITY SINCE 1993

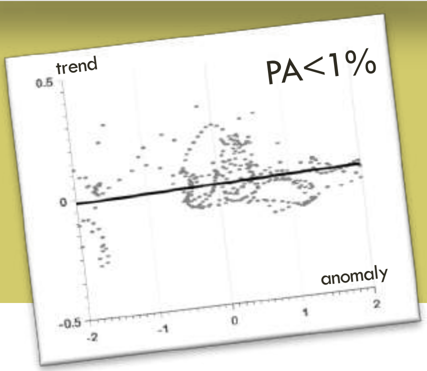


ΔE-P



REGIONS OF AMPLIFICATION





CONTEMPORARY CHANGES IN SALINITY:

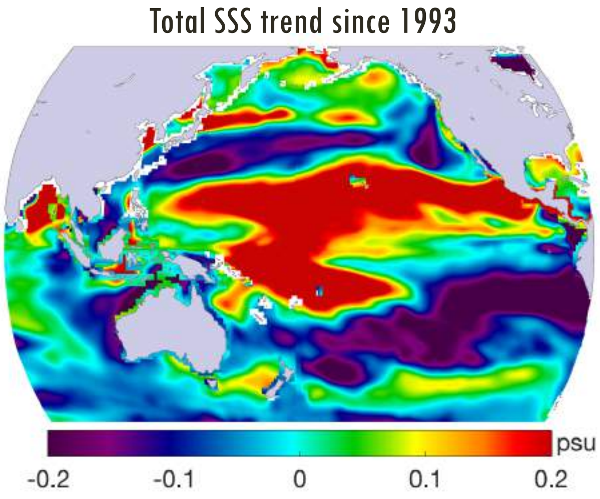
Little evidence of global amplification, despite strong regional changes

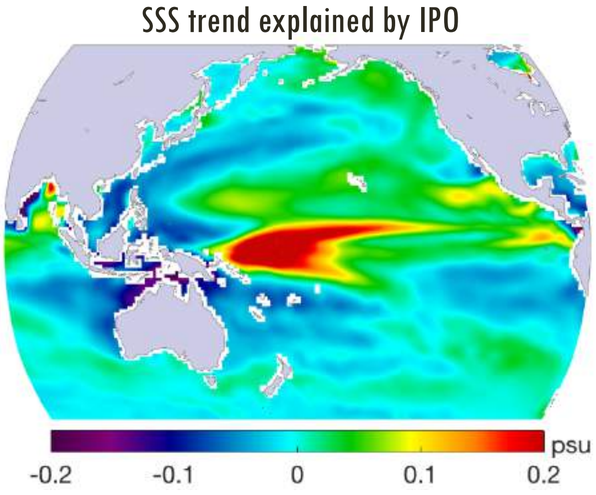
II

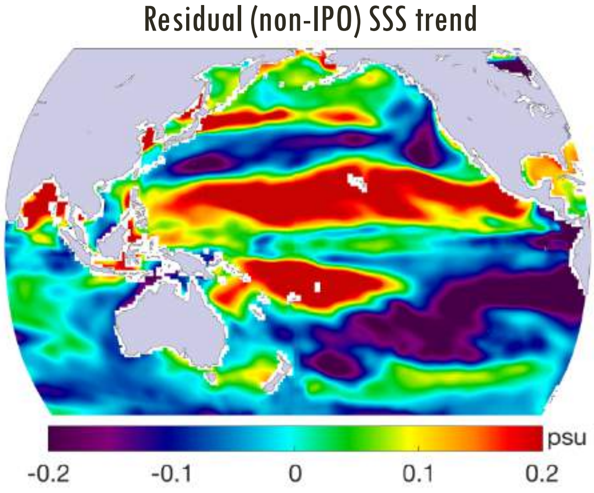
SSS Pattern Amplification in ECCO (2)

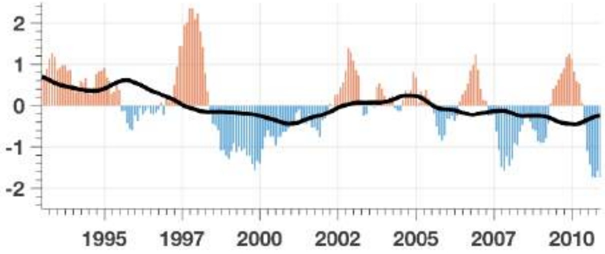
(Slide: Nadya Vinogradova-Shiffer, NASA HQ)

Role of natural variability in modulating SSS trends


Total SSS trend since 1993


SSS trend explained by IPO


Residual (non-IPO) SSS trend

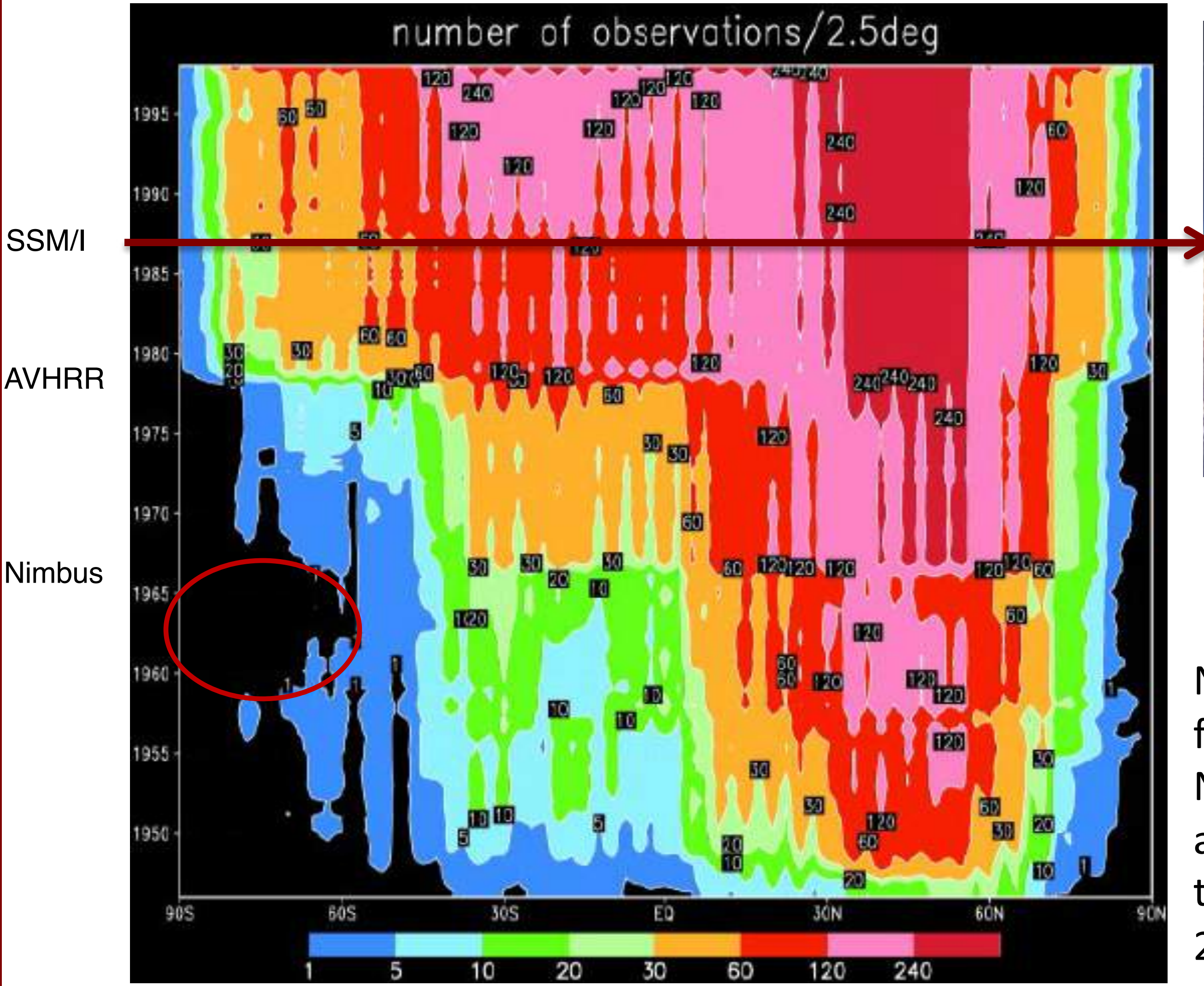


IPO, Hanley et al., 2015

Vinogradova & Ponte, 2017, JCLim

II

Surface Fluxes: Homogeneity

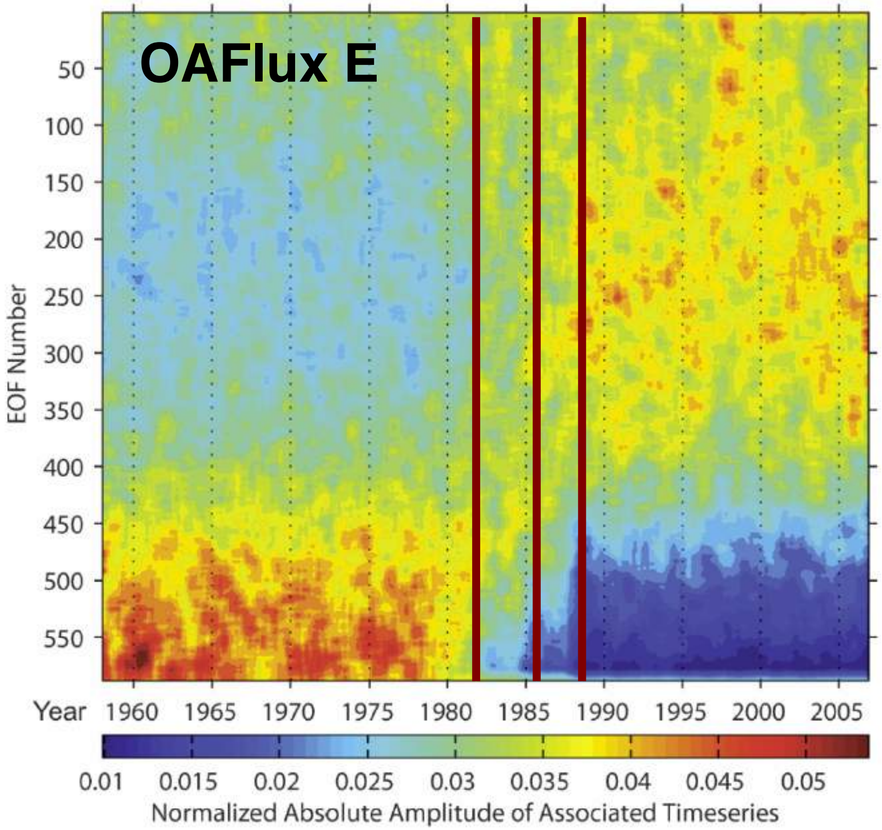


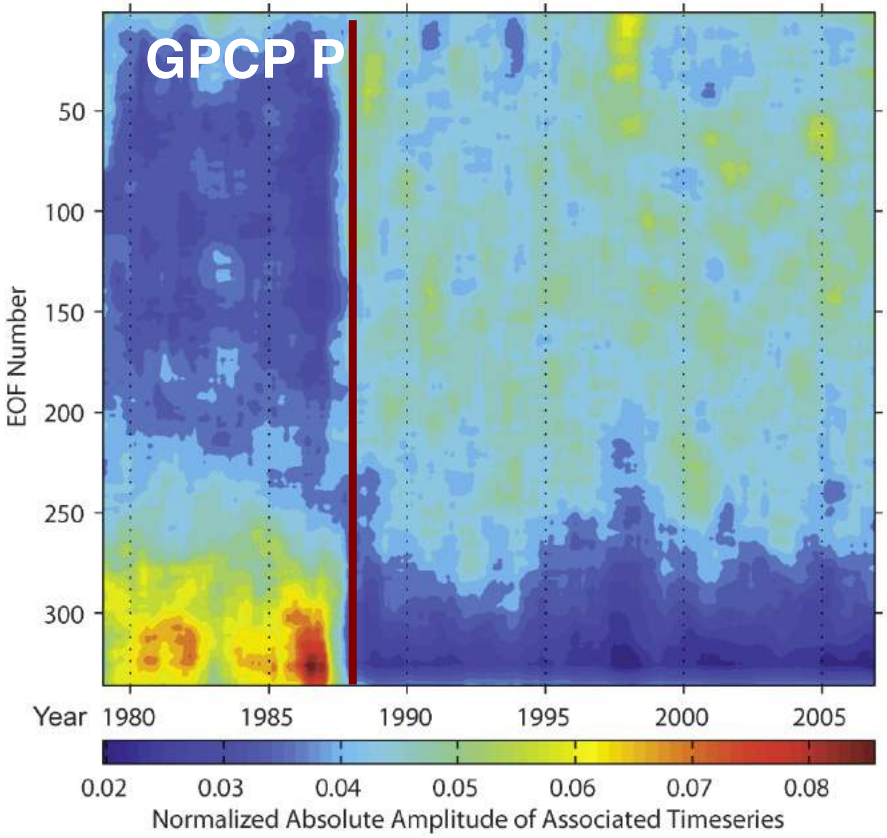
SSM/I Satellite, Image: NASA

Number of observations for each 2.5° grid box. For NCEP-1 Strong changes are evident at indicated times. From: Kistler et al., 2001.

II

Surface Fluxes: Homogeneity



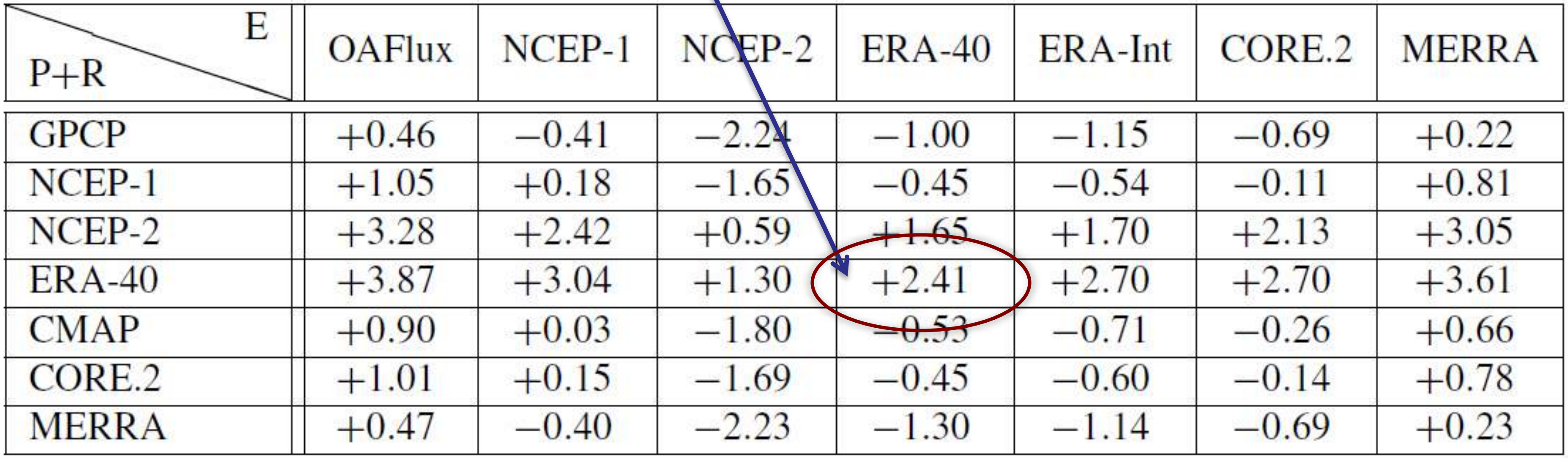


- This analysis visualizes spectral changes (~variance) over time
- (relatively) homogenous period for E-P starts in 1987, *including RA*
- Introduction of AVHRR (1982 -1985), and SSM/I (1987)

II

E and P Uncertainties (large!)

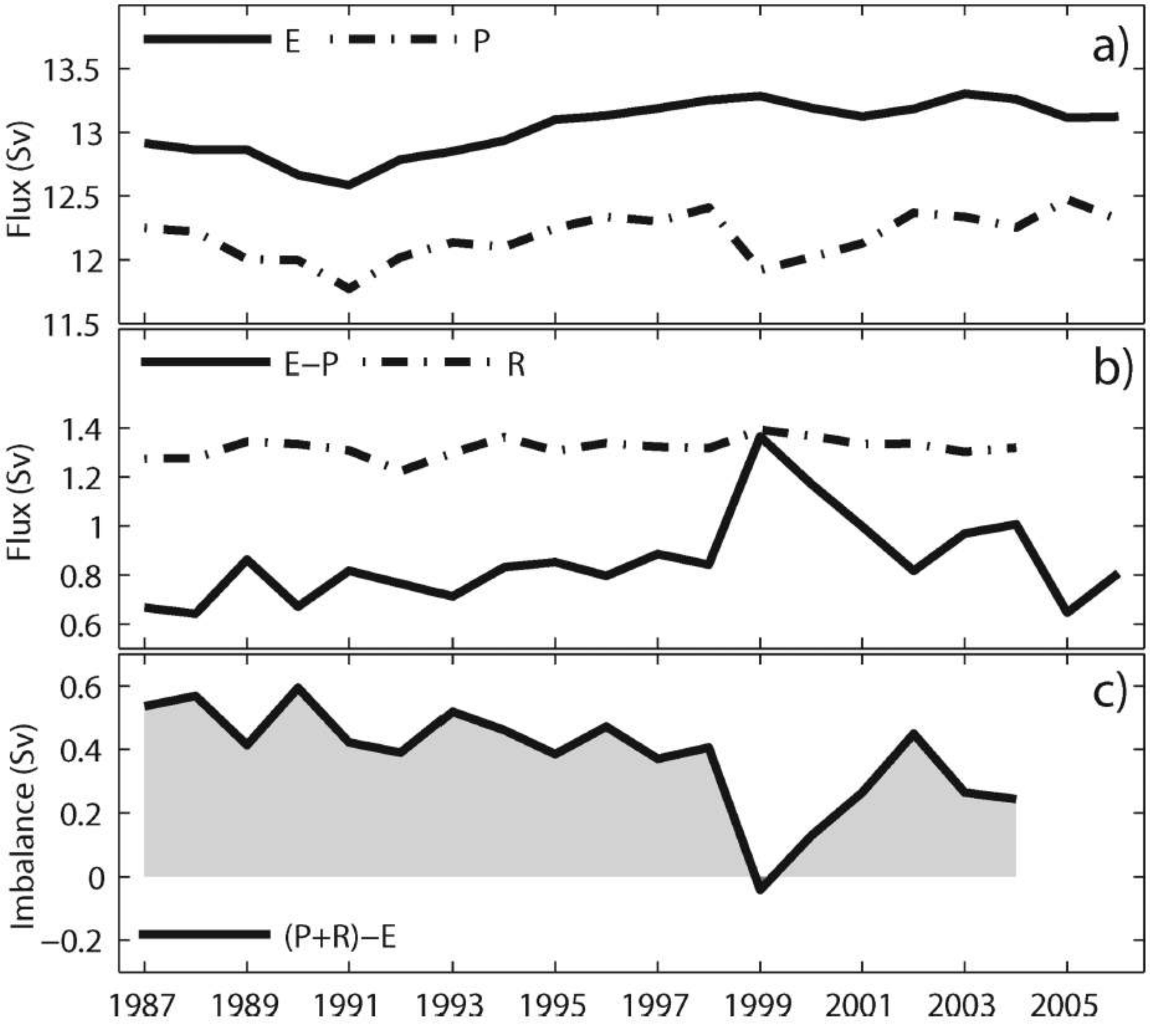
- Not only are there vast differences between E and P products, they are also often internally inconsistent.
- Exceptions: Forced balance (e.g. CORE.2) or state estimates (ECCO v4)



E P+R	OAFlux	NCEP-1	NCEP-2	ERA-40	ERA-Int	CORE.2	MERRA
GPCP	+0.46	−0.41	−2.24	−1.00	−1.15	−0.69	+0.22
NCEP-1	+1.05	+0.18	−1.65	−0.45	−0.54	−0.11	+0.81
NCEP-2	+3.28	+2.42	+0.59	+1.65	+1.70	+2.13	+3.05
ERA-40	+3.87	+3.04	+1.30	+2.41	+2.70	+2.70	+3.61
CMAP	+0.90	+0.03	−1.80	−0.53	−0.71	−0.26	+0.66
CORE.2	+1.01	+0.15	−1.69	−0.45	−0.60	−0.14	+0.78
MERRA	+0.47	−0.40	−2.23	−1.30	−1.14	−0.69	+0.23

II

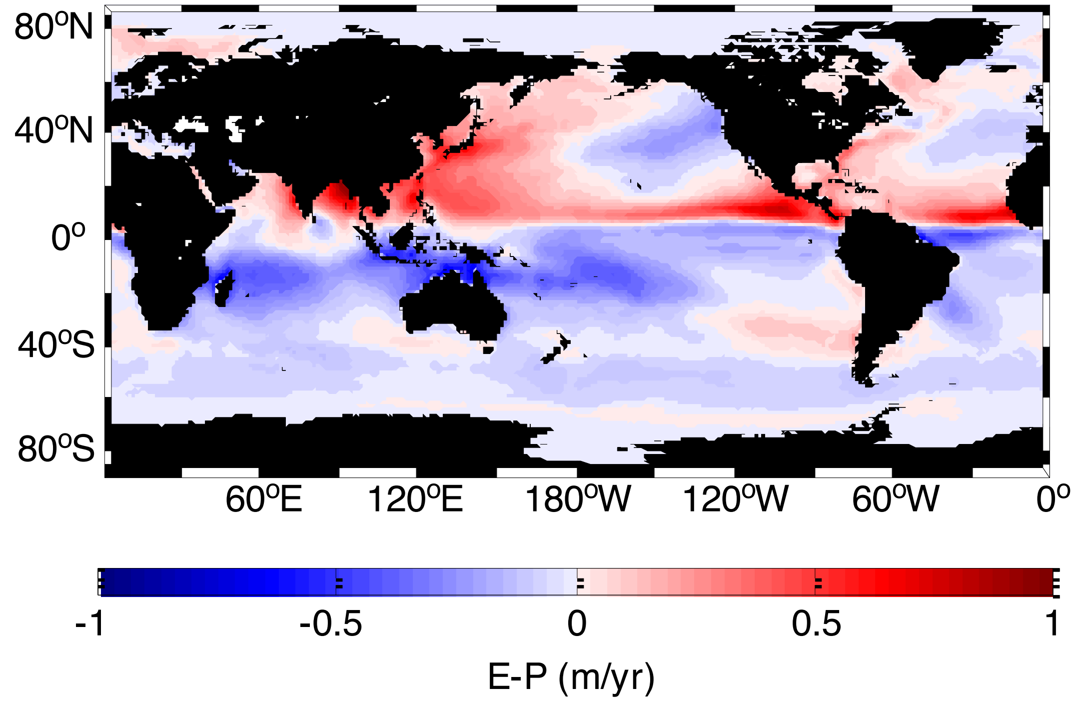
E-P(-R) Balance 1987-2006

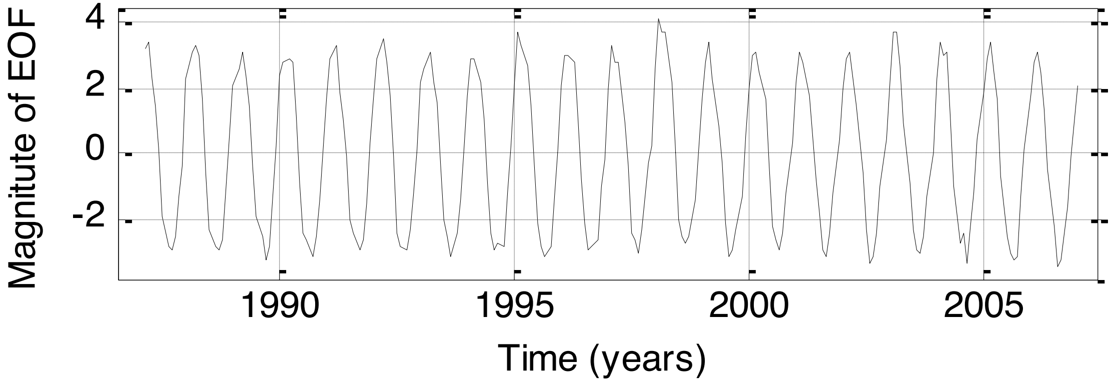


- Imbalance of 0.41 Sv between OAFlux E and GPCP P and Dai&Trenberth R
- Error bars much larger on E, P, possibly R.
- Closes within error bars

II

EOF Analysis of E-P: Mode 1 - 29.4%

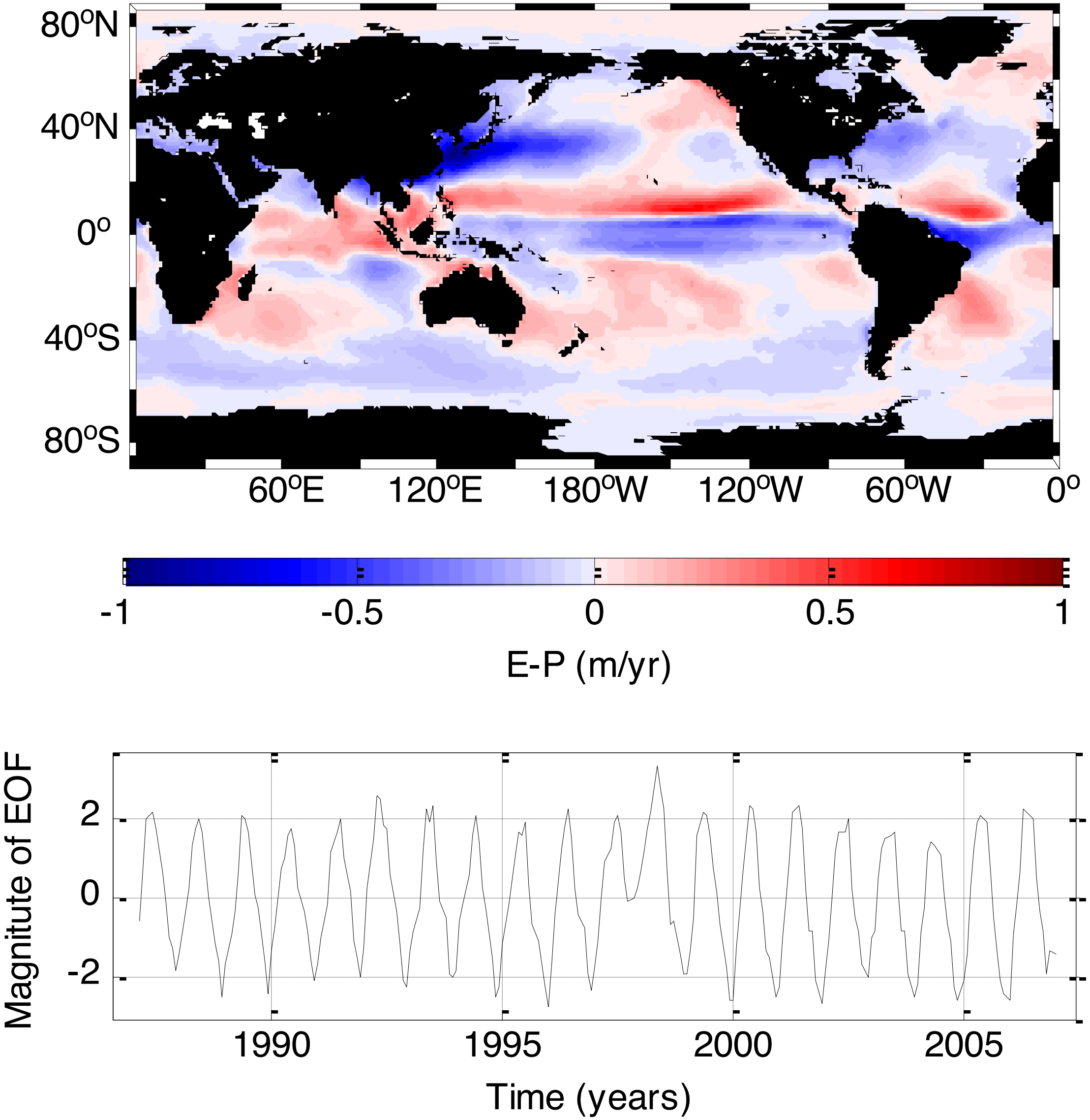




- Seasonal cycle shows ‘flip-flop’ pattern
- Reversal of pattern along eastern boundaries of basins
- No clear change in amplitude over time

II

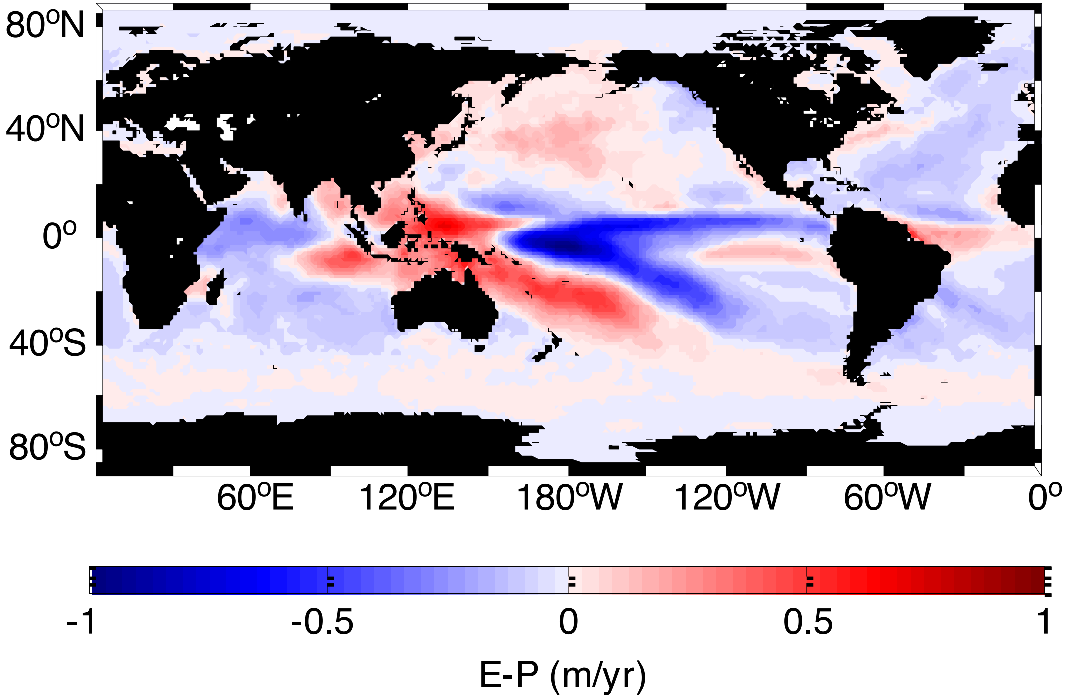
EOF Analysis of E-P: Mode 2 – 9.2%

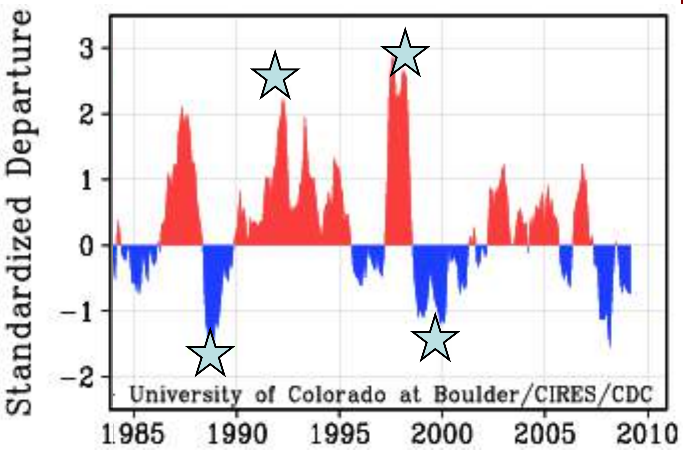


- Intertropical Convergence Zone (ITCZ) shift
- Kuroshio and Gulf stream are clearly negative
- 12-month period of cycle, ENSO effects around 1997
- No clear change in amplitude

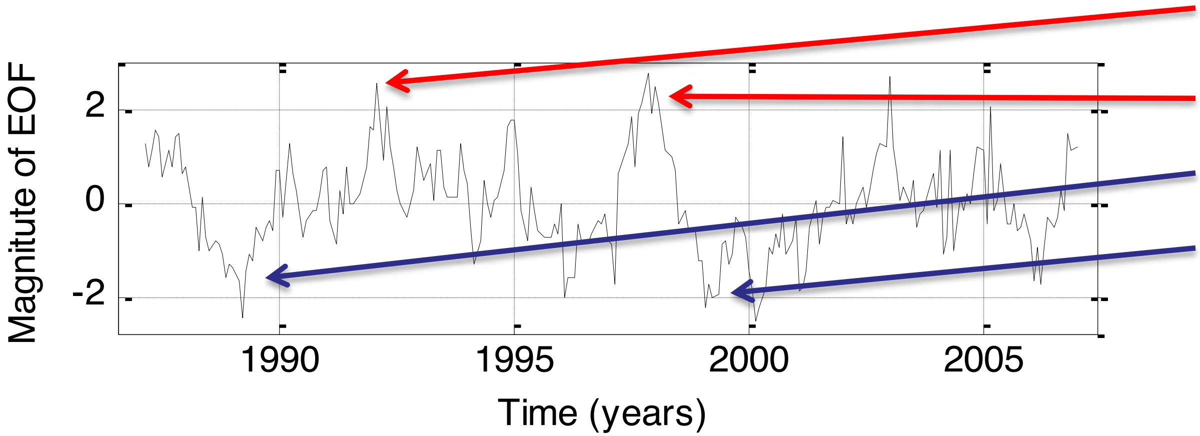
II

EOF Analysis of E-P: Mode 3 – 4.8%





ENSO Multivariate Index (MEI). From: NOAA



1992/1993 El Niño

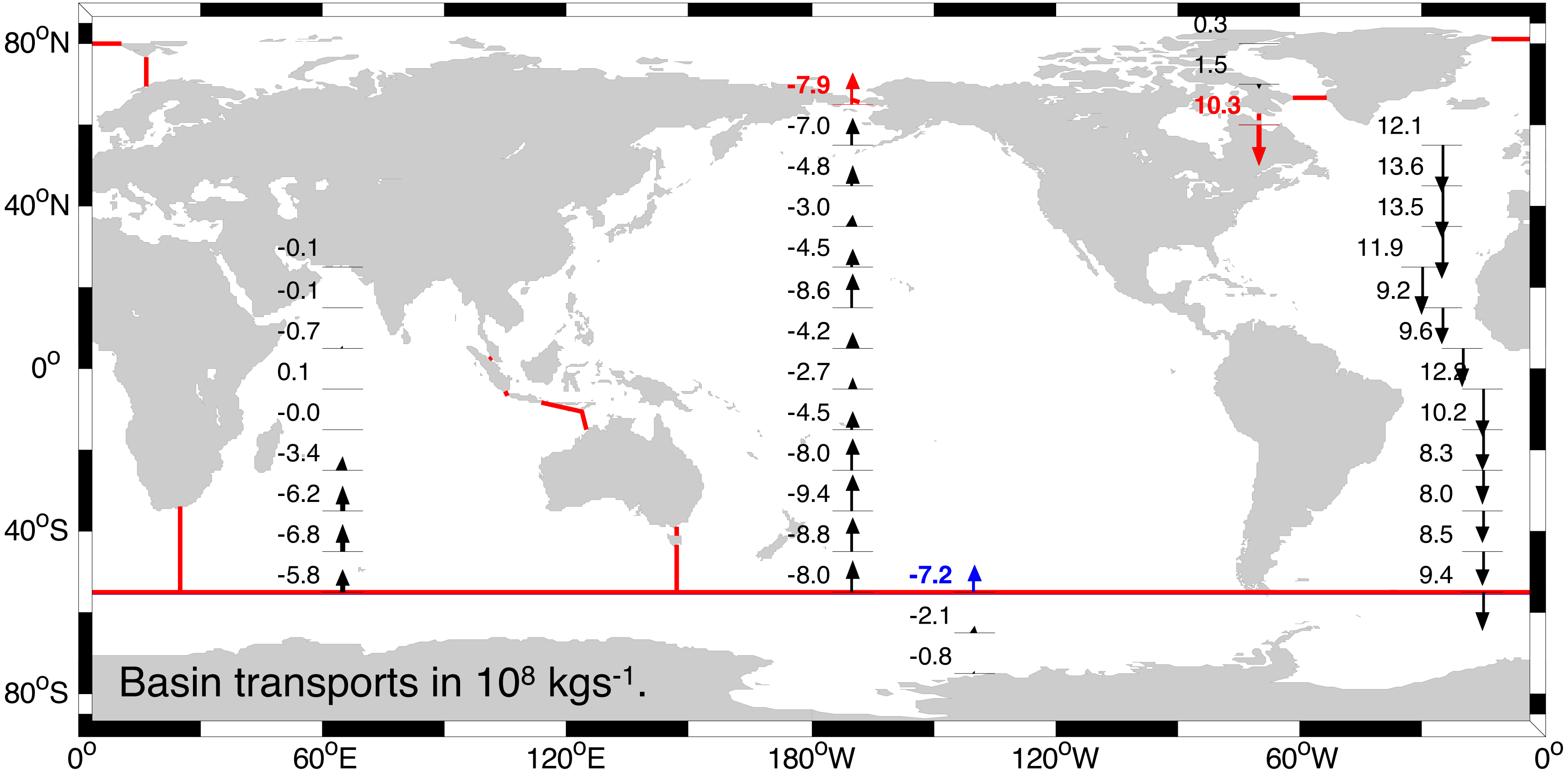
1997 El Niño

1989 La Niña

1999/2000 La Niña

II

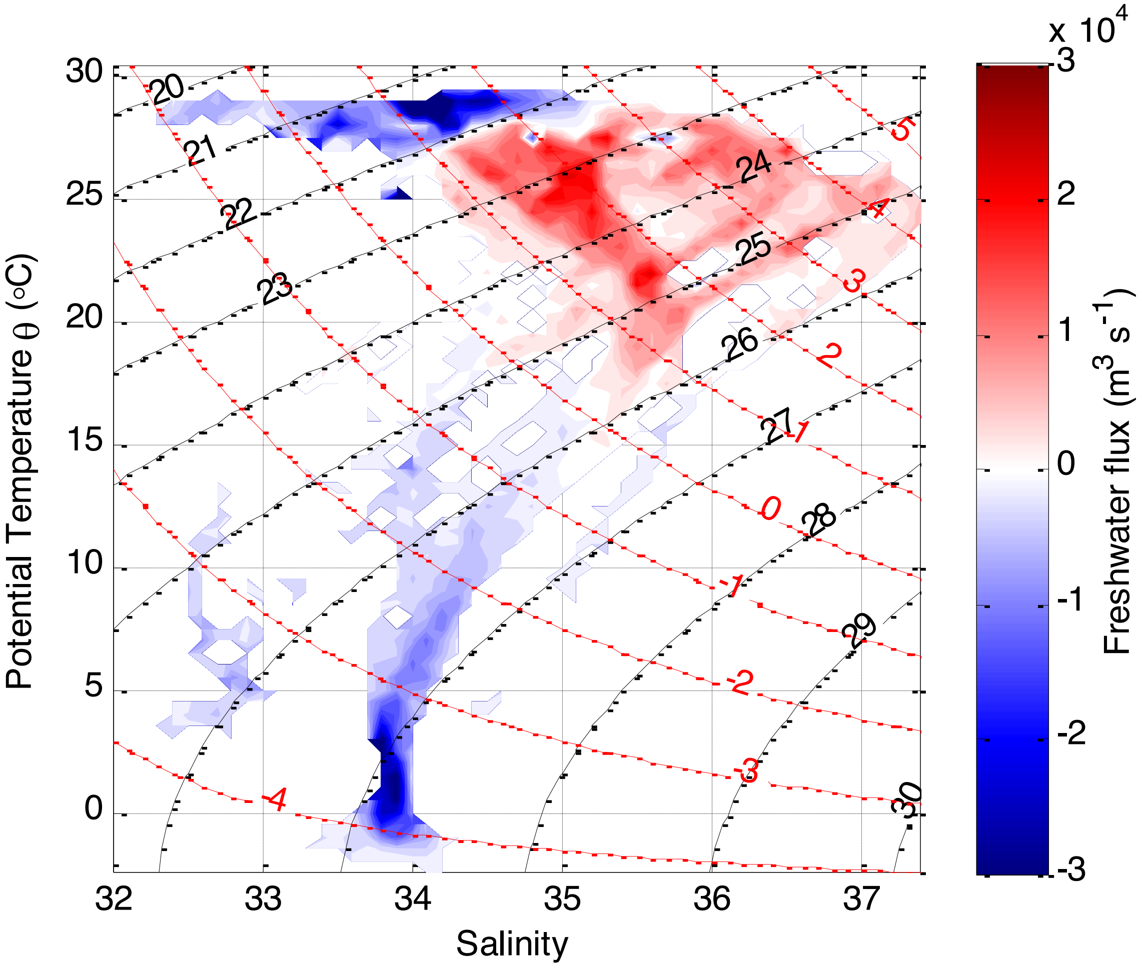
Basin Freshwater Transports



Basin transports in 10^8 kgs^{-1}.

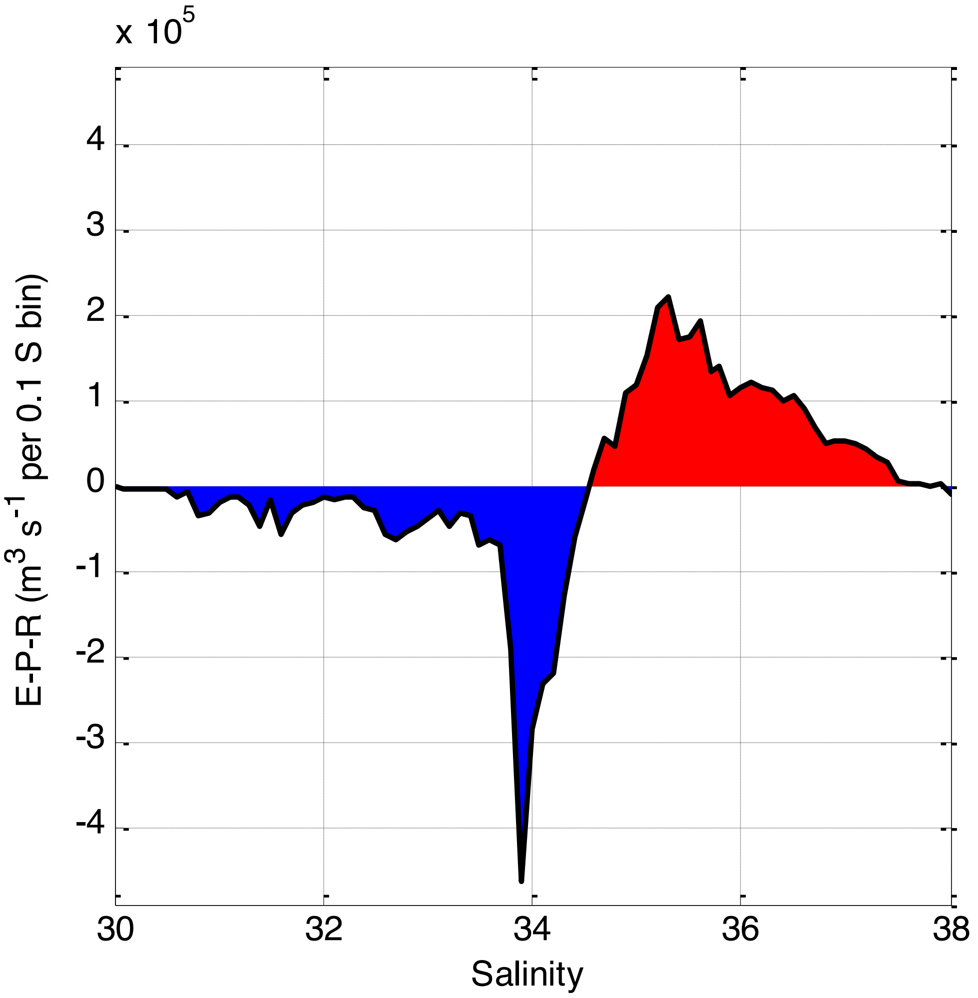
- Arctic Ocean freshwater balance matches observations (freshwater +~3*10^8 kgs^{-1})
- Significant changes compared to Wijffels et al. (1992)

Salinity Variance Estimates



- Fresher areas have net input of freshwater
- Salty areas have net loss of freshwater
- Generation of salinity variance
- Dissipation through downgradient flux

Salinity Variance Estimates



- This is integrating the previous diagram
- Bin size: 0.1 in salinity
- Net evaporation (~salt input) at high salinities, net precipitation in fresh areas
- Down-gradient flux in the interior (advective and diffusive)

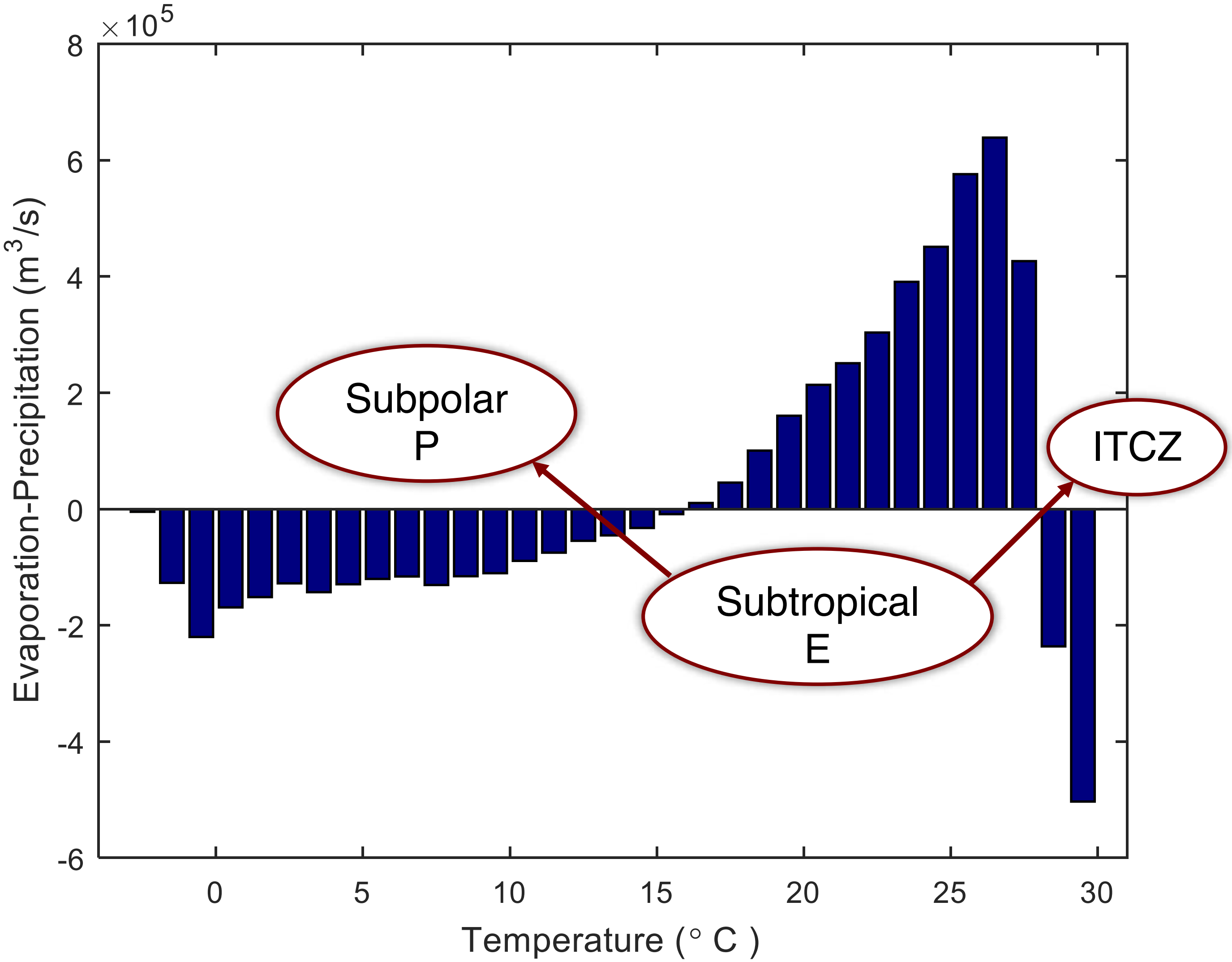
III Sources and Sinks of the Global Water Cycle

Trivial (but sometimes overlooked):

E and P occur on different space- and time-scales

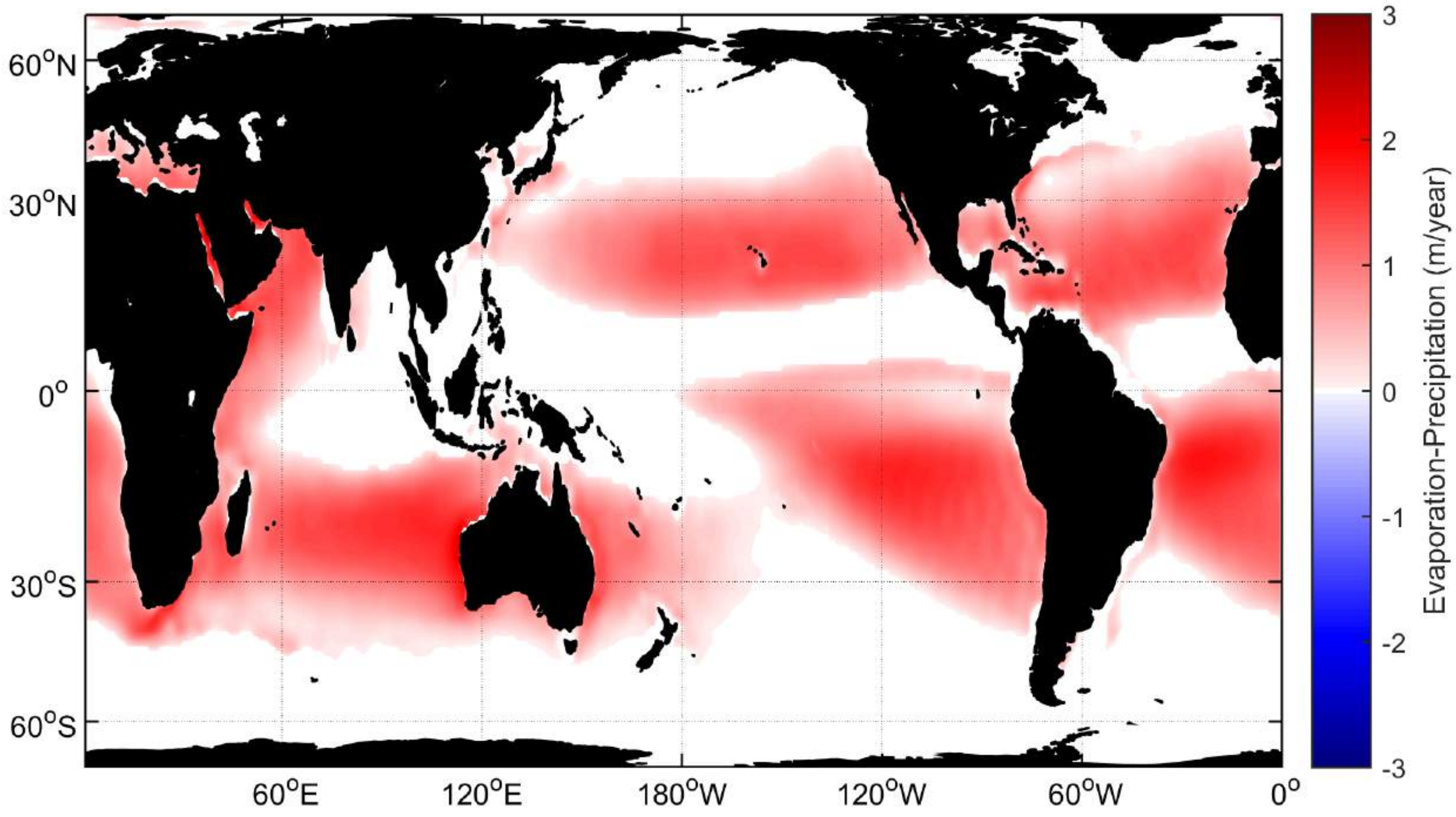
III

Sources and Sinks of the Global Water Cycle



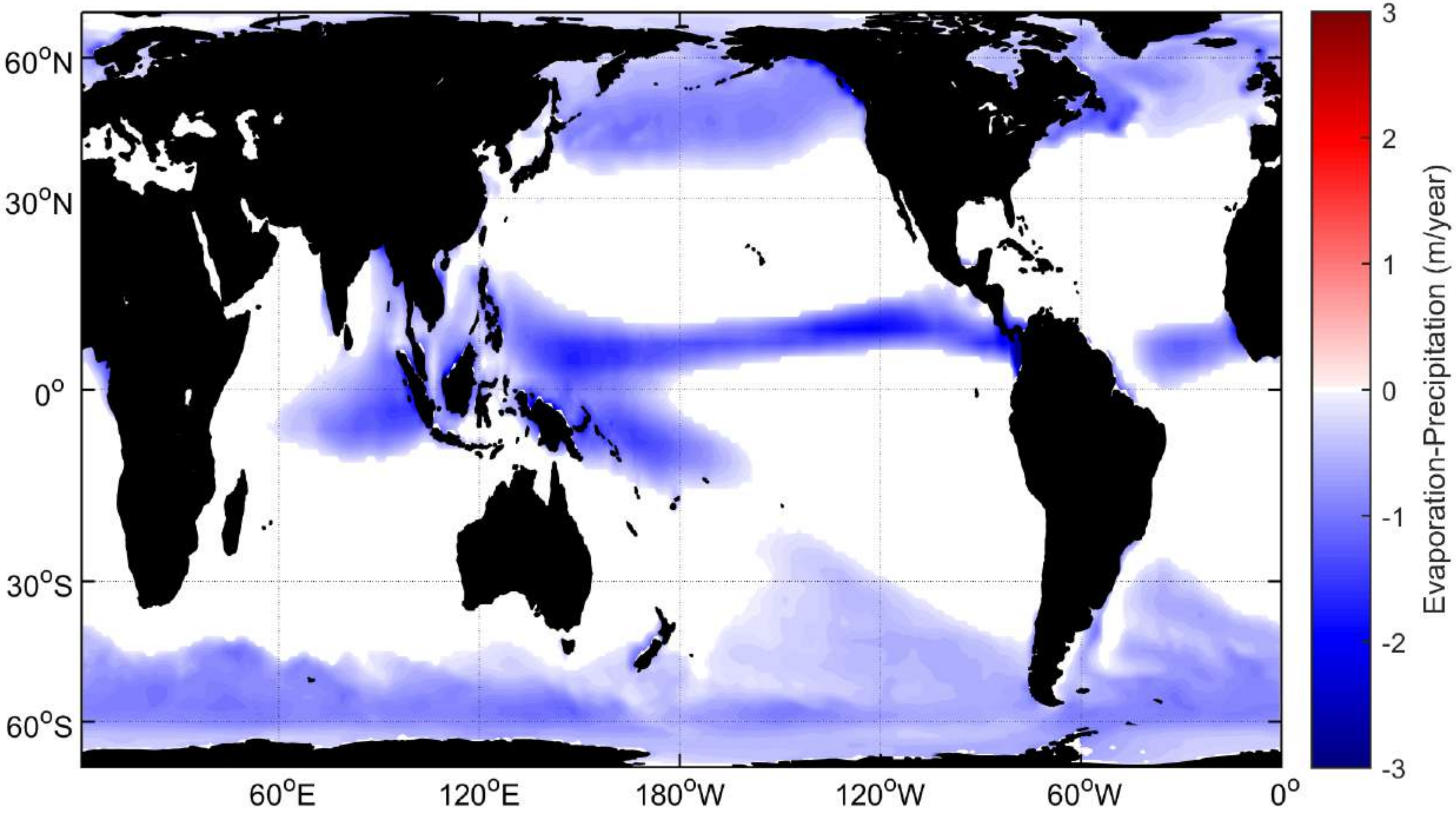
Evaporation-Precipitation binned by SST

III Sources and Sinks of the Global Water Cycle



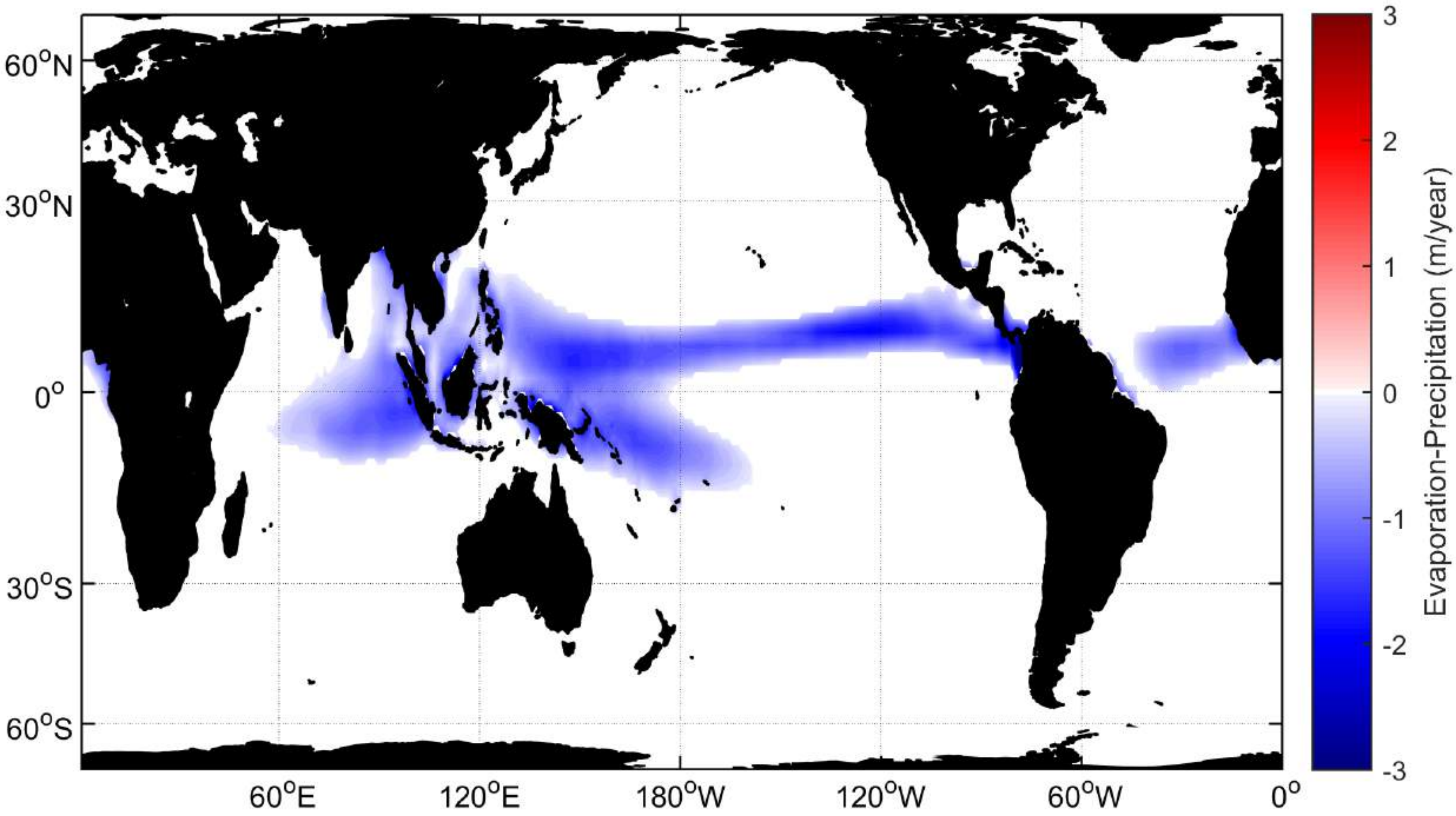
Positive Component (E>P)

III Sources and Sinks of the Global Water Cycle



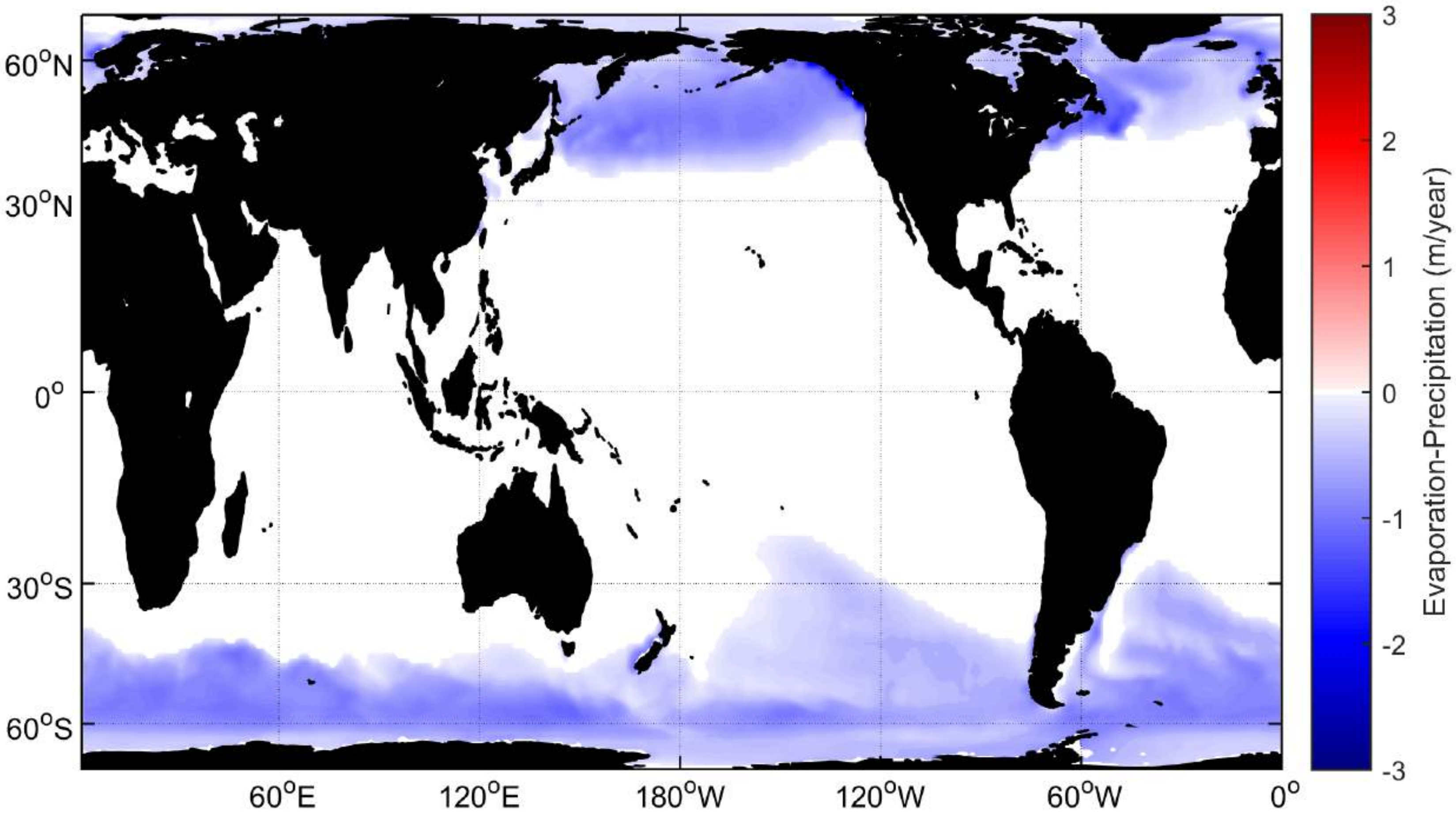
Negative Component (P>E)

III Sources and Sinks of the Global Water Cycle



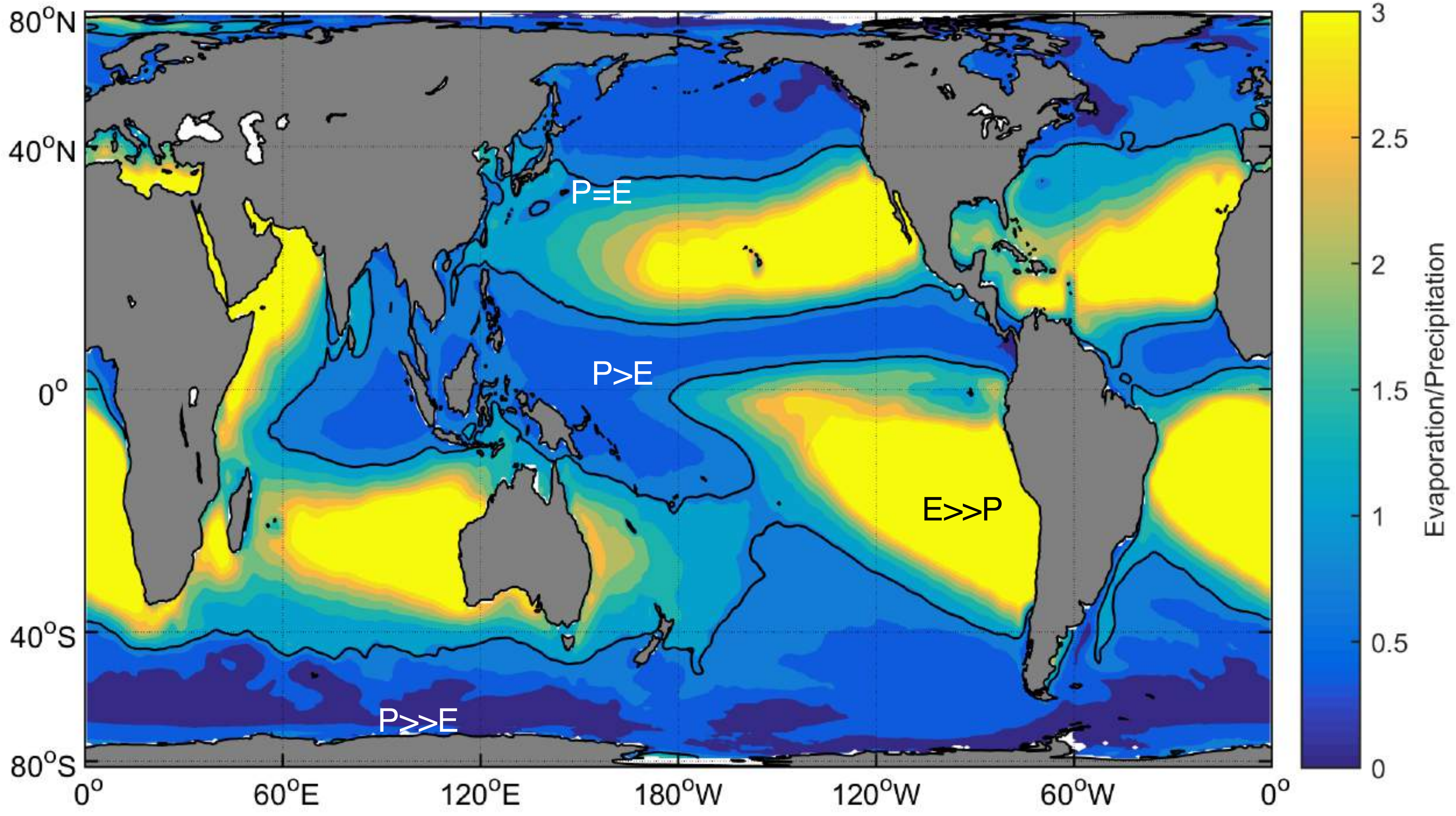
P>E in the ITCZ

III Sources and Sinks of the Global Water Cycle



P>E outside the ITCZ (“high” latitudes)

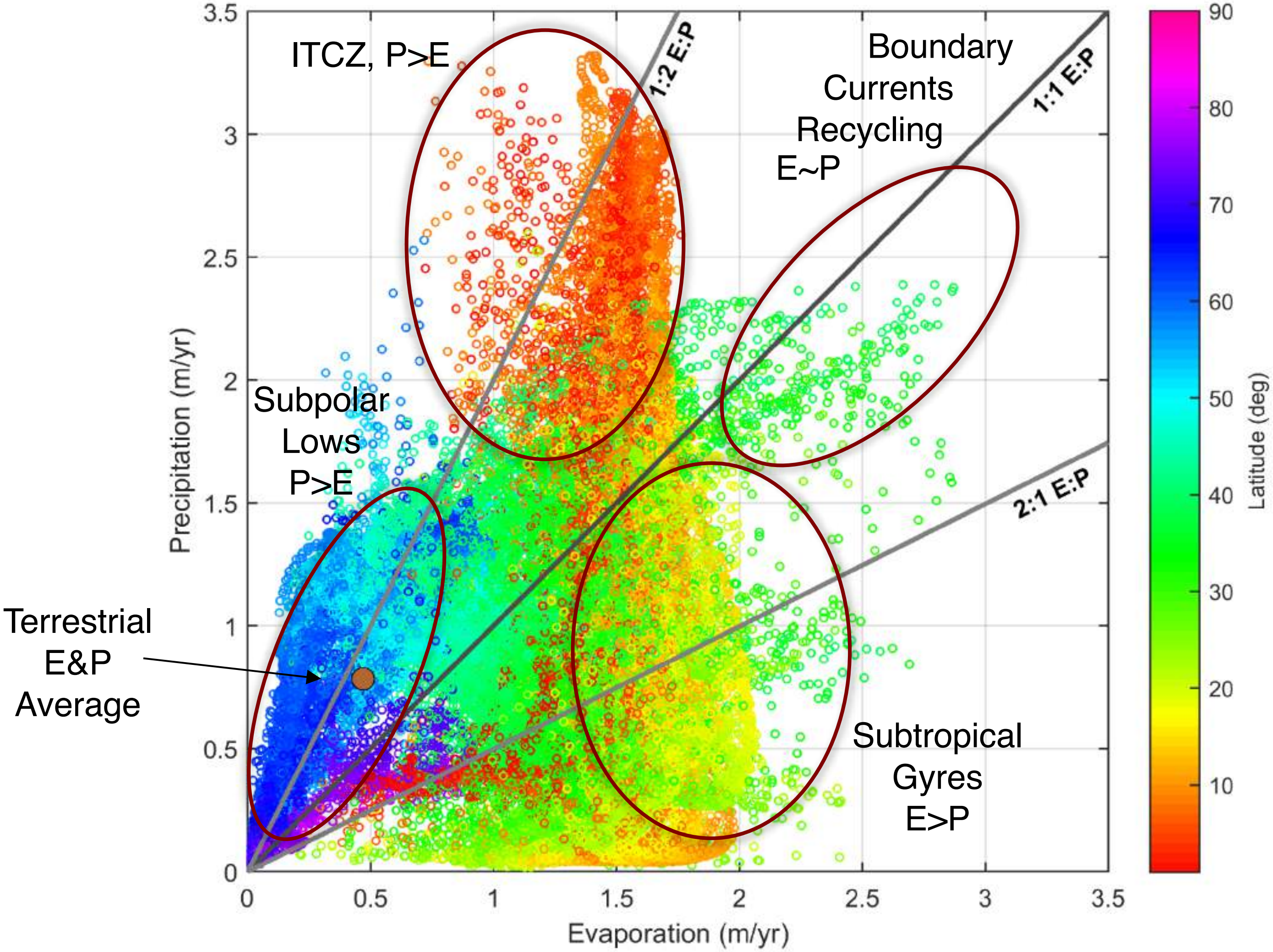
III Sources and Sinks of the Global Water Cycle



E:P Ratio, quite different from E-P (black line is 1:1)

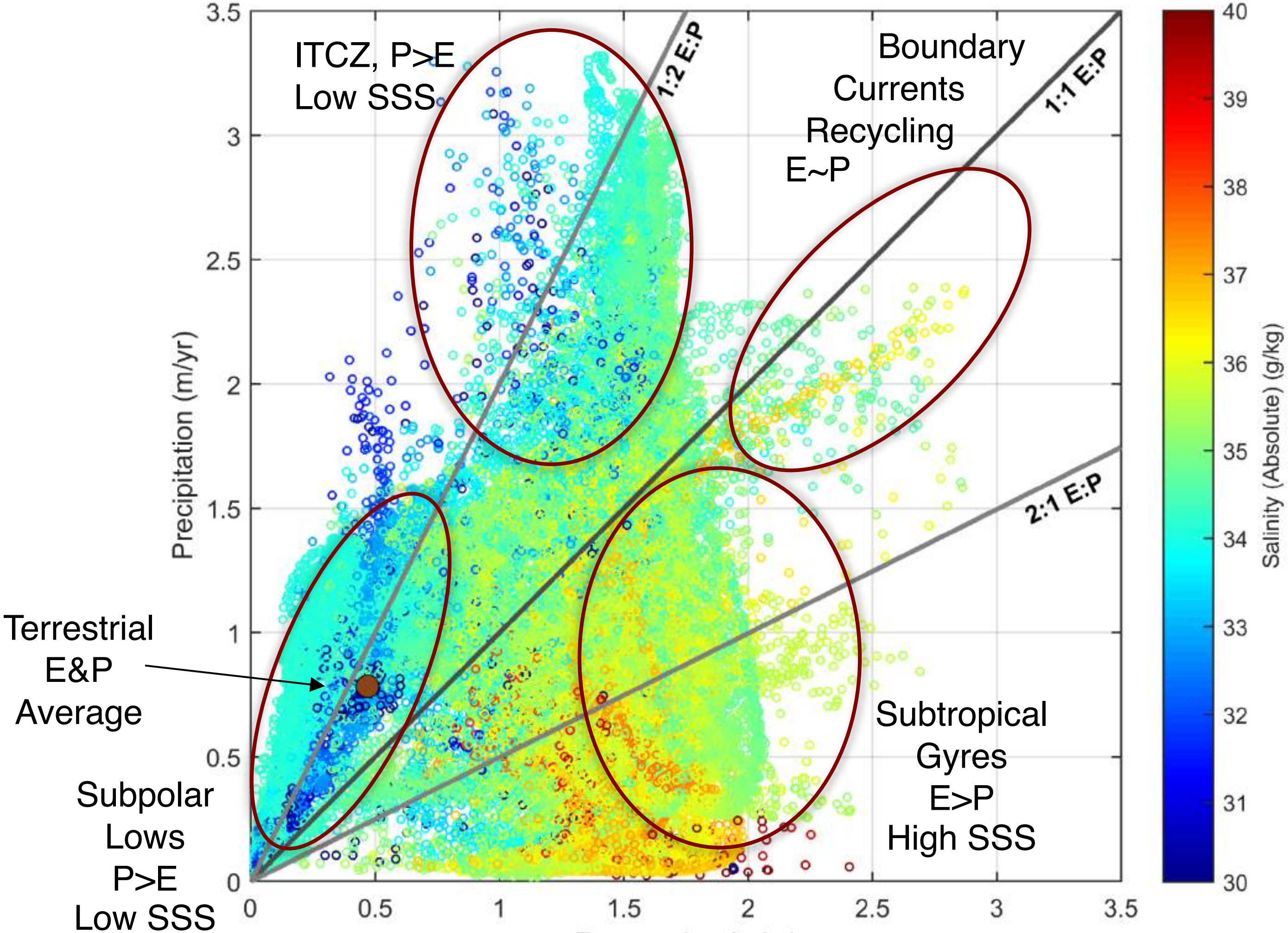
III

Sources and Sinks of the Global Water Cycle



Global E:P by Latitude

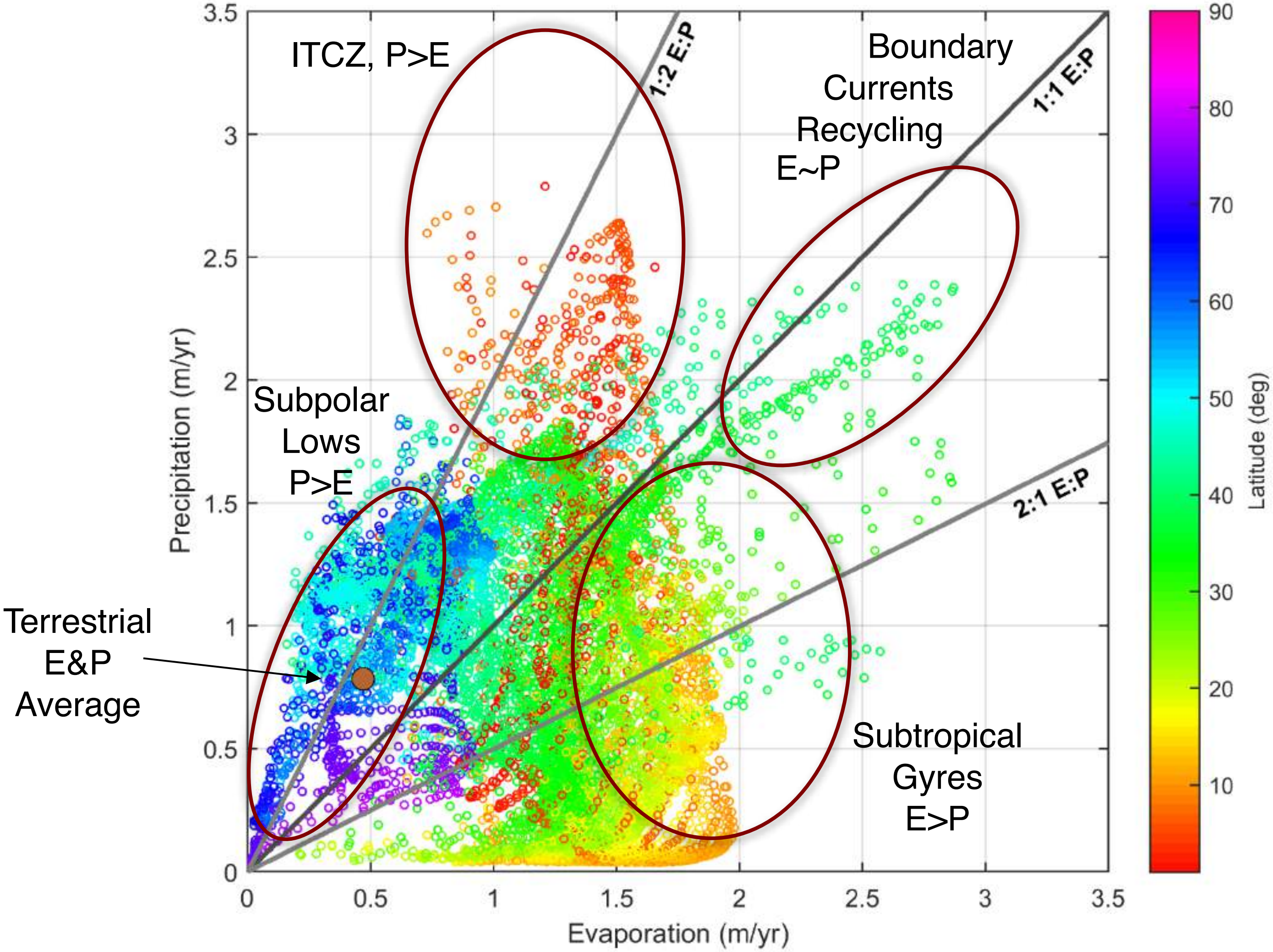
III Sources and Sinks of the Global Water Cycle



Global E:P by Absolute Salinity (g/kg)

III

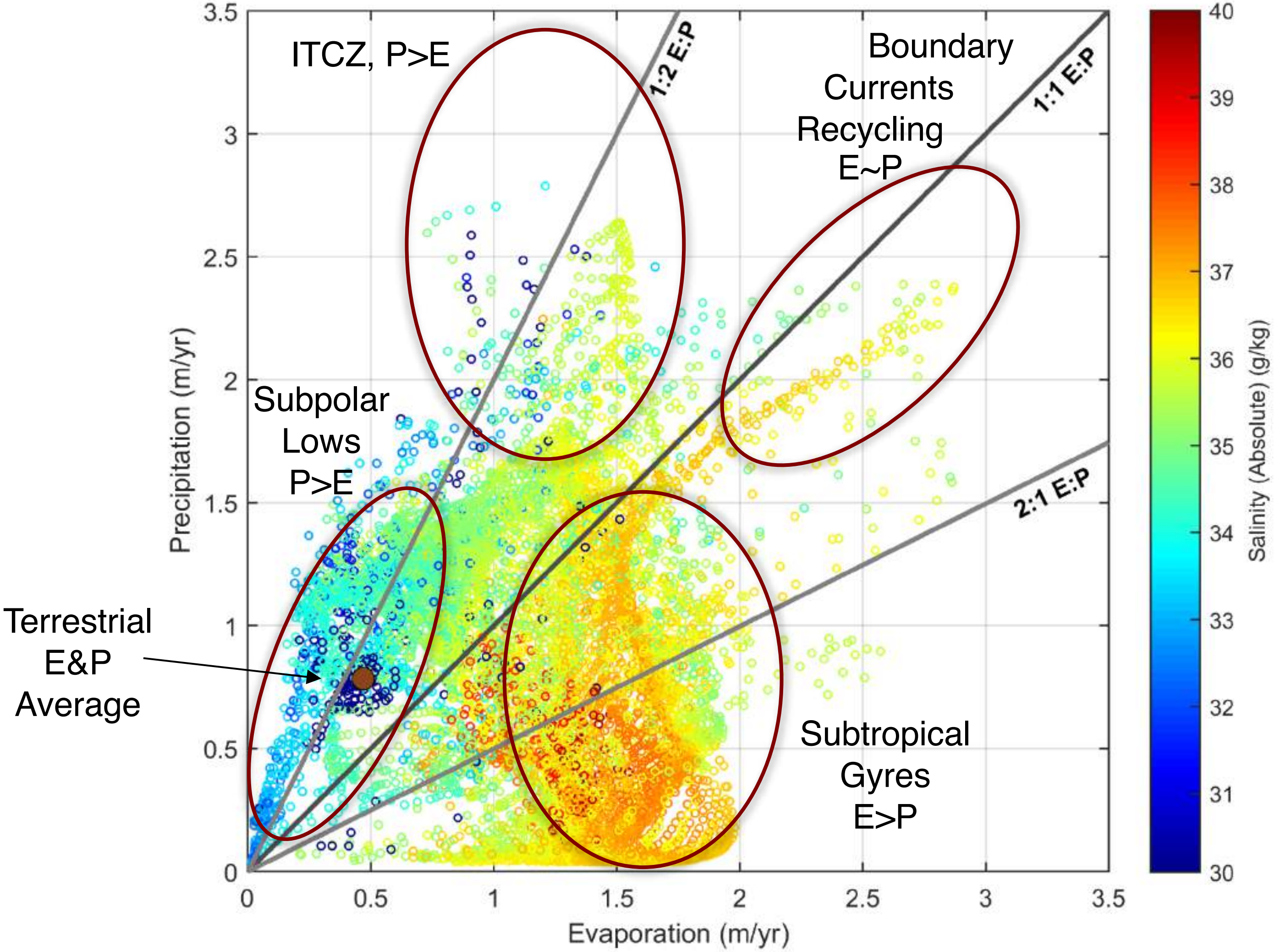
Sources and Sinks of the Global Water Cycle



Atlantic E:P by Latitude

III

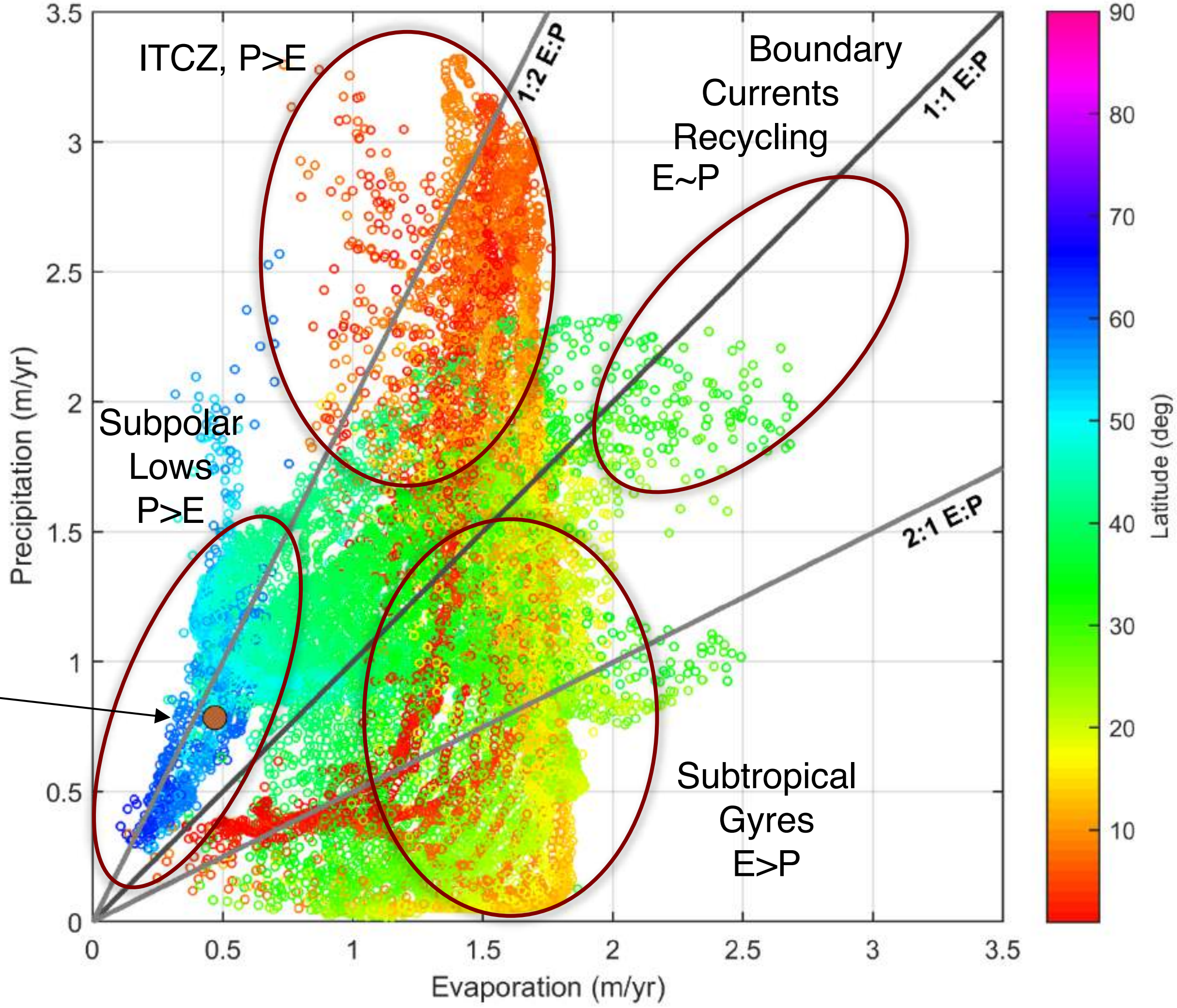
Sources and Sinks of the Global Water Cycle



Atlantic E:P by Absolute Salinity (g/kg)

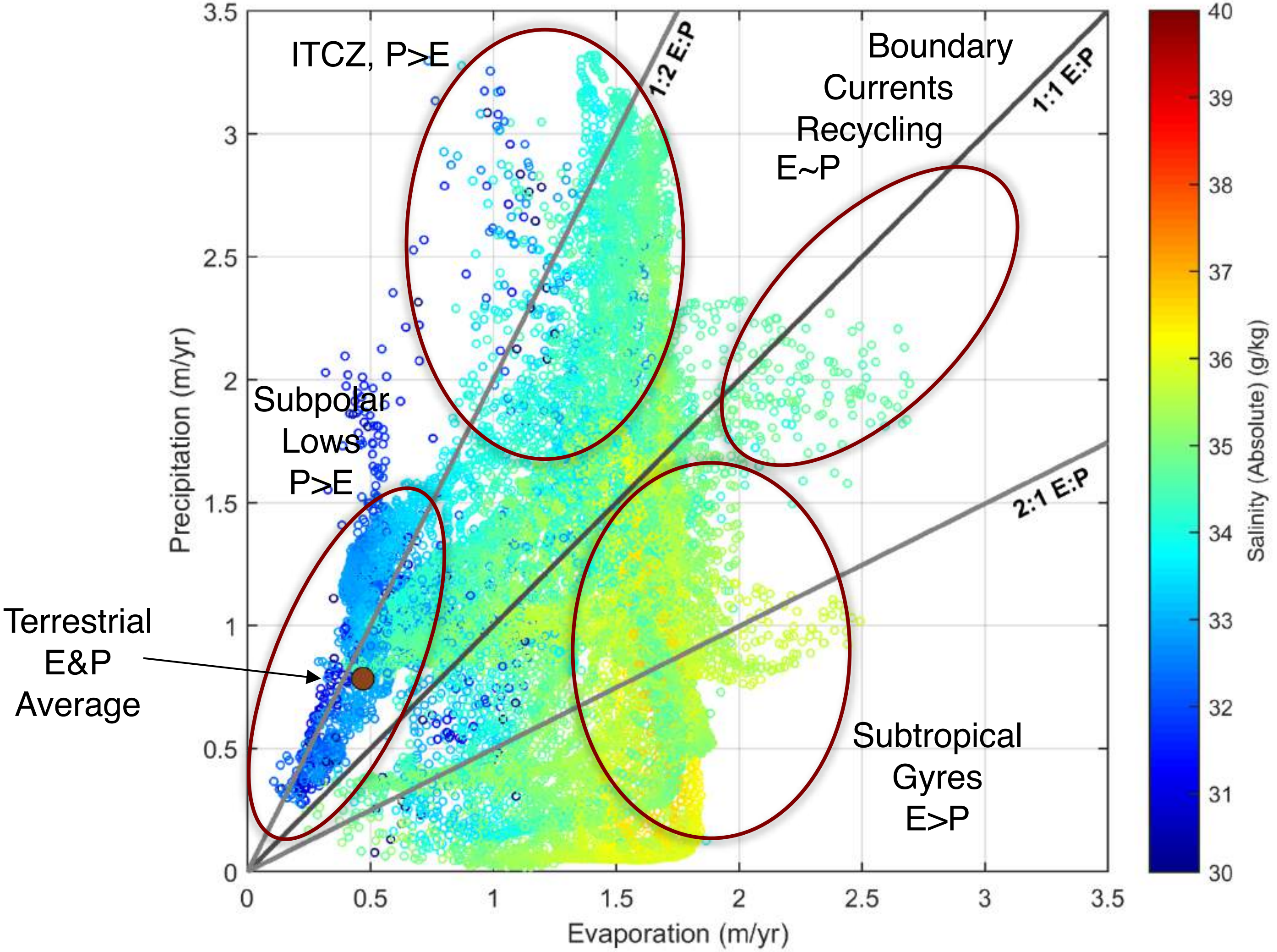
III

Sources and Sinks of the Global Water Cycle



Pacific Ocean E:P by Latitude

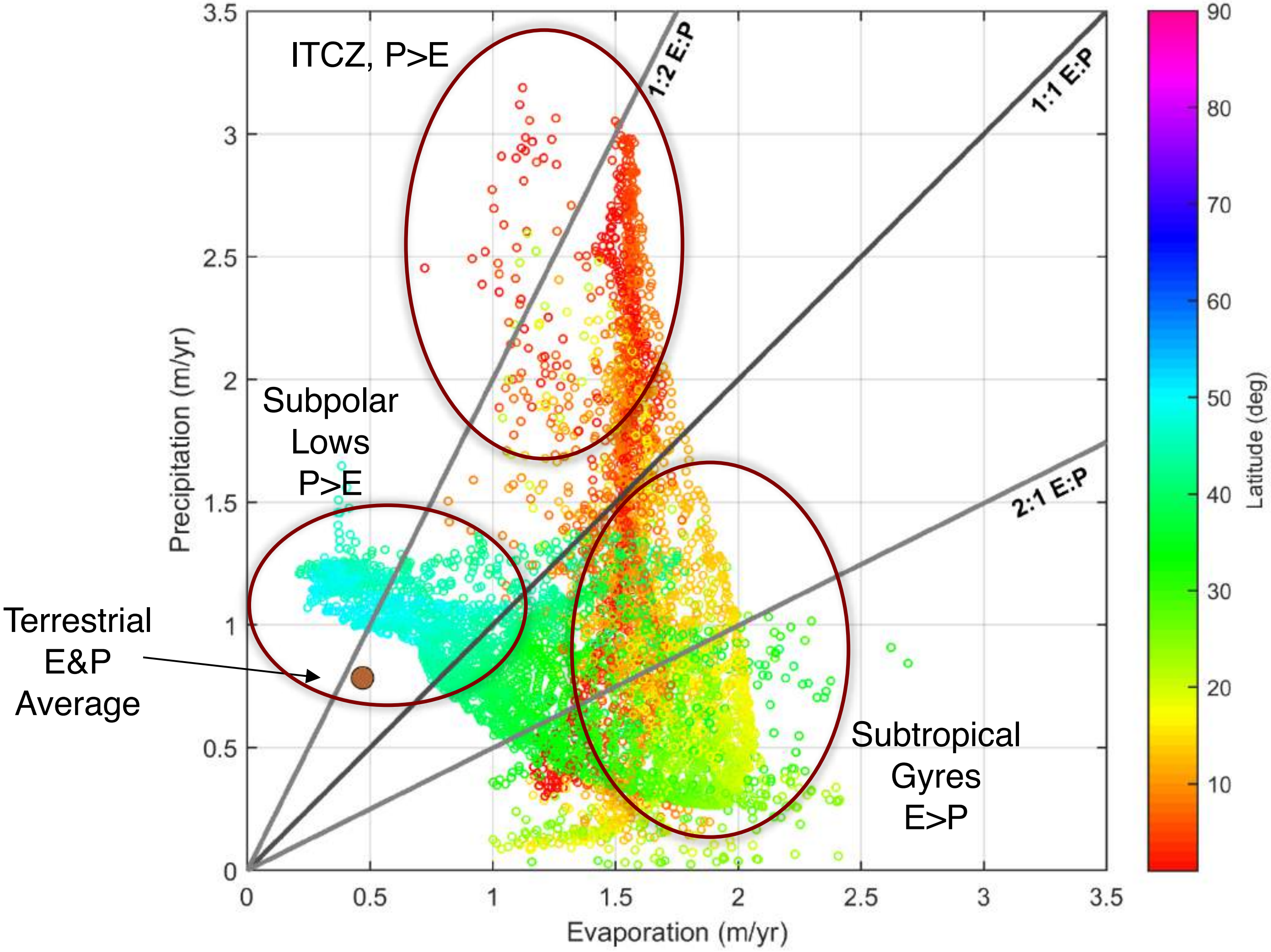
Sources and Sinks of the Global Water Cycle



Pacific Ocean E:P by Absolute Salinity (g/kg)

III

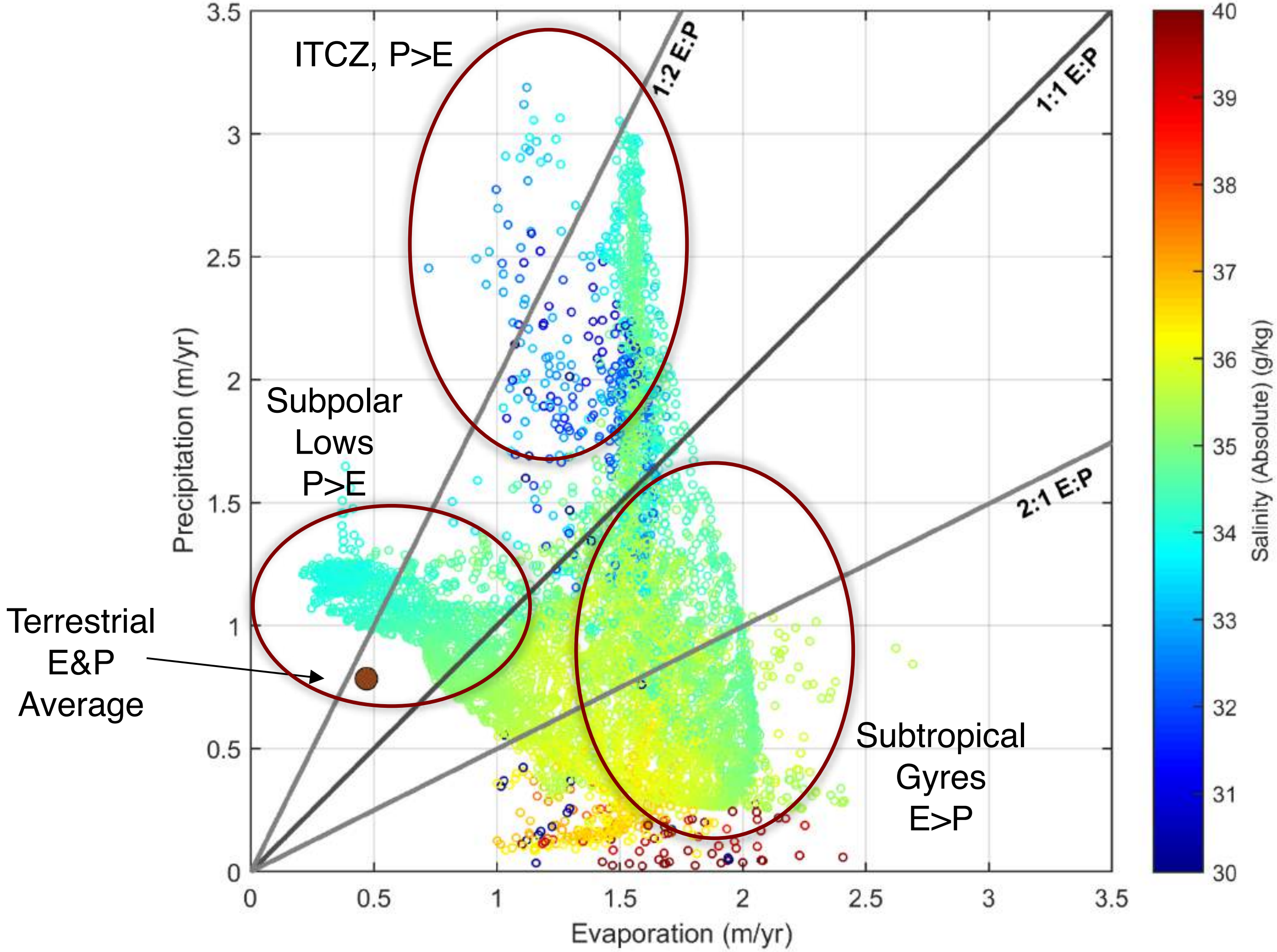
Sources and Sinks of the Global Water Cycle



Indian Ocean E:P by Latitude

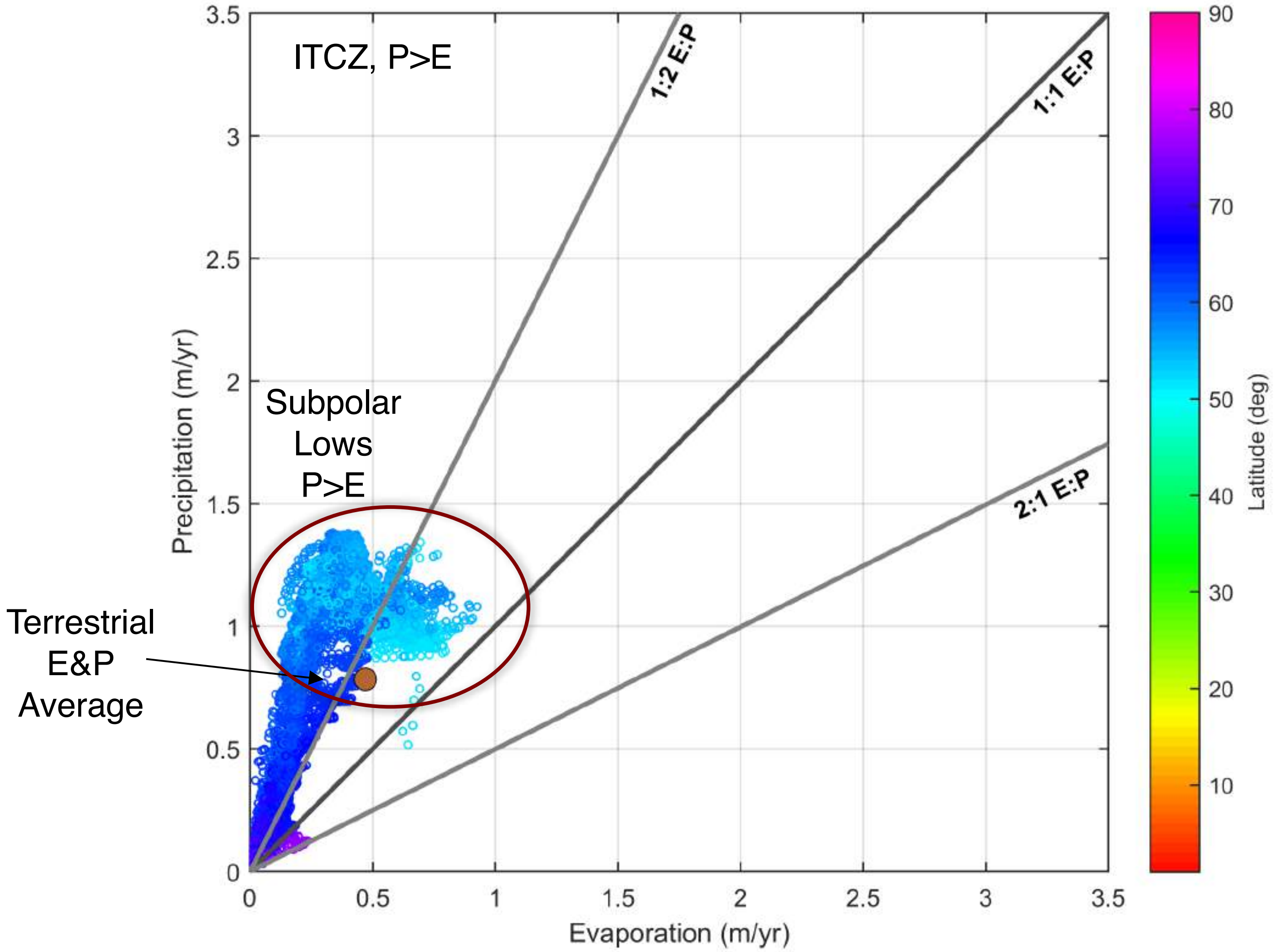
III

Sources and Sinks of the Global Water Cycle



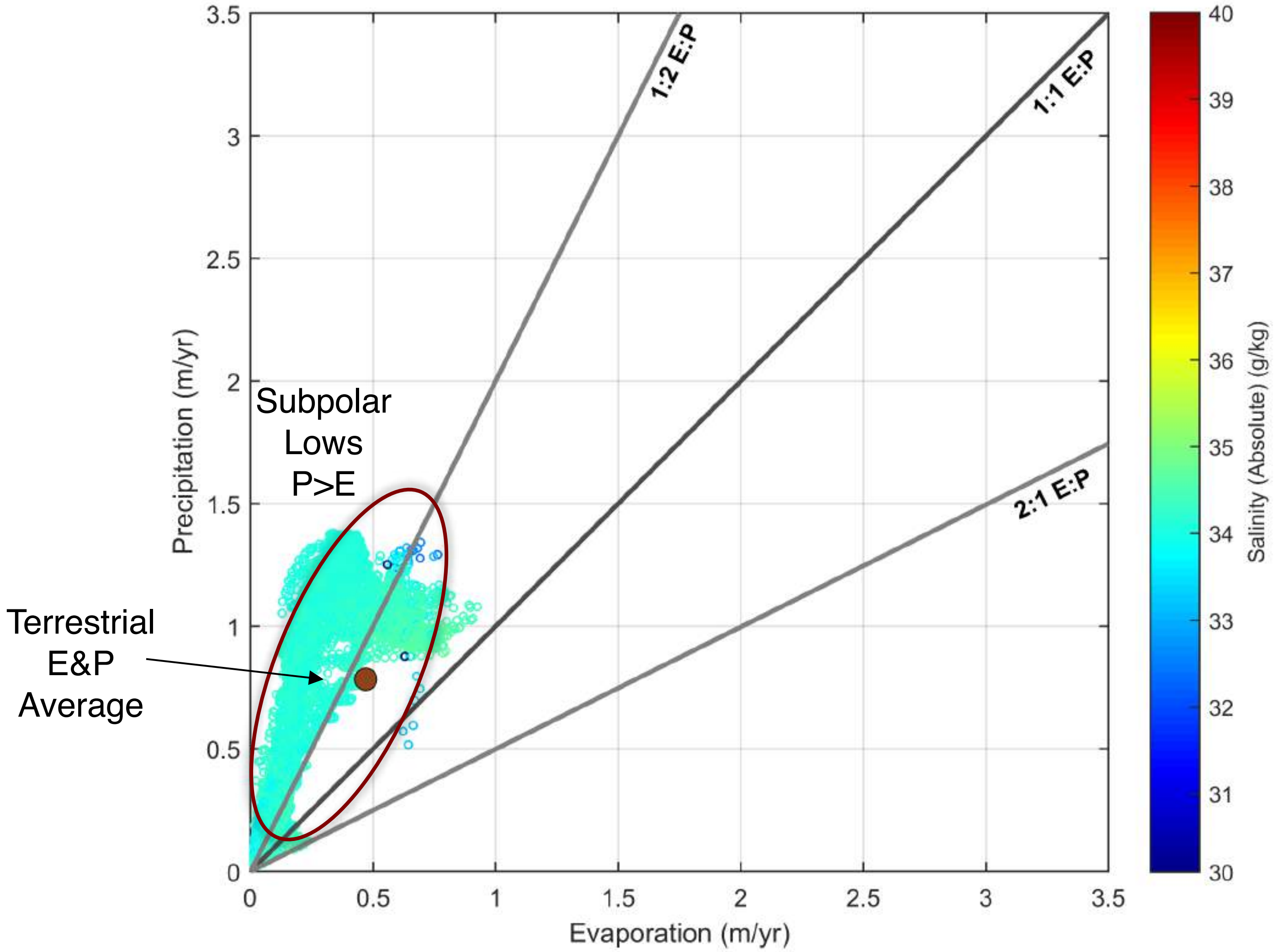
Indian Ocean E:P by Absolute Salinity (g/kg)

III Sources and Sinks of the Global Water Cycle



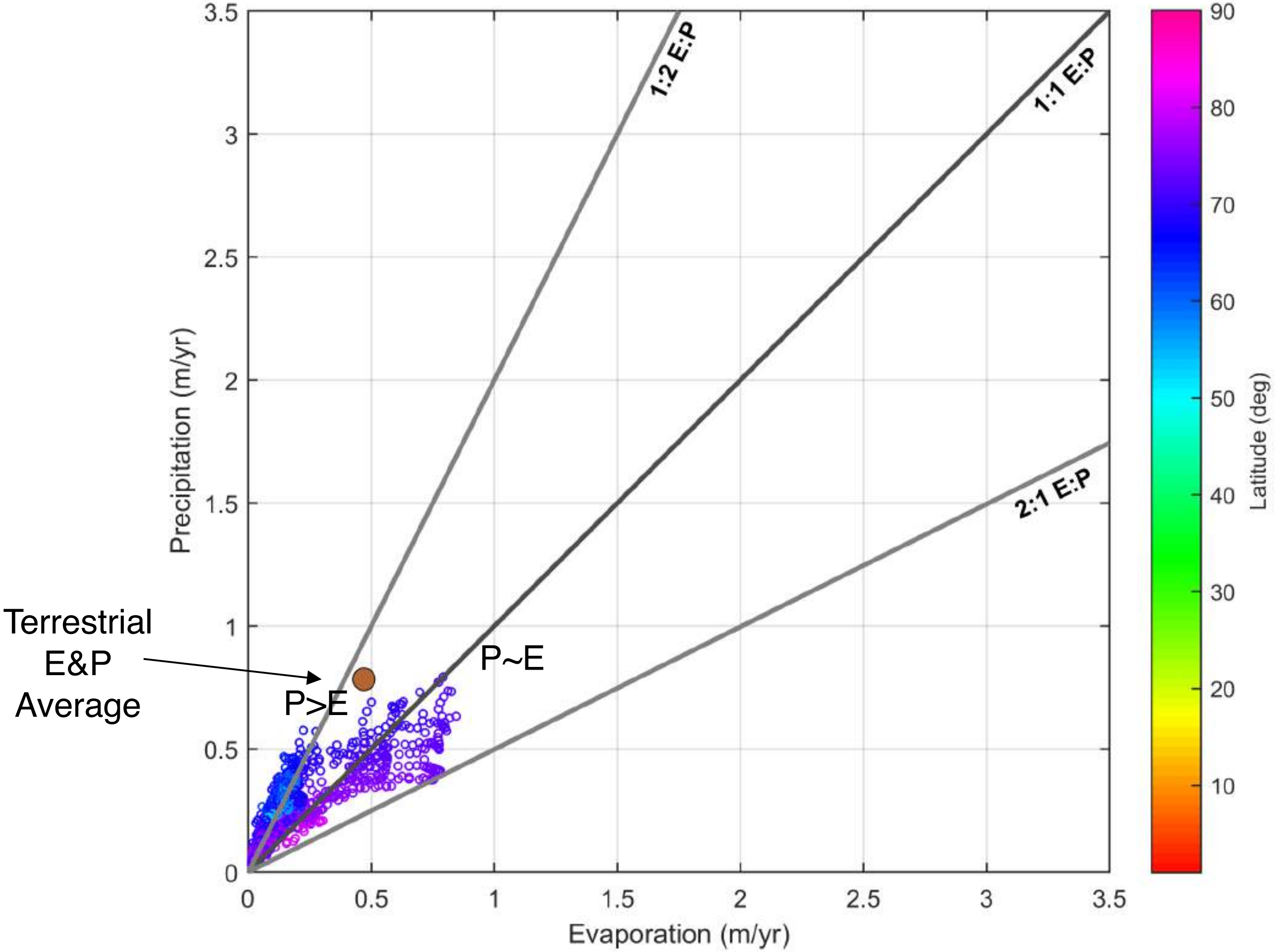
Southern Ocean E:P by Latitude

III Sources and Sinks of the Global Water Cycle



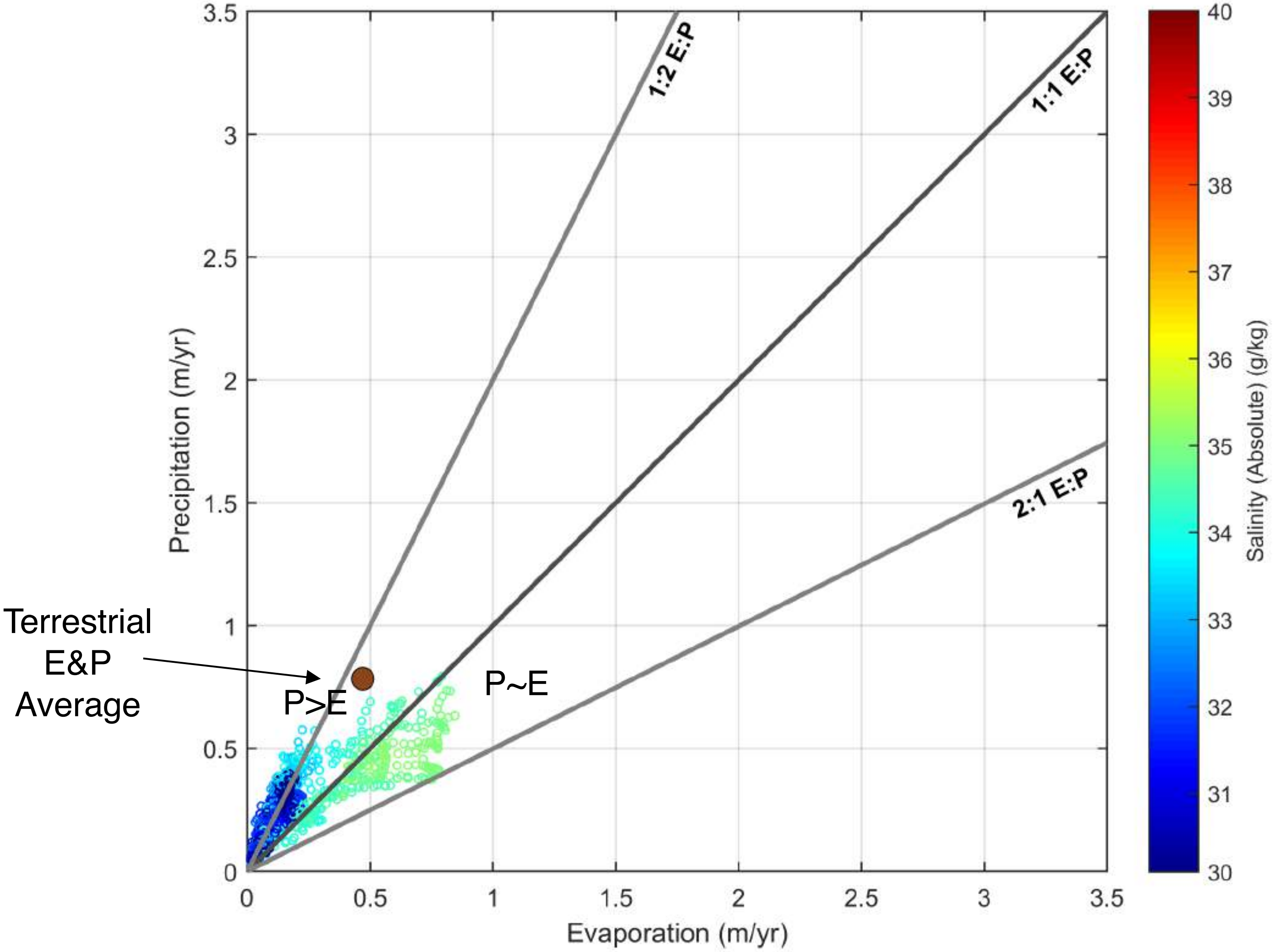
Southern Ocean E:P by Absolute Salinity (g/kg)

III Sources and Sinks of the Global Water Cycle



Arctic E:P by Latitude

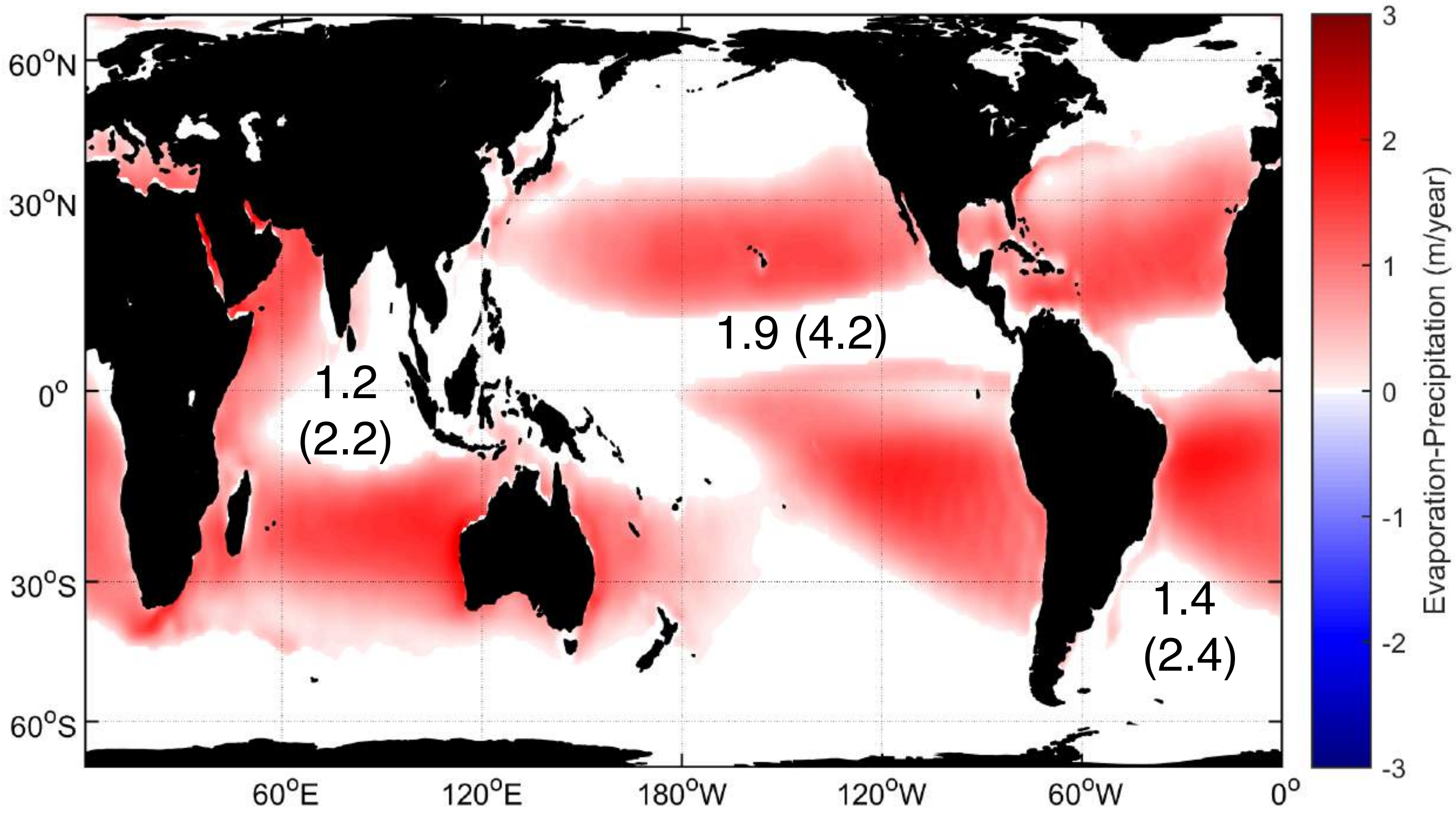
III Sources and Sinks of the Global Water Cycle



Arctic E:P by Absolute Salinity (g/kg)

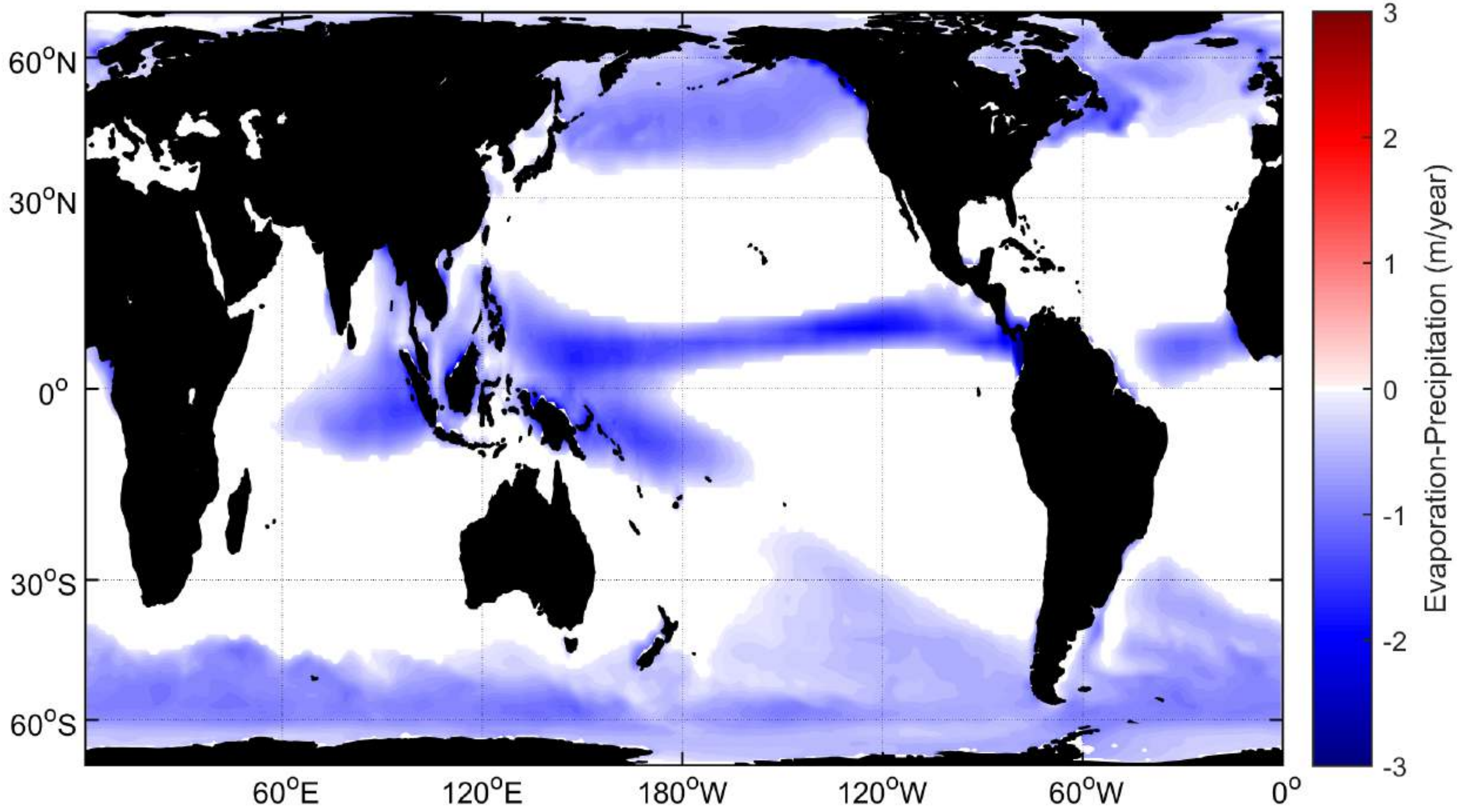
III

Sources and Sinks of the Global Water Cycle



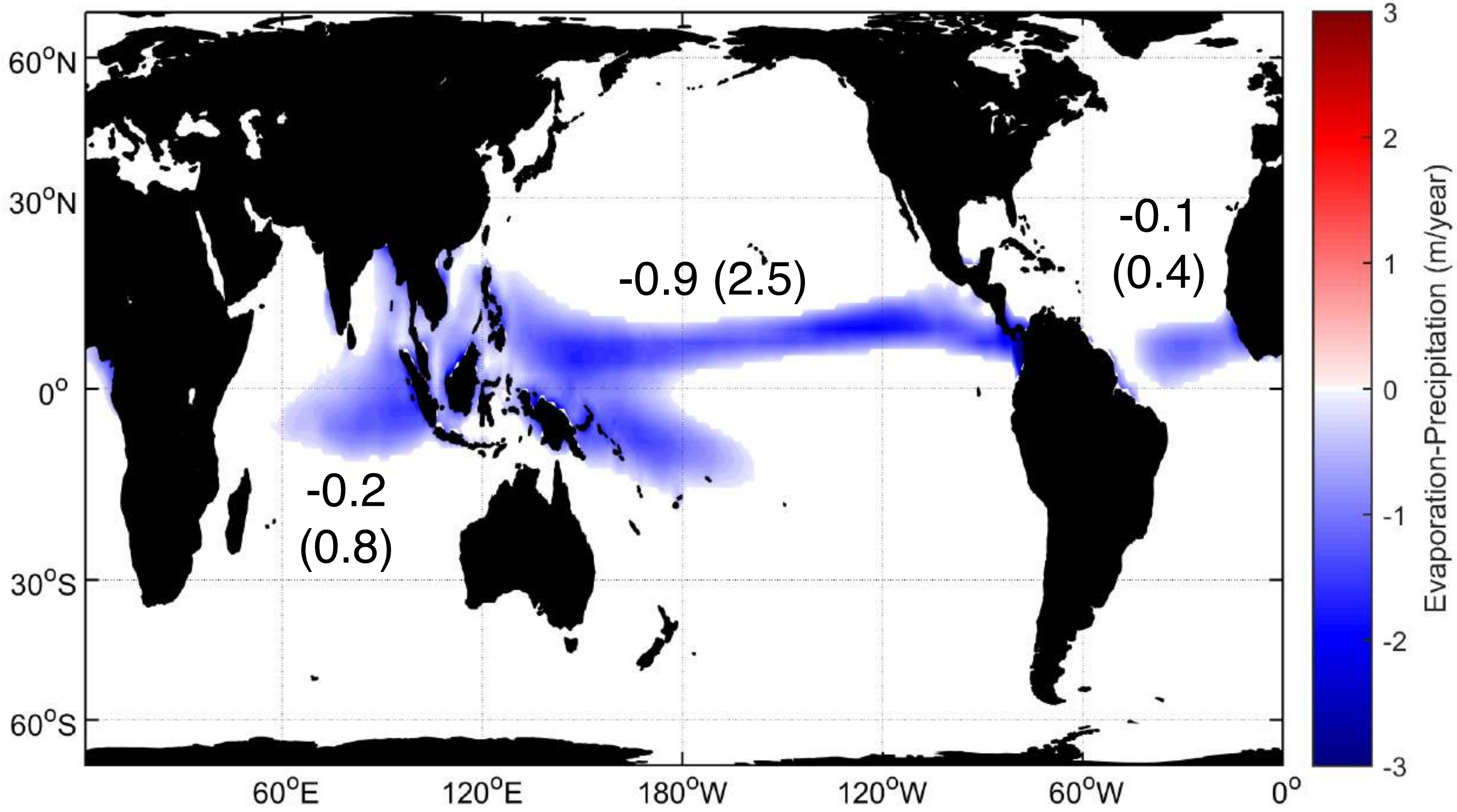
Global export: ~4.5 Sv. E in E>P: 8.8 Sv (~2:1)

III Sources and Sinks of the Global Water Cycle



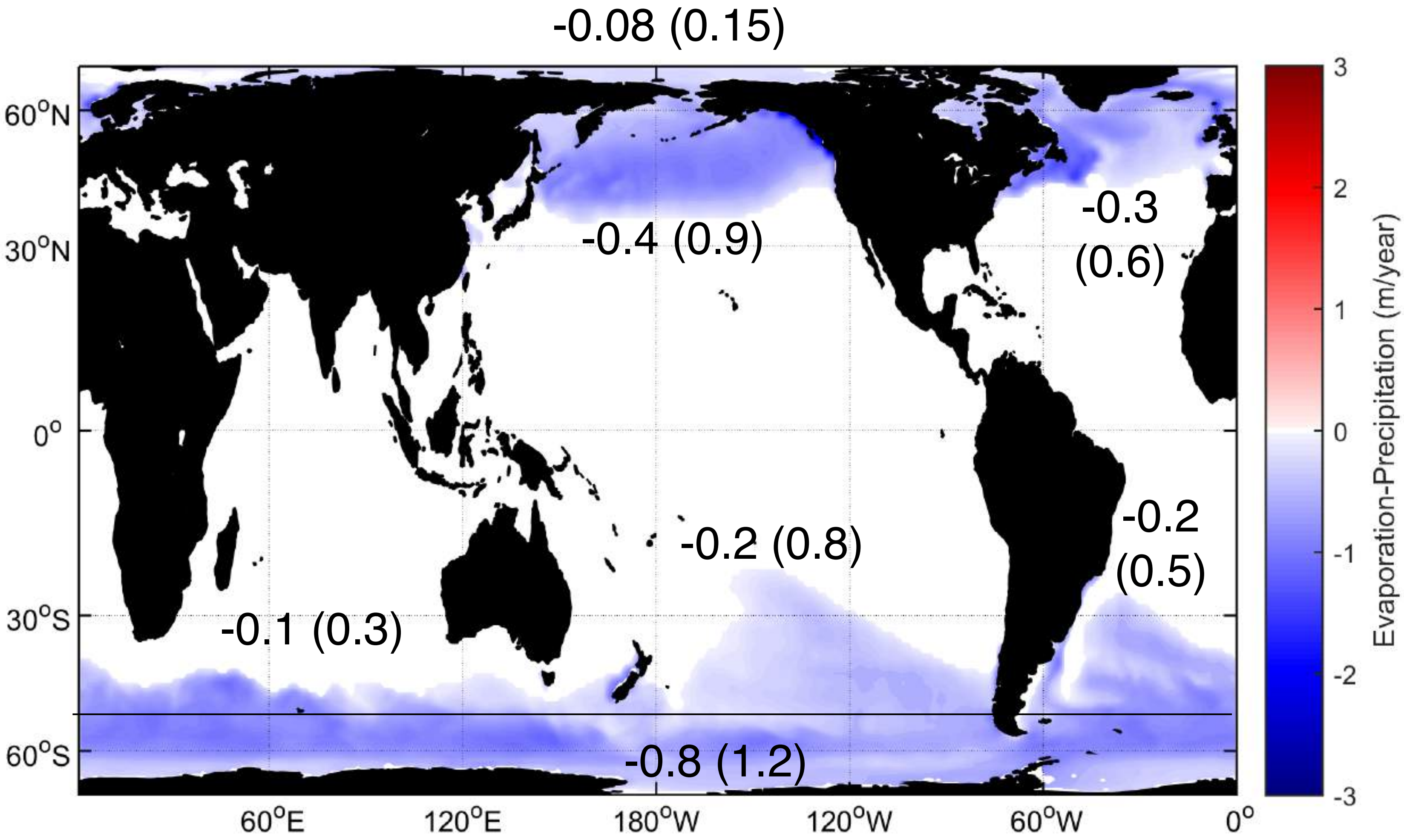
Global Values: ~ -3.3 Sv, P in P>E ~ 8.1

III Sources and Sinks of the Global Water Cycle



Global Value ~ -1.2 Sv. P in P>E: ~3.7 Sv. (1:3)

III Sources and Sinks of the Global Water Cycle



Global Value: ~ -2.1 Sv. P in P>E: ~ -4.5 Sv (1:2)

C

Water Cycle Conclusions

- Approximately 4.5 Sv export from subtropics
- ~1.2 Sv to ITCZ, 1.2 to land & 2.1 Sv to high latitudes
- Recycling is strongest in ITCZ: P=3-4E
- Average recycling in evaporation dominated areas is ~ E=2P
- Excellent agreement with recent isotope estimates (Benetti *et al.*, 2017)
- Implications for both variance generation and remote sensing (indicator for patchiness)

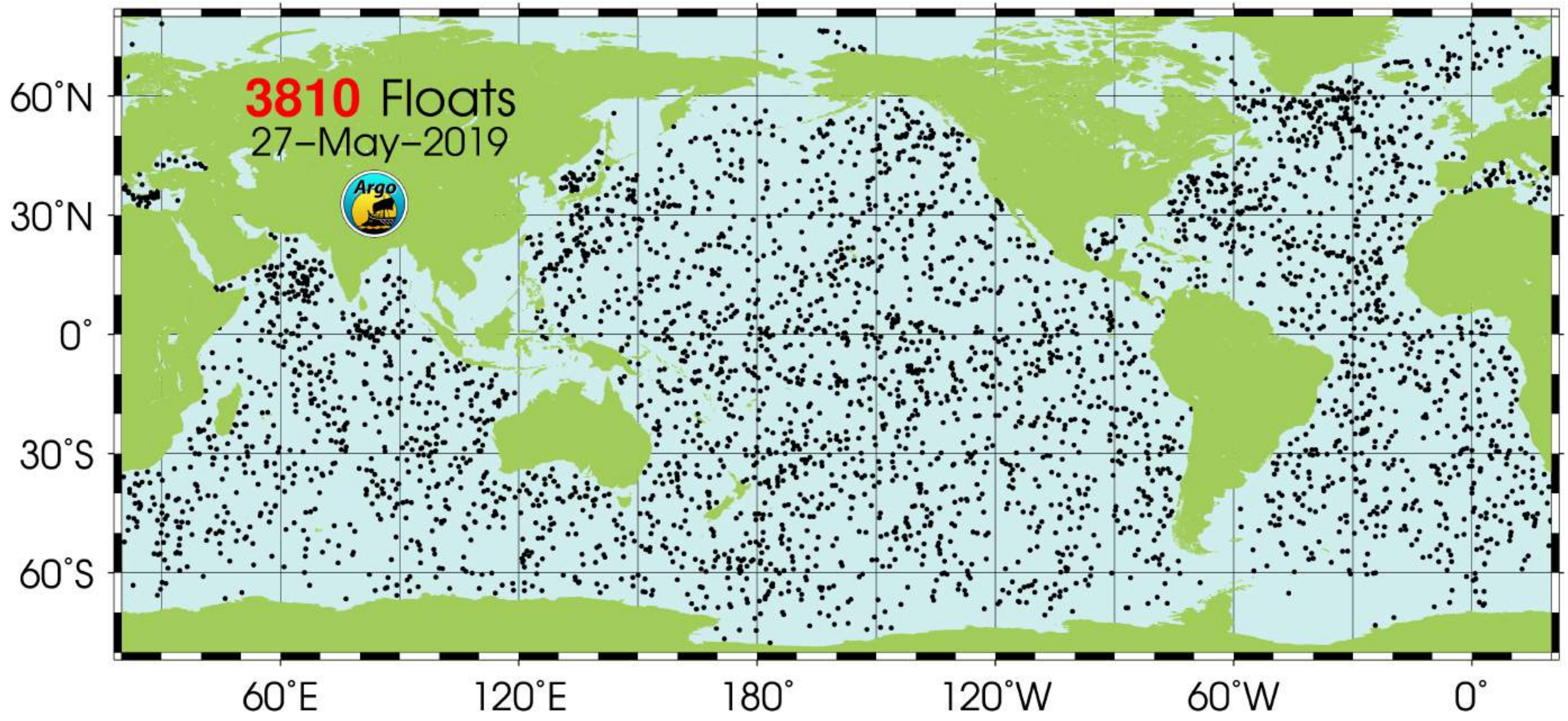
III

NASA Field Campaigns

- With the launch of Aquarius/SAC-D, NASA’s Ocean Salinity Science Team (OSST) has grown
- Dedicated Process Studies to understand the link between E-P(-R) and SSS
- SPURS-1 was located in the North Atlantic Salinity Maximum (subtropical gyre), 2012-2013
- SPURS-2 was located in the East Pacific Fresh Pool under the Intertropical Convergence Zone (ITCZ)

III

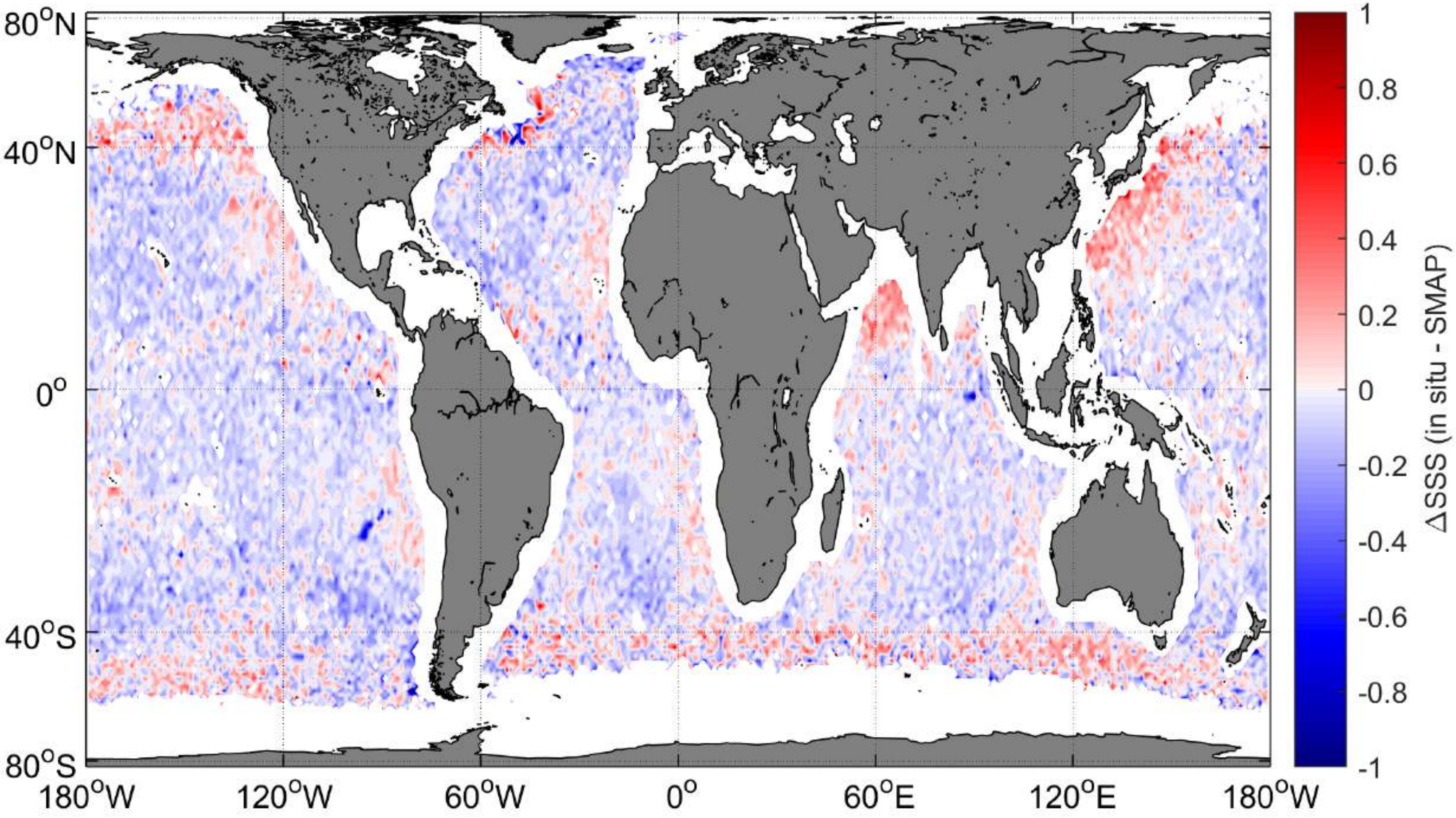
In Situ Sampling



- Argo Float Distribution, realistically sampling 2.5 x 2.5 ° every month
- Sampling depth mismatch

III

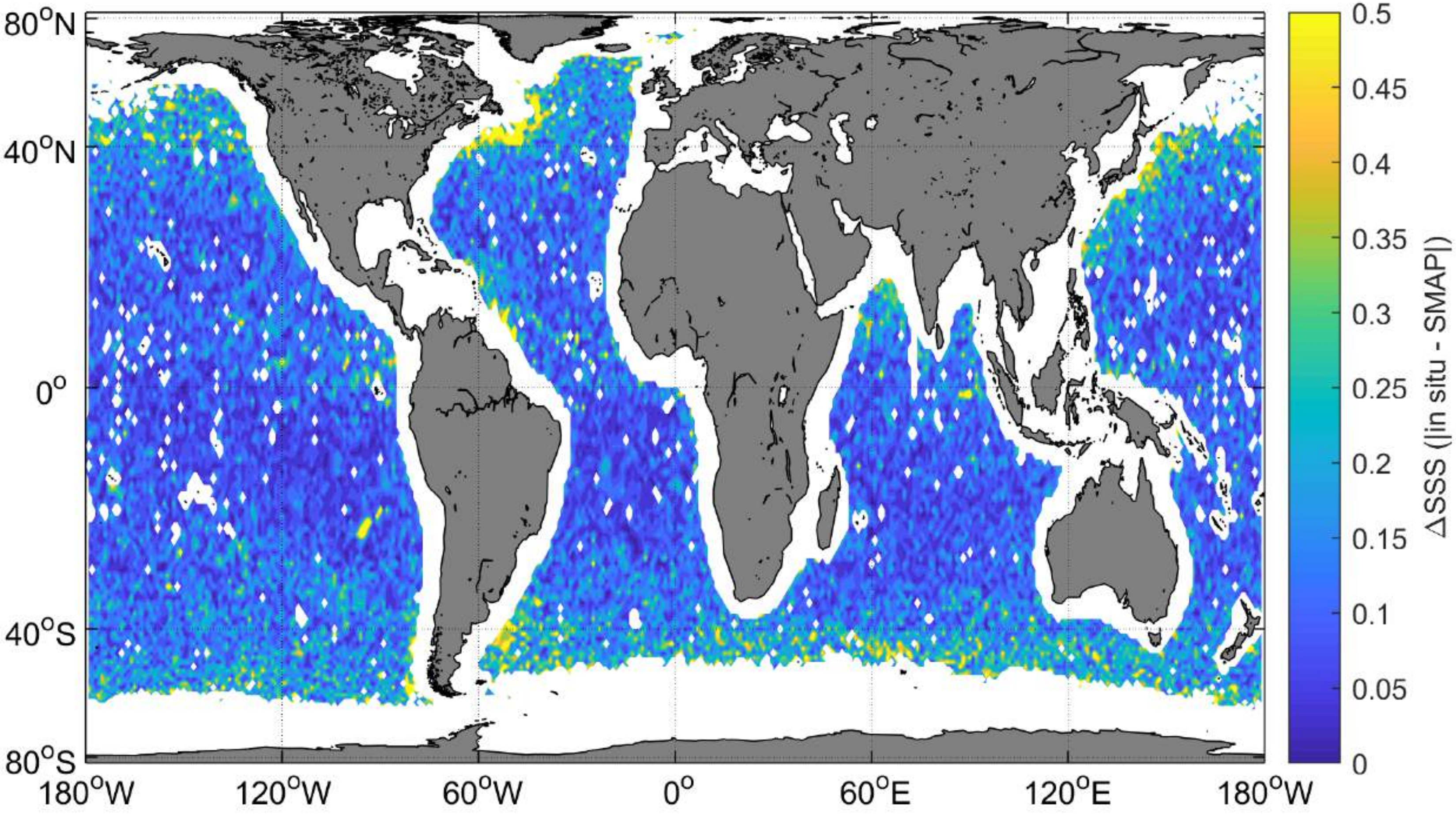
In Situ – Satellite Match-Ups



- We match each in situ observation with L2 SMAP data…
- 50km, +/- 3.5 day search, averaging all data
- Overall excellent, some remaining problems with RFI/Galaxy/Land

III

In Situ – Satellite Match-Ups

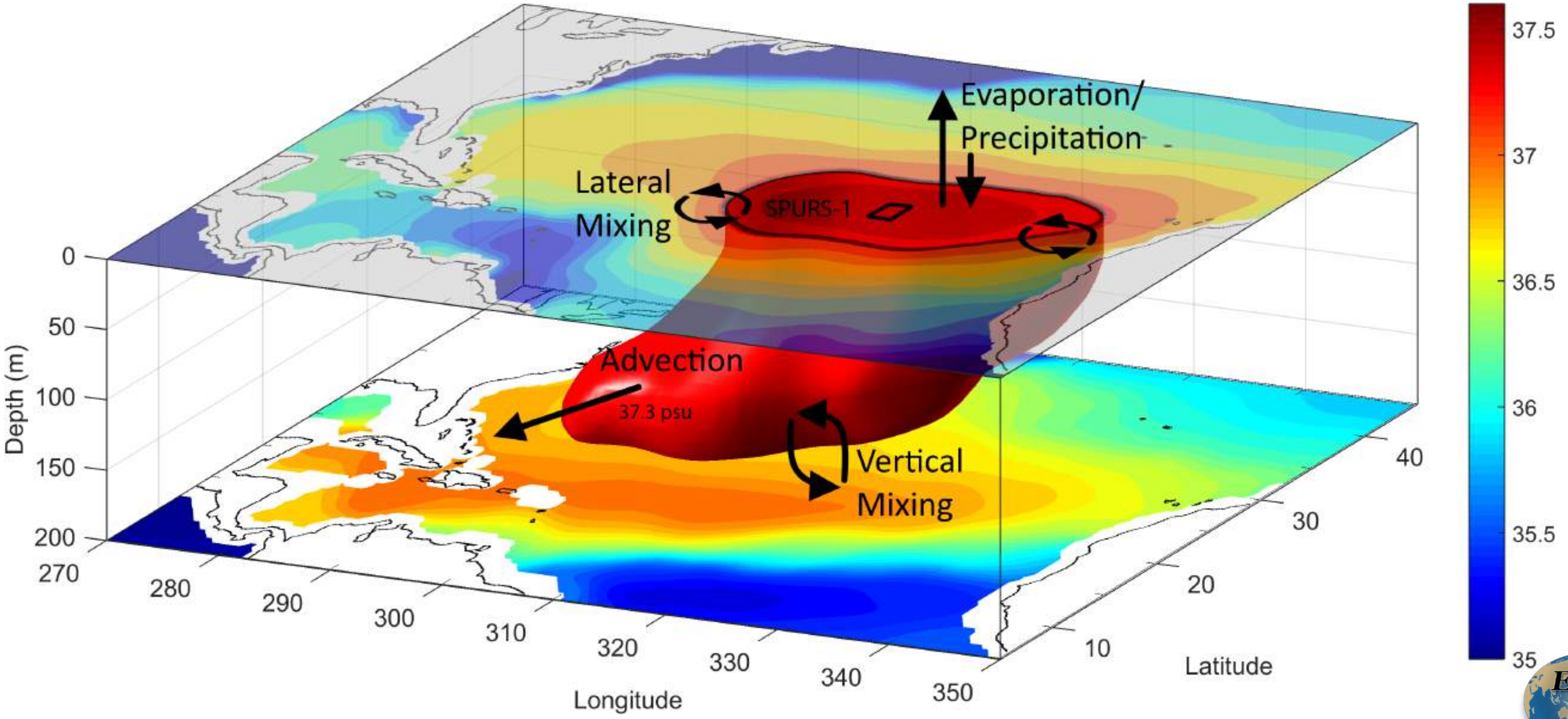


- Same search criteria as before, but taking the absolute value
- Mean absolute difference for the duration of SMAP (May 2015 - Mar 2019)

III

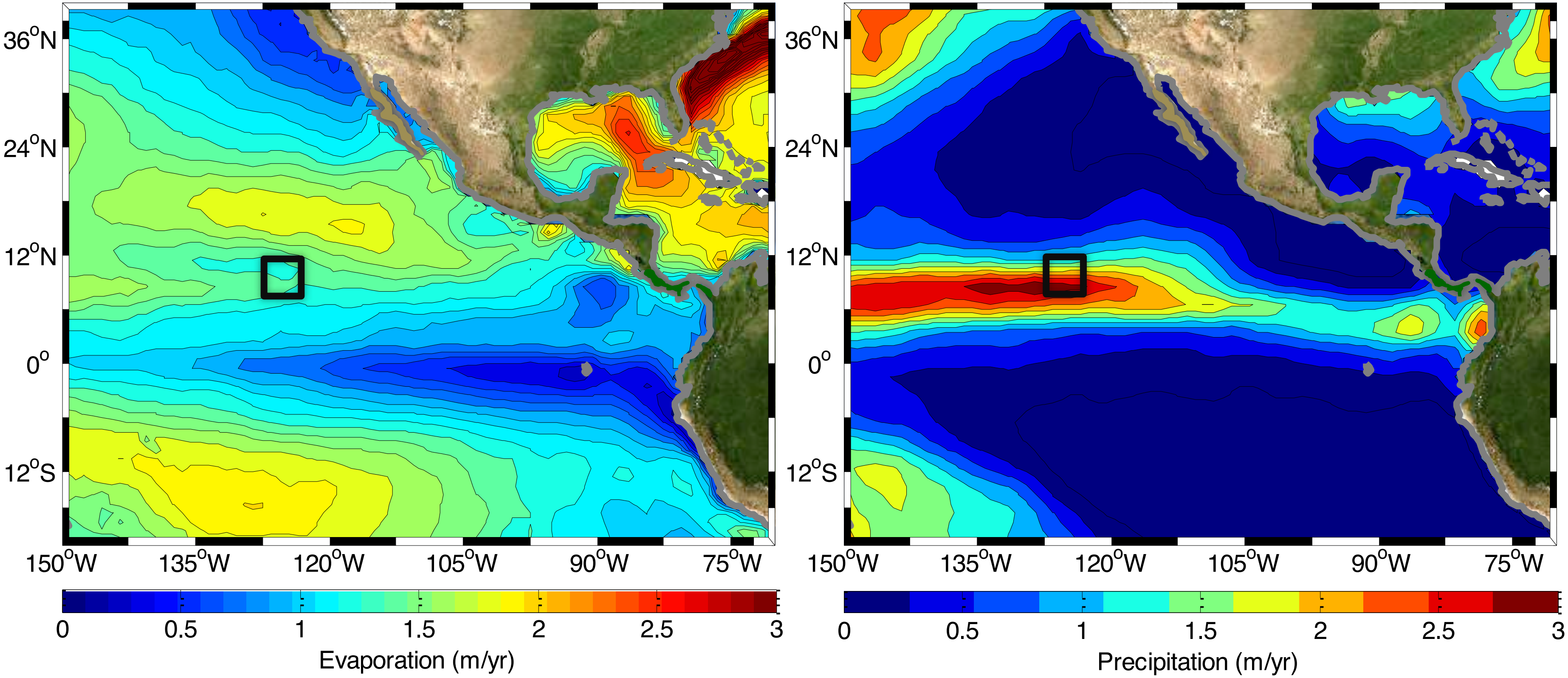
SPURS-1: Evaporation Dominated

- Salt is a useful tracer (Isohaline Budgeting): Mean advection along constant salinity, balance between surface fluxes and lateral and vertical mixing.
- Bryan and Bachman, 2015; Schmitt and Blair, 2015.



III

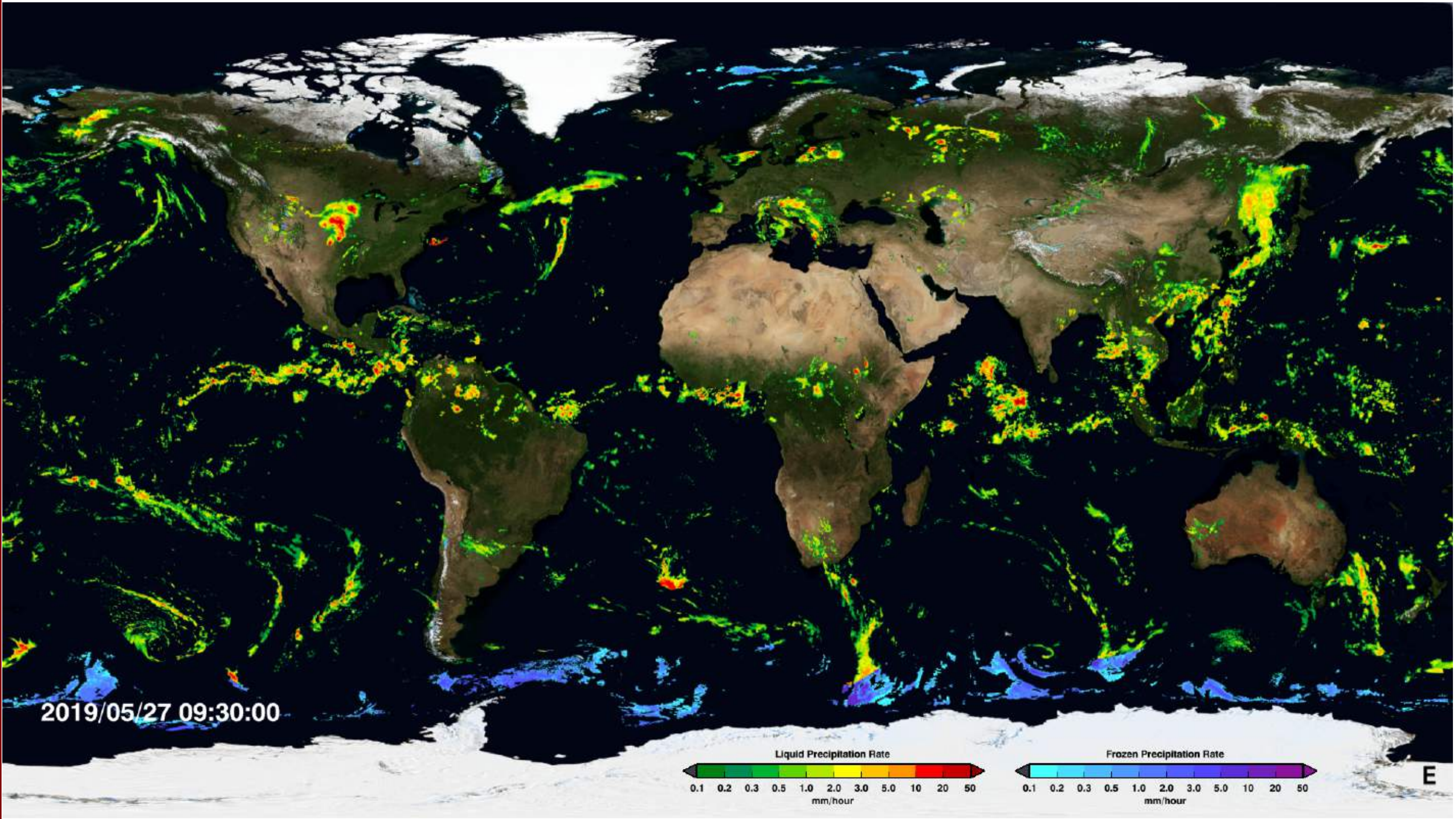
SPURS2: Precipitation Dominated



- Moderate (1-1.5 m/yr) Evaporation (OAFlux 3)
- Heavy precipitation (~3m/yr) (GPCP 2.2)

III

The Precipitation Problem (II)



- Peak precipitation ~10mm/hr in the ITCZ

The Precipitation Problem

- Precipitation is extremely patchy
- IMERG is considered “high resolution”
- Stratiform vs convective rain (bad news for satellites)

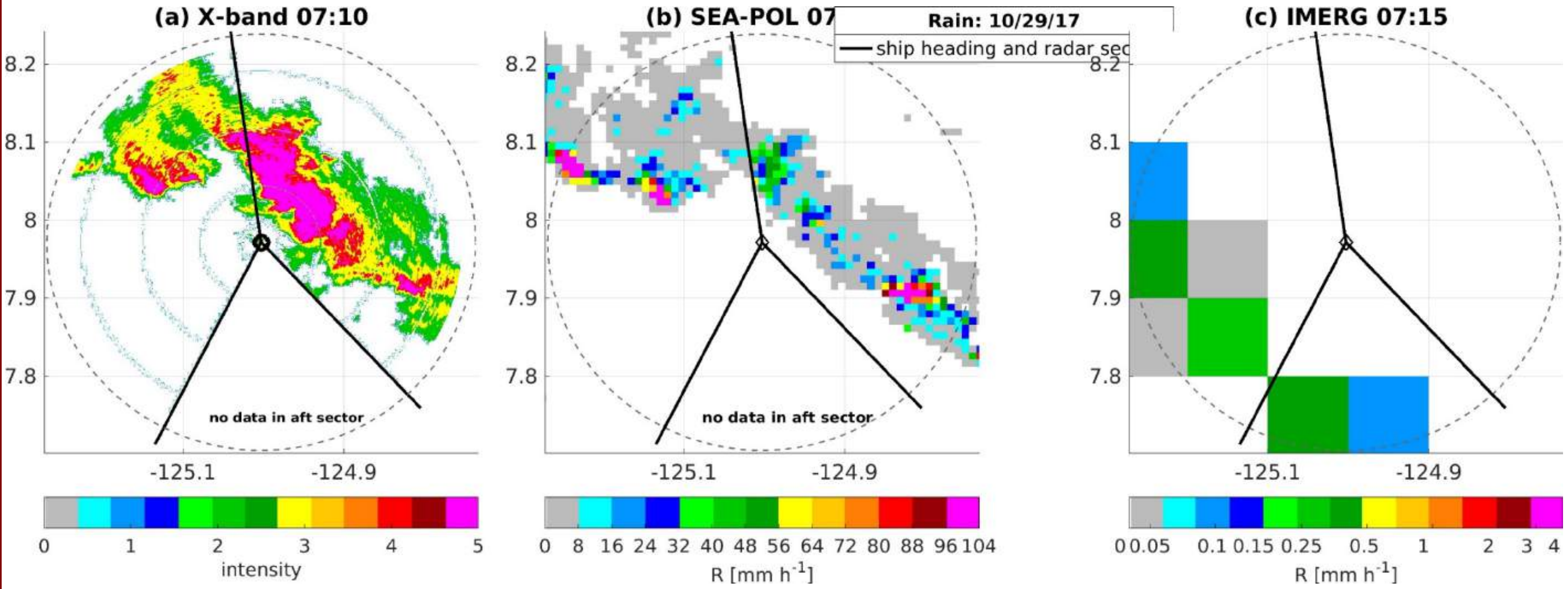
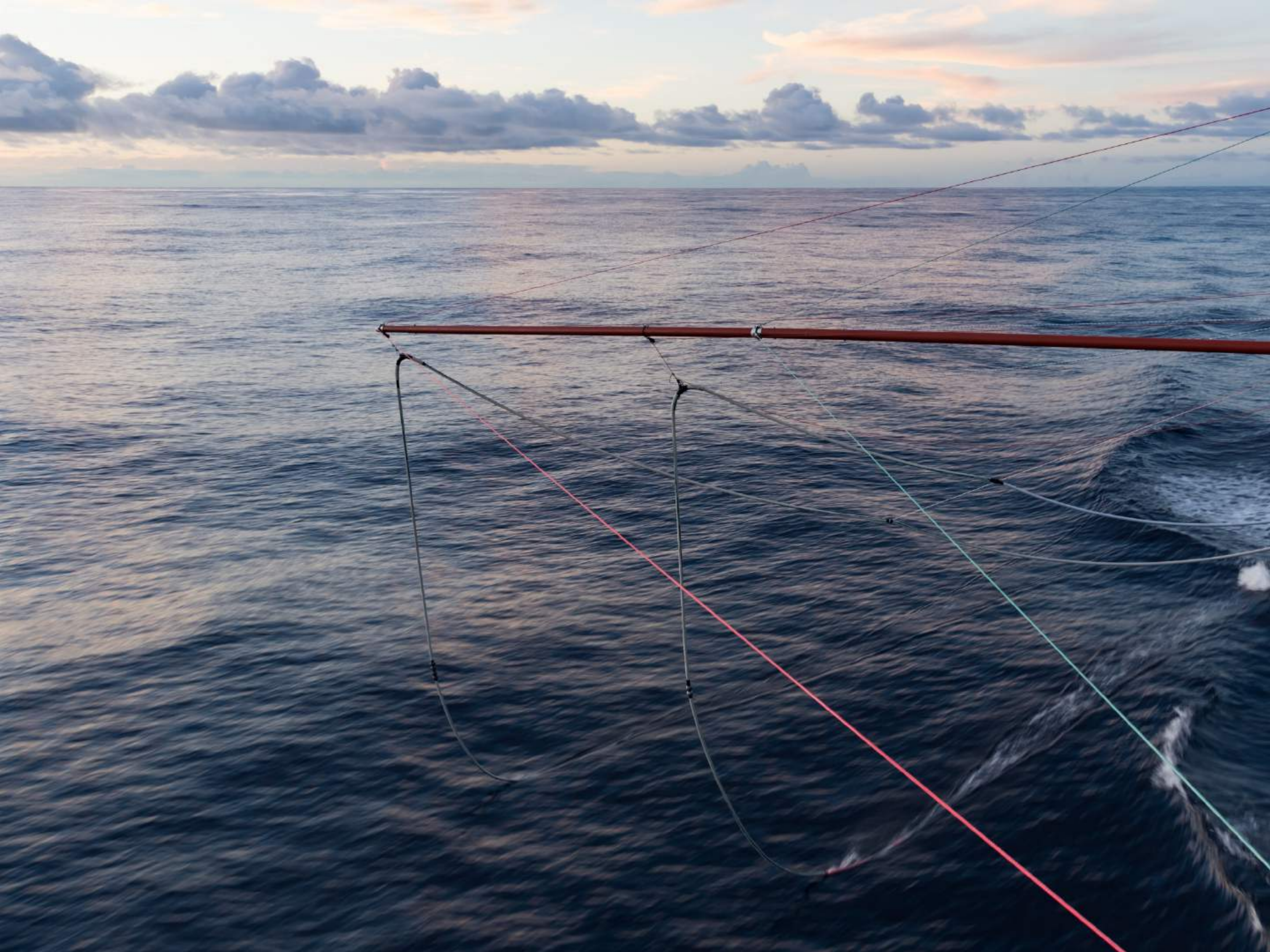
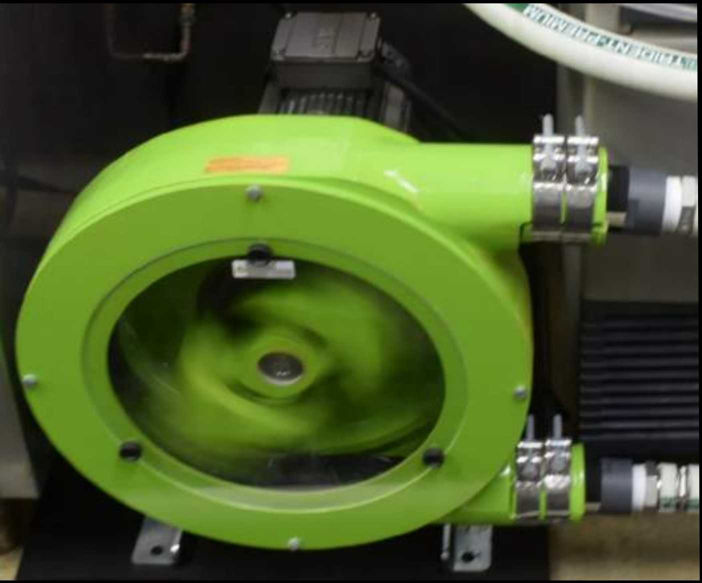


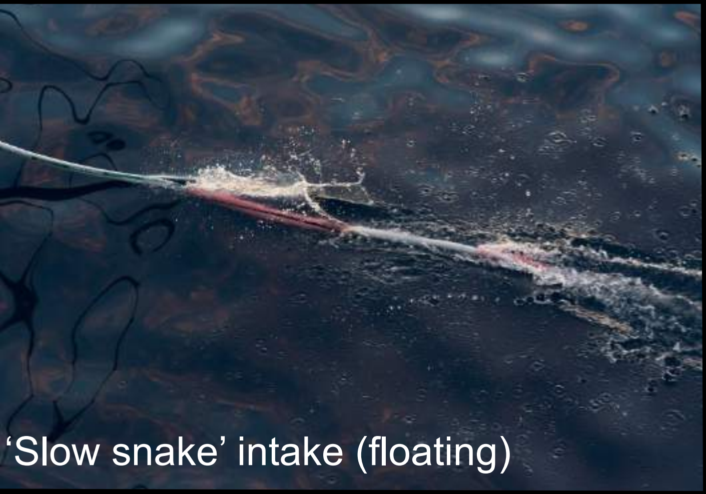
Figure courtesy of E. Thompson, APL-UW

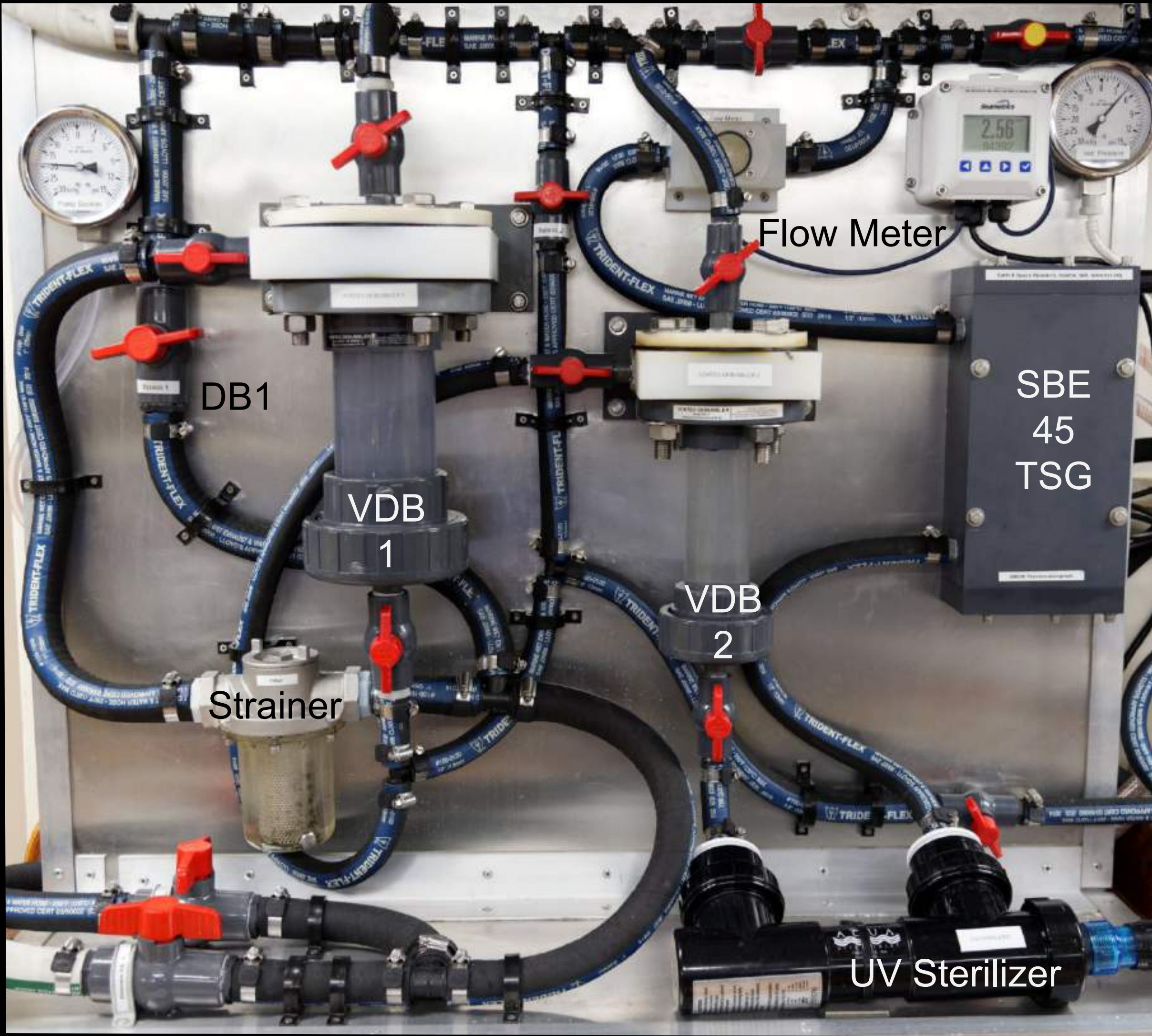


III

Salinity Snake (II)

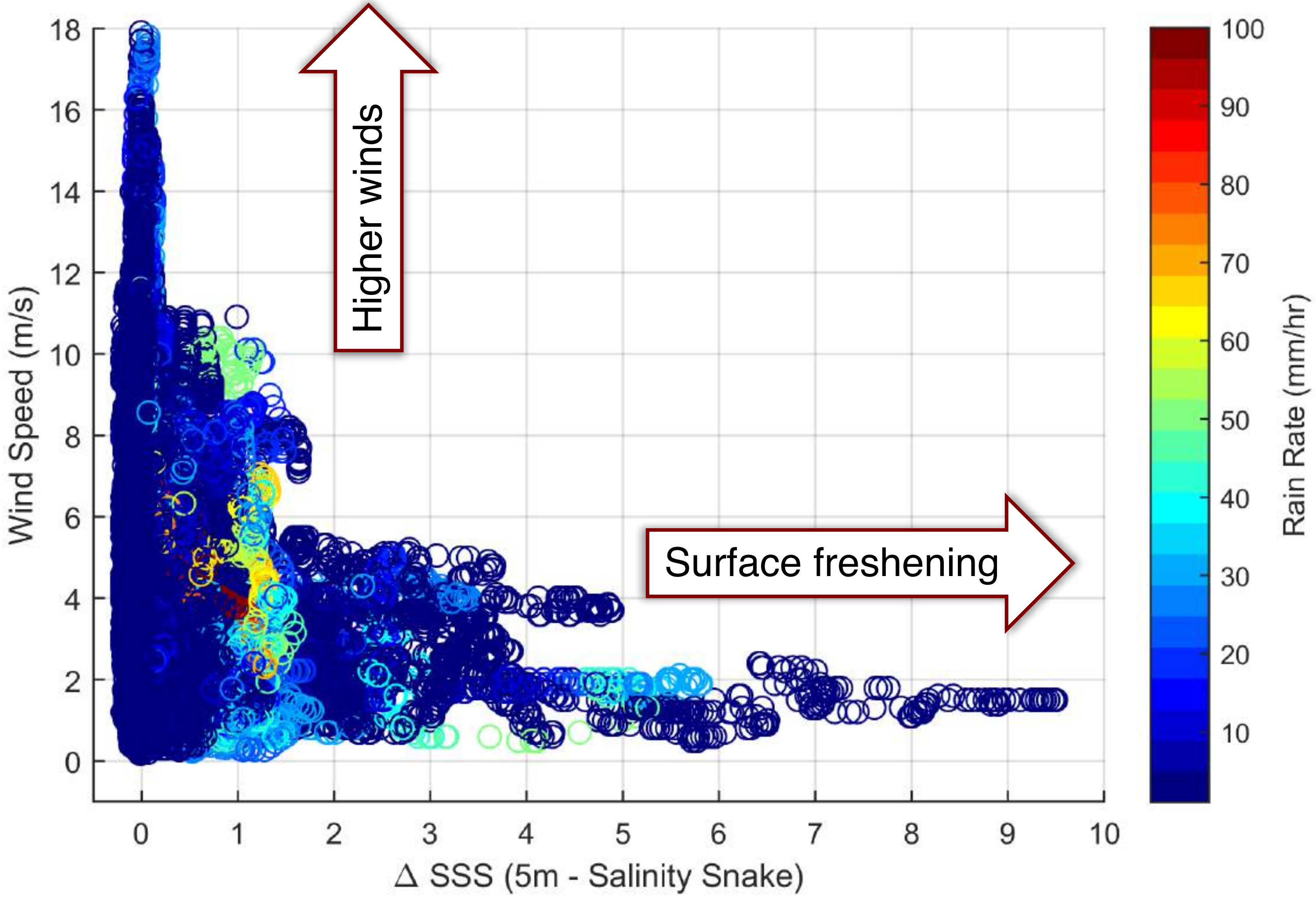






ΔSSS

- Difference between radiometric depth (1-2 cm) and bulk (5m) salinity, clearly wind speed dependent!



In Situ Sampling

- Systematic vertical ΔSSS (5m-0m) in ITCZ (<12°) from SPURS-2 salinity snake deployments is 0.07 g/kg
- Patchy rain causes freshwater lenses, filaments, fronts…
- These features increase the RMSD (not RMSE) between in-situ and satellite observations -> 0.17 g/kg
- Sub-footprint variability may be underestimated when using bulk salinity measurements (~5m):
    - Horizontal variance decreases with depth (RR1720, ITCZ)

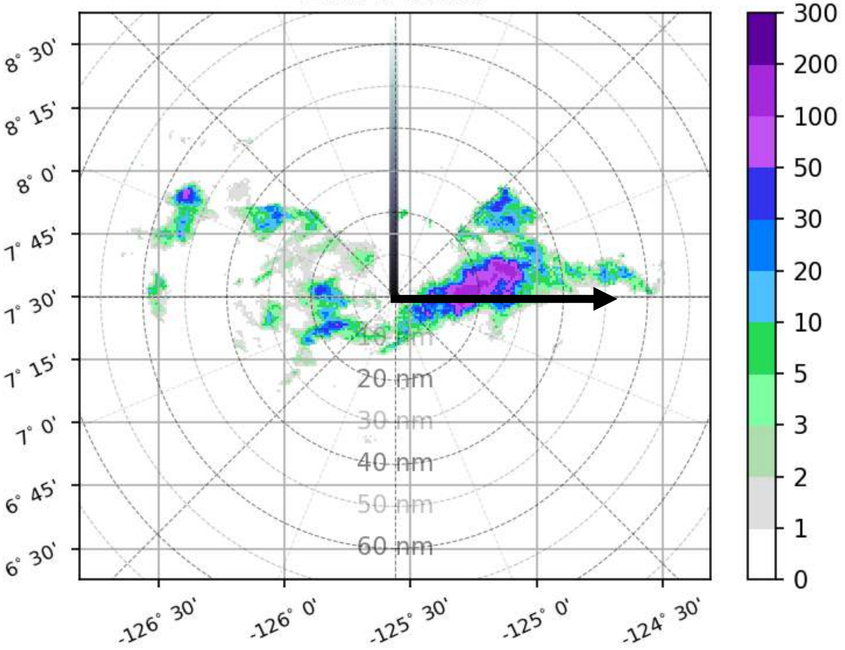
Salinity Snake	USPS 2m	USPS 3m	TSG 5m
0.26	0.19	0.18	0.16

-
    - … consequently a problem for state estimates, too, even when using L3 data

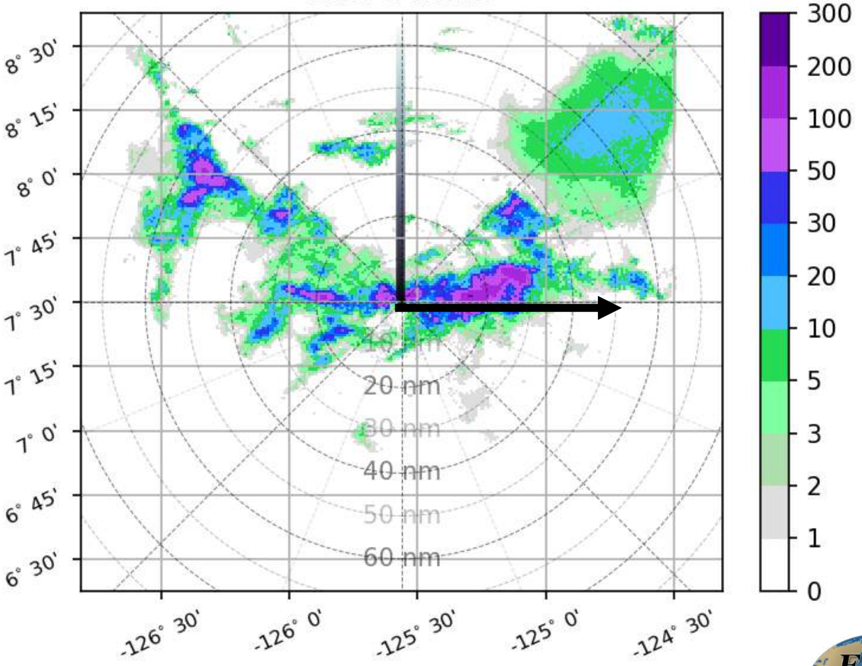
III

A Case Study: SPURS-2 Freshwater Lens

- Very good match-up between Salinity Snake and SMAP
- Low wind speeds (2-5 m/s), vessel has just turned to 090T, steaming East through the freshwater
- Note the rain (>100mm in less than 2 hours)



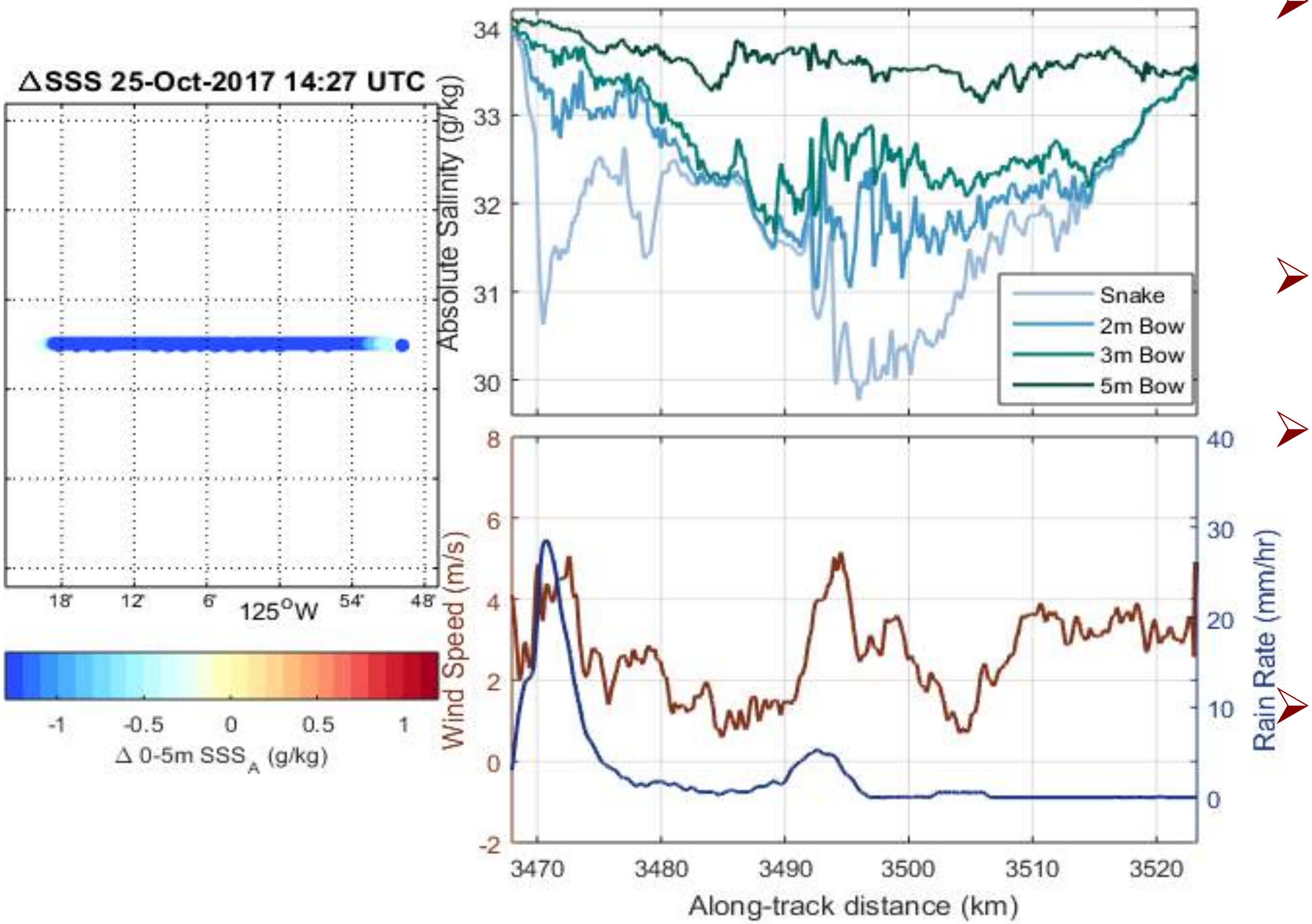
Last 2 hours



Last 6 hours

III

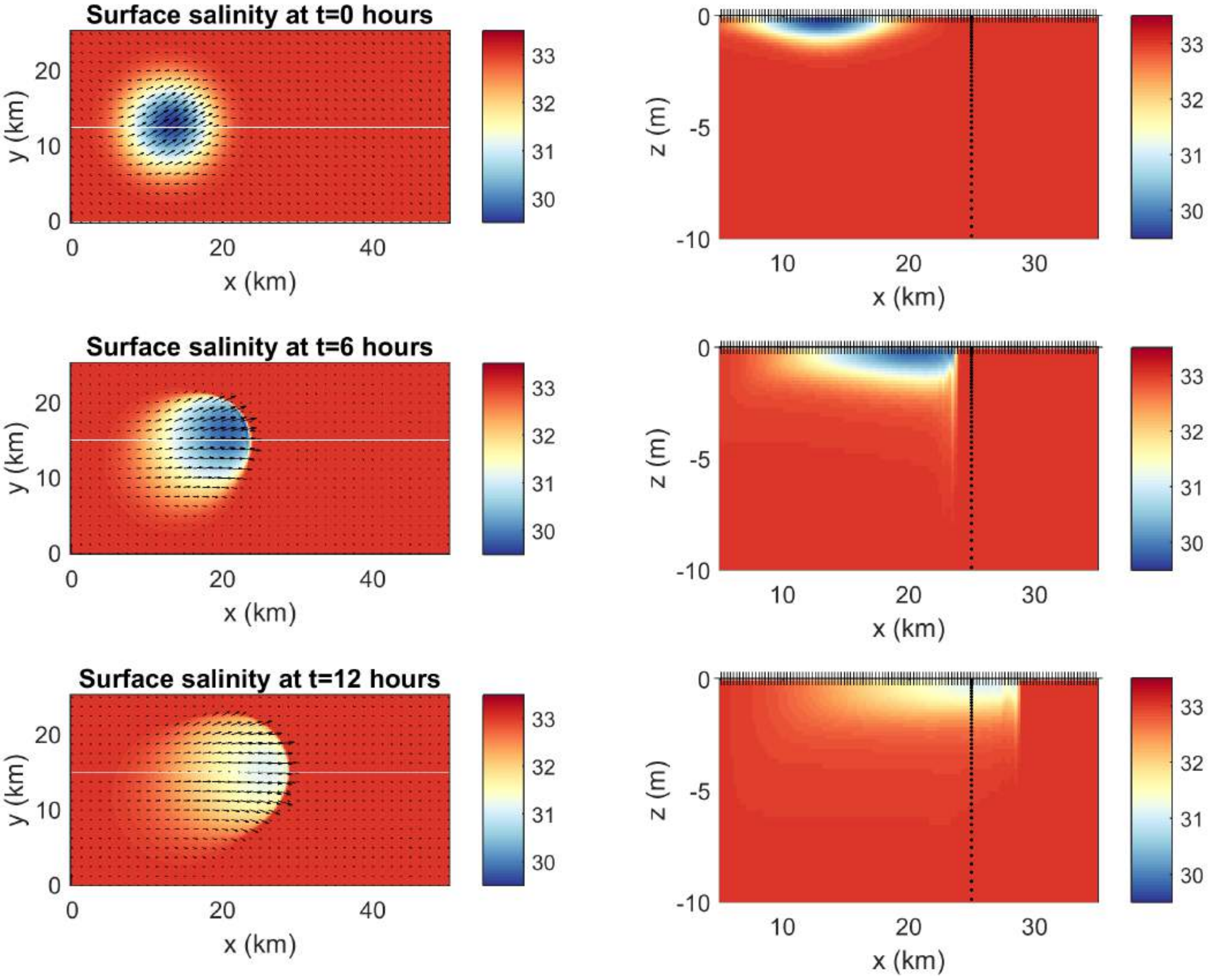
A Case Study: SPURS-2 Freshwater Lens



- 50 km feature with >4 g/kg peak freshening
- Evident in SMAP
- Anomalies visible in SMAP and SMOS
- Enhanced mixing and interleaving

III

A Simple Model to Explain Dissipation



- 100 m horizontal resolution, 150 vertical levels
- Constant 4 m/s wind from SE
- Sharp front with enhanced mixing replicated
- Wind-driven surface velocities highly asymmetrical (see vectors)

C

The Take-Home

- The Global Ocean Freshwater Cycle and Salinity are intrinsically linked
- Evaporation and Precipitation occur on *very* different space and time scales
- Estimates of E and P are (highly) questionable in the tropics
- Satellite SSS, especially SMAP, has become incredibly useful
- Salinity budgets help in understanding the surface flux/advective/diffusive balance
- Small scale patchiness (particularly in the ITCZ) is underestimated

Thank You!
Questions?