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
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

- Oceans dominate fluxes and reservoirs
- Generally ‘mis-represented’

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

- ITCZ clearly visible
- High latitudes
- Sub-tropical gyres almost cloud-free
- Source: Blue Marble NG
...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
Mean Evaporation (1987-2006)

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

Advective effects visible
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
Increased water holding capability in the atmosphere

Implied amplification of water cycle with increasing global temperatures

~7.6%/K
Pattern Amplification

- Temperatures are rising...
- Changes in SSS?
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**
CONTEMPORARY CHANGES IN WATER CYCLE:

Average amplification $\sim 5\%$ — consistent with Clausius-Clapeyron equation

$^\ast$Equivalent $7.6\%$ °C and $0.65$ °C change
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 - Jan 1992

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
Contemporary Changes in Salinity:

Little evidence of global amplification, despite strong regional changes.
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

Vinogradova & Ponte, 2017, JCLim
Number of observations for each 2.5° grid box. For NCEP-1 Strong changes are evident at indicated times. From: Kistler et al., 2001.
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)
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)

<table>
<thead>
<tr>
<th>P+R</th>
<th>E</th>
<th>OAFlux</th>
<th>NCEP-1</th>
<th>NCEP-2</th>
<th>ERA-40</th>
<th>ERA-Int</th>
<th>CORE.2</th>
<th>MERRA</th>
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<tbody>
<tr>
<td>GPCP</td>
<td>+0.46</td>
<td>-0.41</td>
<td>-2.24</td>
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<td>-1.15</td>
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<td>NCEP-1</td>
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<td>+3.87</td>
<td>+3.04</td>
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<td>CMAP</td>
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<tr>
<td>CORE.2</td>
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<td>+0.15</td>
<td>-1.69</td>
<td>-0.45</td>
<td>-0.60</td>
<td>-0.14</td>
<td>+0.78</td>
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<tr>
<td>MERRA</td>
<td>+0.47</td>
<td>-0.40</td>
<td>-2.23</td>
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</tbody>
</table>
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
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
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
EOF Analysis of E-P: Mode 3 – 4.8%

**ENSO Multivariate Index (MEI). From: NOAA**

- 1997 El Niño
- 1989 La Niña
- 1999/2000 La Niña
Basin Freshwater Transports

Arctic Ocean freshwater balance matches observations (freshwater +\(\sim 3\times 10^8\) 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
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)
Trivial (but sometimes overlooked):

E and P occur on different space- and time-scales
Evaporation - Precipitation binned by SST

Sources and Sinks of the Global Water Cycle

Evaporation - Precipitation (m^3/s)

Temperature (°C)

Subpolar P

Subtropical E

ITCZ
III Sources and Sinks of the Global Water Cycle

Positive Component (E>P)
Negative Component (P>E)
III

Sources and Sinks of the Global Water Cycle

P>E in the ITCZ
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
Sources and Sinks of the Global Water Cycle

Global E:P by Absolute Salinity (g/kg)
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)
Sources and Sinks of the Global Water Cycle

Indian Ocean E:P by Latitude
Indian Ocean E:P by Absolute Salinity (g/kg)
Southern Ocean $E:P$ by Latitude
III
Sources and Sinks of the Global Water Cycle

Southern Ocean E:P by Absolute Salinity (g/kg)
Arctic E:P by Latitude
Arctic E:P by Absolute Salinity (g/kg)
Global export: ~4.5 Sv. E in E>P: 8.8 Sv (~2:1)
Global Values: $\sim -3.3$ Sv, $P$ in $P>E \sim 8.1$
Global Value ~ -1.2 Sv. P in P>E: ~3.7 Sv. (1:3)
Global Value: $\sim -2.1 \text{ Sv. P in P>E: } \sim -4.5 \text{ Sv (1:2)}$
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)
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).
Argo Float Distribution, realistically sampling 2.5 x 2.5 ° every month

Sampling depth mismatch
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
Same search criteria as before, but taking the absolute value

Mean absolute difference for the duration of SMAP (May 2015 - Mar 2019)
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.
SPURS2: Precipitation Dominated

- Moderate (1-1.5 m/yr) Evaporation (OAFlux 3)
- Heavy precipitation (~3m/yr) (GPCP 2.2)
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
Precipitation is extremely patchy. IMERG is considered "high resolution". Stratiform vs convective rain courtesy of E. Thompson, APL-UW.
Salinity Snake (II)

‘Slow snake’ intake (floating)
Difference between radiometric depth (1-2 cm) and bulk (5m) salinity, clearly wind speed dependent!
Systematic vertical $\Delta$SSS (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)

<table>
<thead>
<tr>
<th>Salinity Snake</th>
<th>USPS 2m</th>
<th>USPS 3m</th>
<th>TSG 5m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.26</td>
<td>0.19</td>
<td>0.18</td>
<td>0.16</td>
</tr>
</tbody>
</table>

... consequently a problem for state estimates, too, even when using L3 data
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)
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
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)
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?