



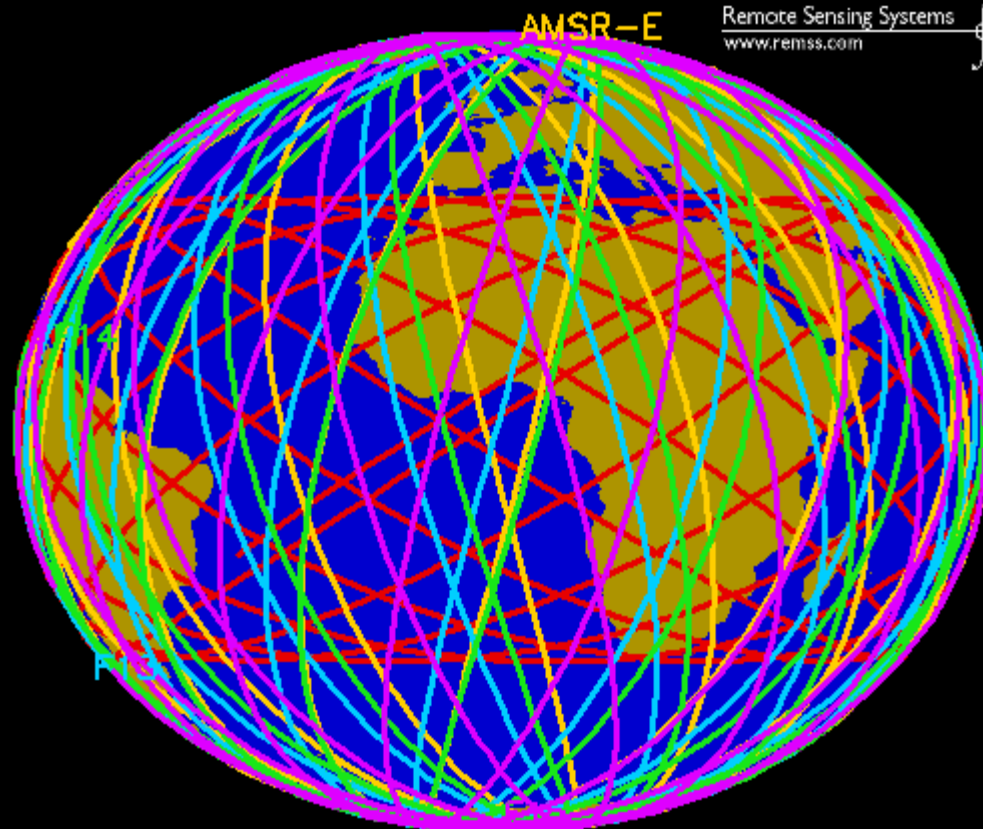
Closing the Water Cycle over the Ocean using a Constellation of Satellites

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Remote Sensing Systems, Santa Rosa, CA, USA

89th AMS Annual Meeting
Phoenix, AZ, USA
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Earth Observation with a Constellation of Radiometers

SSM/I: F13, F14, F15 ; TMI ; AMSR-E





The Physical Principles

- Averaging over the whole globe on monthly or longer time scales:

$$\text{Evap} = \text{Precip}$$

- Averaging over a month or longer at a particular location:

$$\text{Div (WVT)} = \text{Evap} - \text{Precip}$$

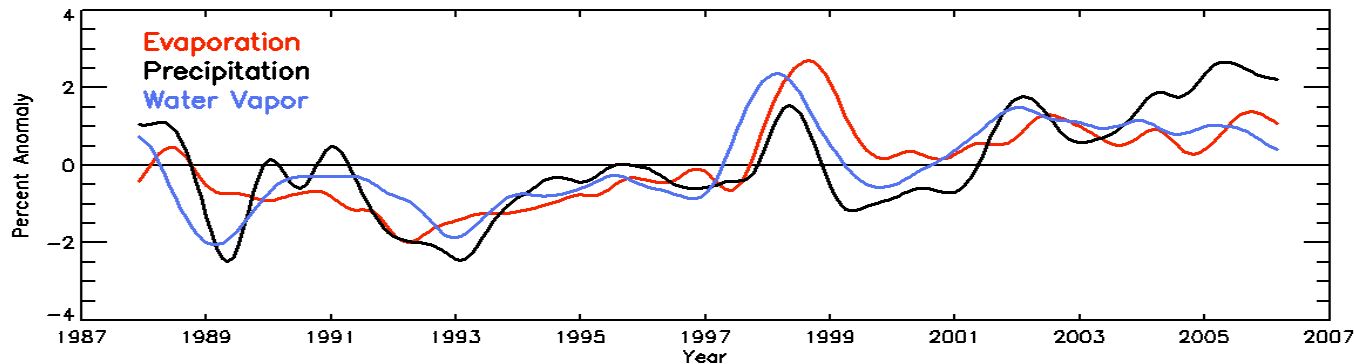


The Data

- Evaporation
 - Satellite surface wind speed retrievals
 - Reynolds sea surface temperature
 - Climatologies of relative humidity and air temperature
 - Wentz et al., 2007, *Science*
- Precipitation
 - Satellite rain rate retrievals
 - Diurnal and other intersatellite adjustments
 - Climatological rain-to-precipitation adjustment
 - Hilburn and Wentz, 2008, *J. Appl. Meteor. Climatol.*
- Water Vapor/Transport/Divergence
 - Satellite water vapor retrievals
 - Satellite wind speeds with directions variationally assigned (Ardizzone/Atlas winds)
 - Climatological vector adjustment SFC to WVT



Global Trends in Evaporation, Precipitation, and Water Vapor

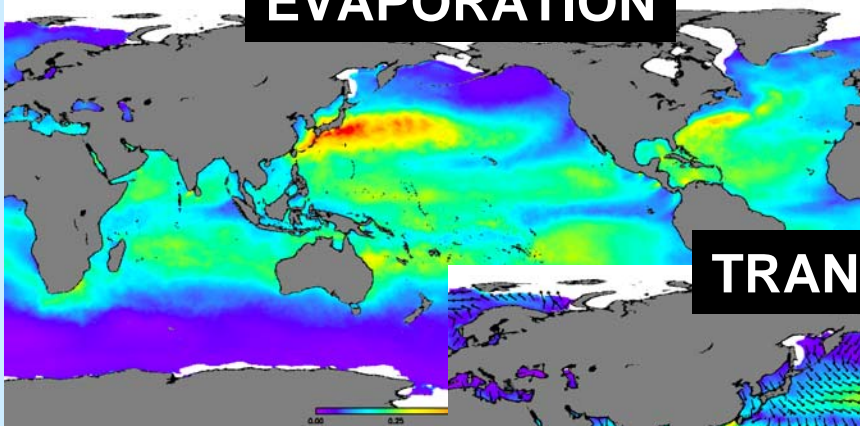


- Climate models predict and satellite data show that water vapor in the atmosphere increases with temperature at a rate predicted by the Clausius-Clapeyron relationship
- Climate models predict that precipitation will increase with temperature at a rate three times less than the C-C rate
- Satellite data find that over the last 20 years, precipitation has increased at the same rate as water vapor; in contrast to the muted response by models
- Satellite data also find that evaporation (a physically independent retrieval from precipitation) also increases at the same rate as water vapor
- Note: satellite precipitation trends are due to increases in heavy precipip.

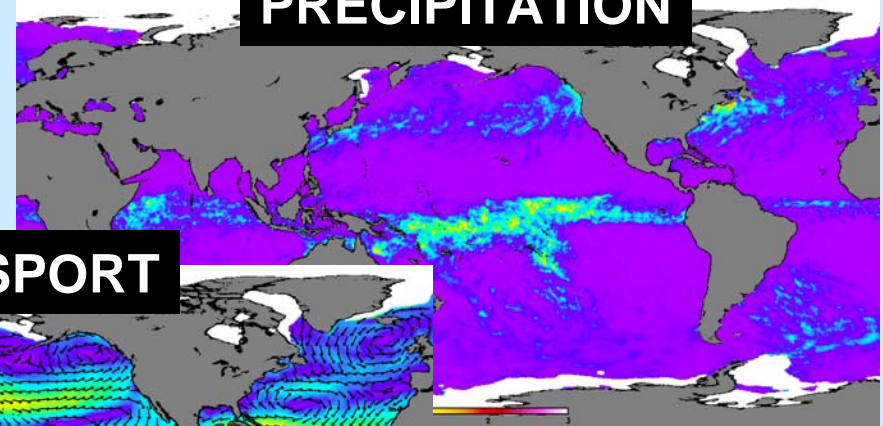


PMWC Product at www.remss.com 1987-2006, Monthly, 0.25-degree

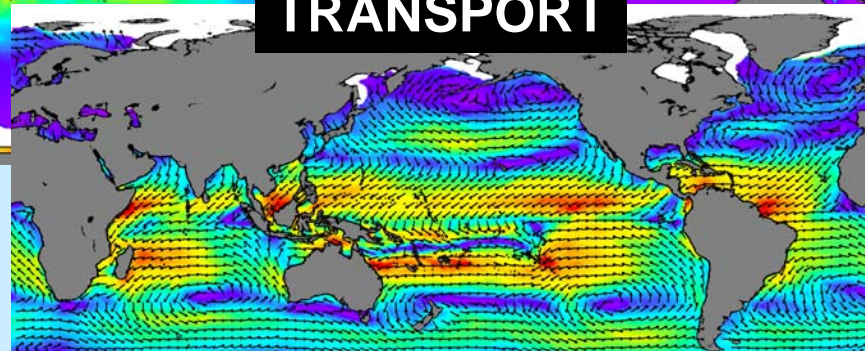
EVAPORATION



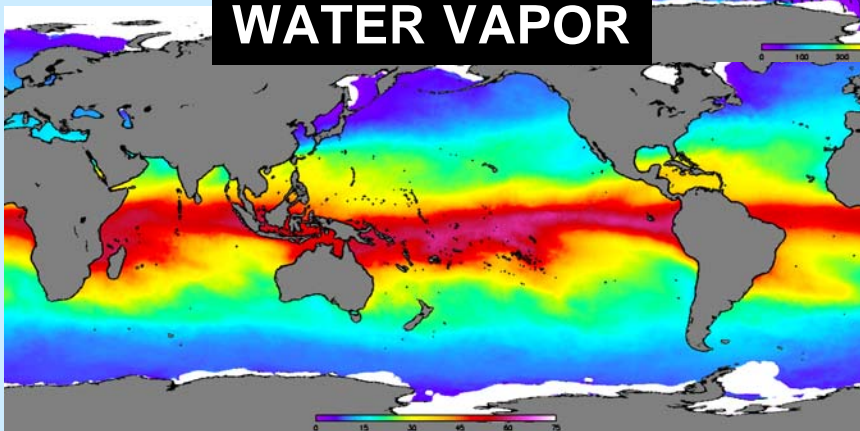
PRECIPITATION



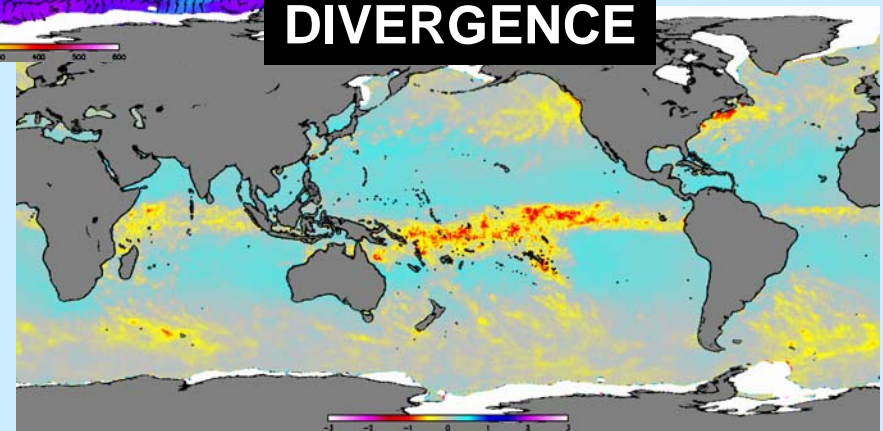
TRANSPORT



WATER VAPOR



DIVERGENCE





Deriving Water Vapor Transport

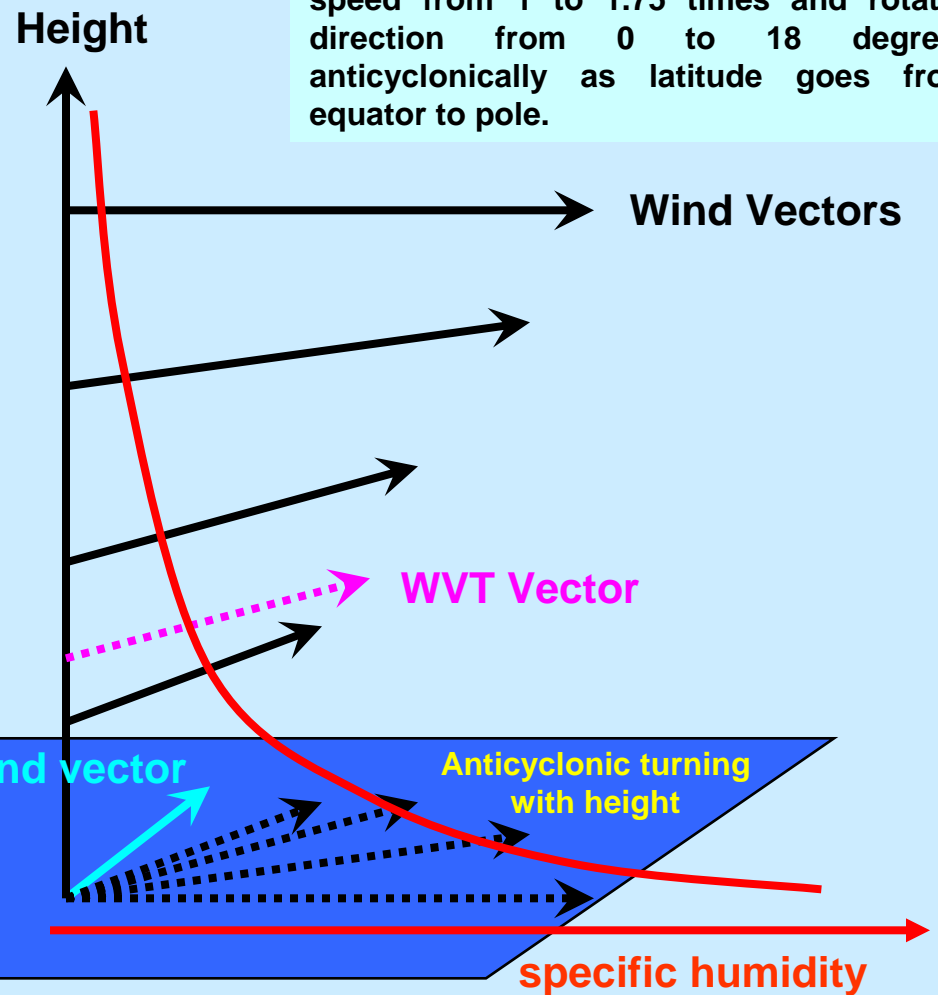
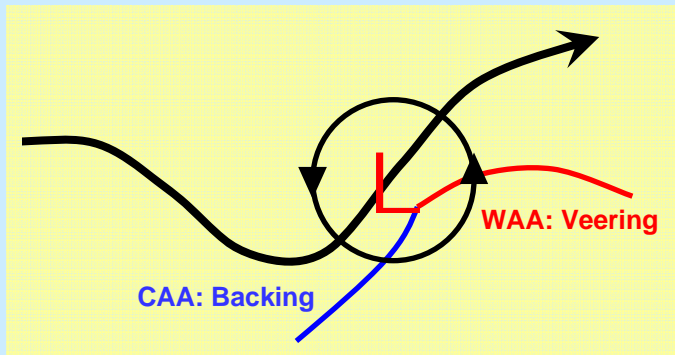
- Feature tracking to deduce transport velocity
 - Problems with non-conservation of water vapor and the optical flow aperture problem, also issues near coastlines
 - Tested using on-orbit simulation with NCEP wind and humidity
 - Monthly average transports are ok... but the divergence field lacks proper structure
- Ardizzone/Atlas Winds (Level 2.5)
 - Based on our radiometer wind speeds, but assigned a direction using a variational method
 - A very high quality climate data record
 - Enthusiastically recommend its use!

SFC to WVT Adjustment

$$\vec{Q}_{WVT} = \int_0^{p_s} \vec{W} q \frac{dp}{g}$$

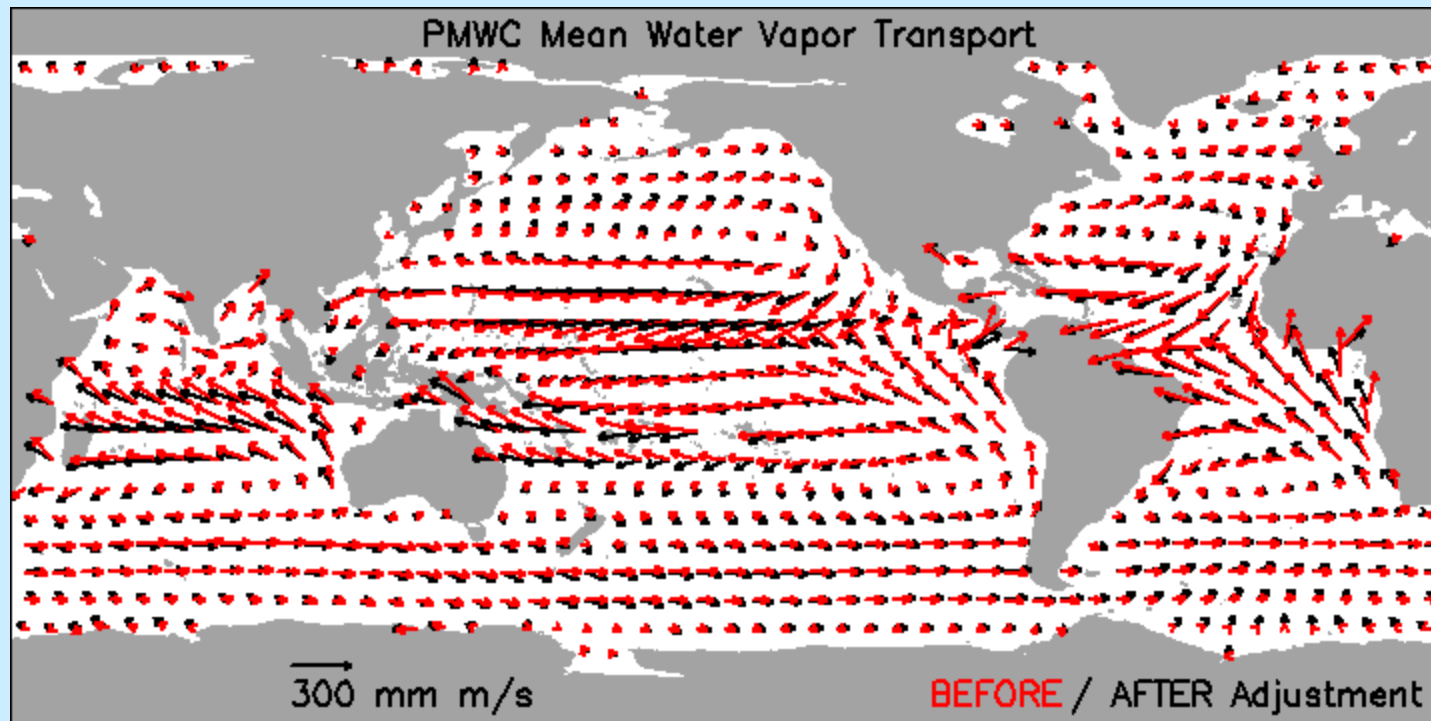
$$V = \int_0^{p_s} q \frac{dp}{g}$$

Climatological adjustment is based on NCEP surface winds and NCEP vertically integrated water vapor transport; increases speed from 1 to 1.75 times and rotates direction from 0 to 18 degrees anticyclonically as latitude goes from equator to pole.





Example of WVT Adjustment



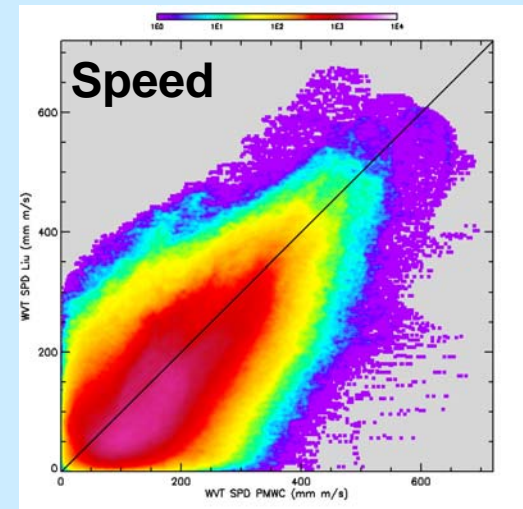
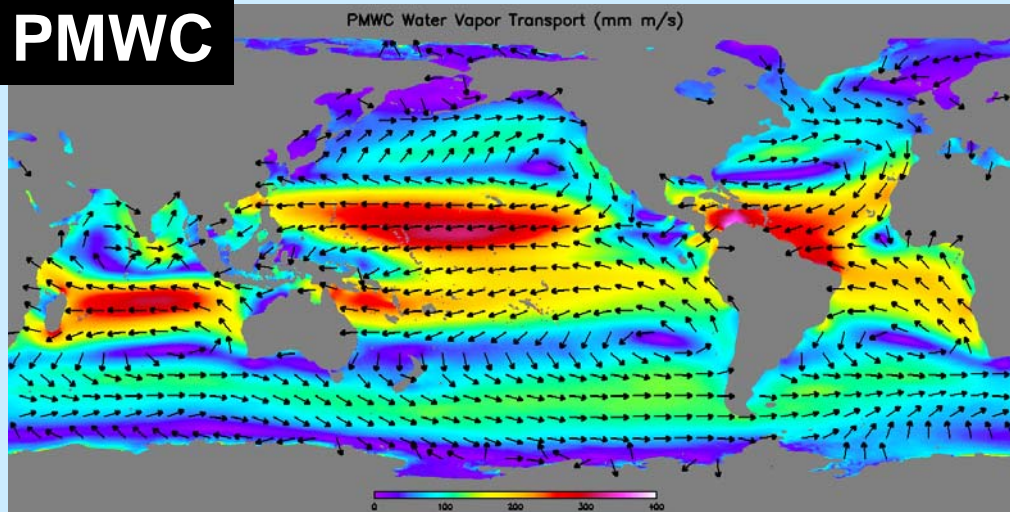
- Any climatological adjustment is inherently large scale and has little effect on divergence; so we also adjust the transport vectors to minimize the difference between transport divergence and E-P
- Net effect: mostly rotate direction of vectors; median rotation of 12 degrees



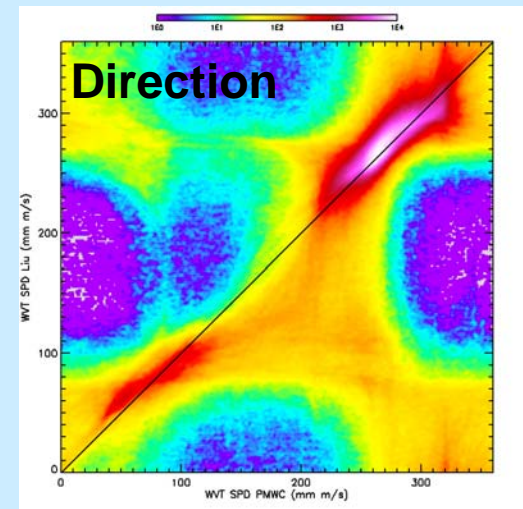
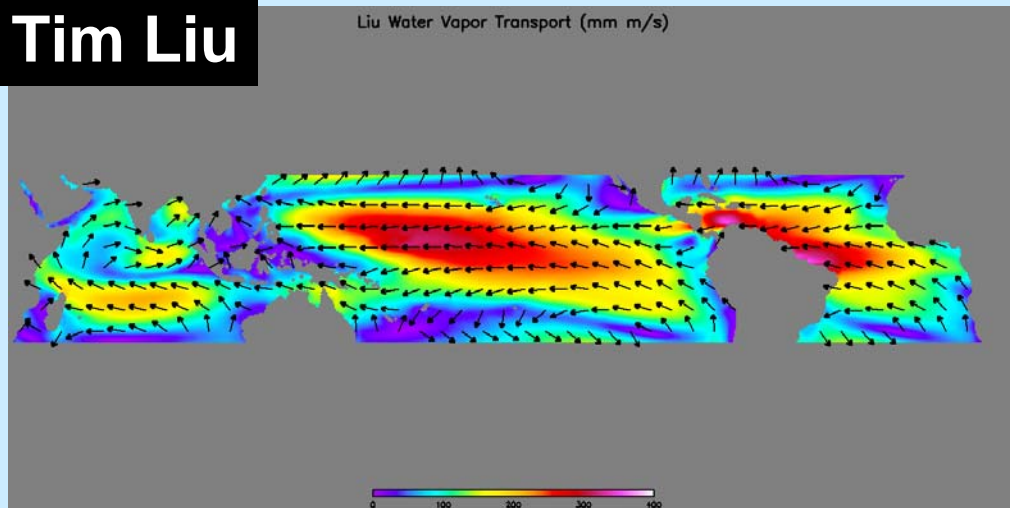
Water Vapor Transport

2000-2005

PMWC



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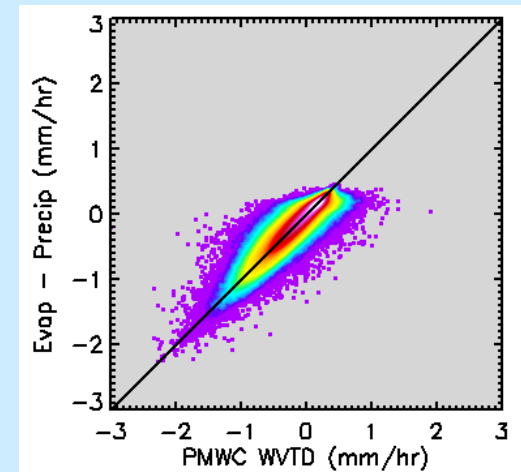
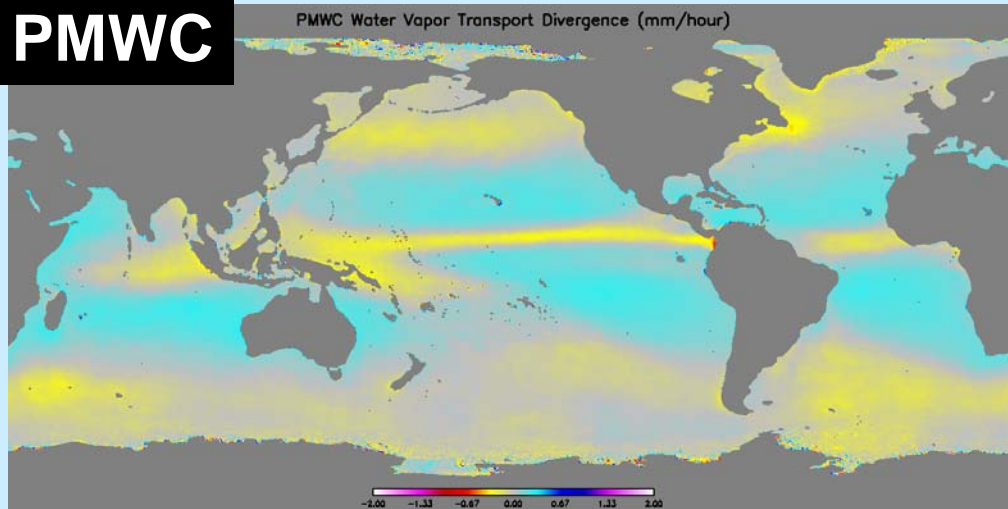




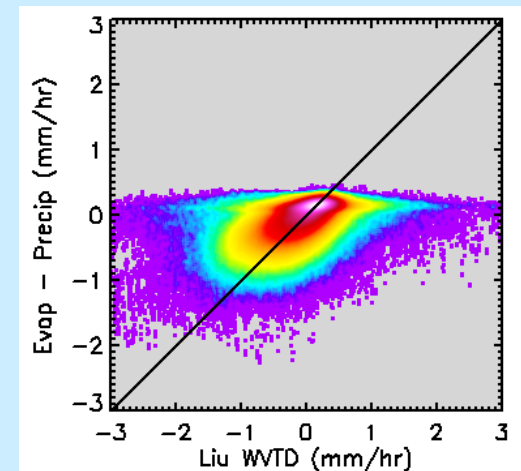
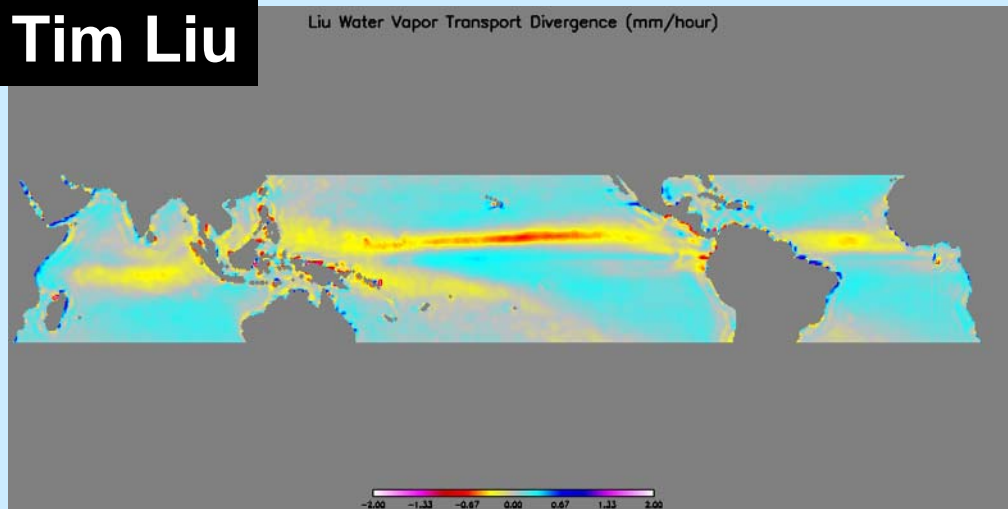
Water Vapor Transport Divergence

2000-2005

PMWC



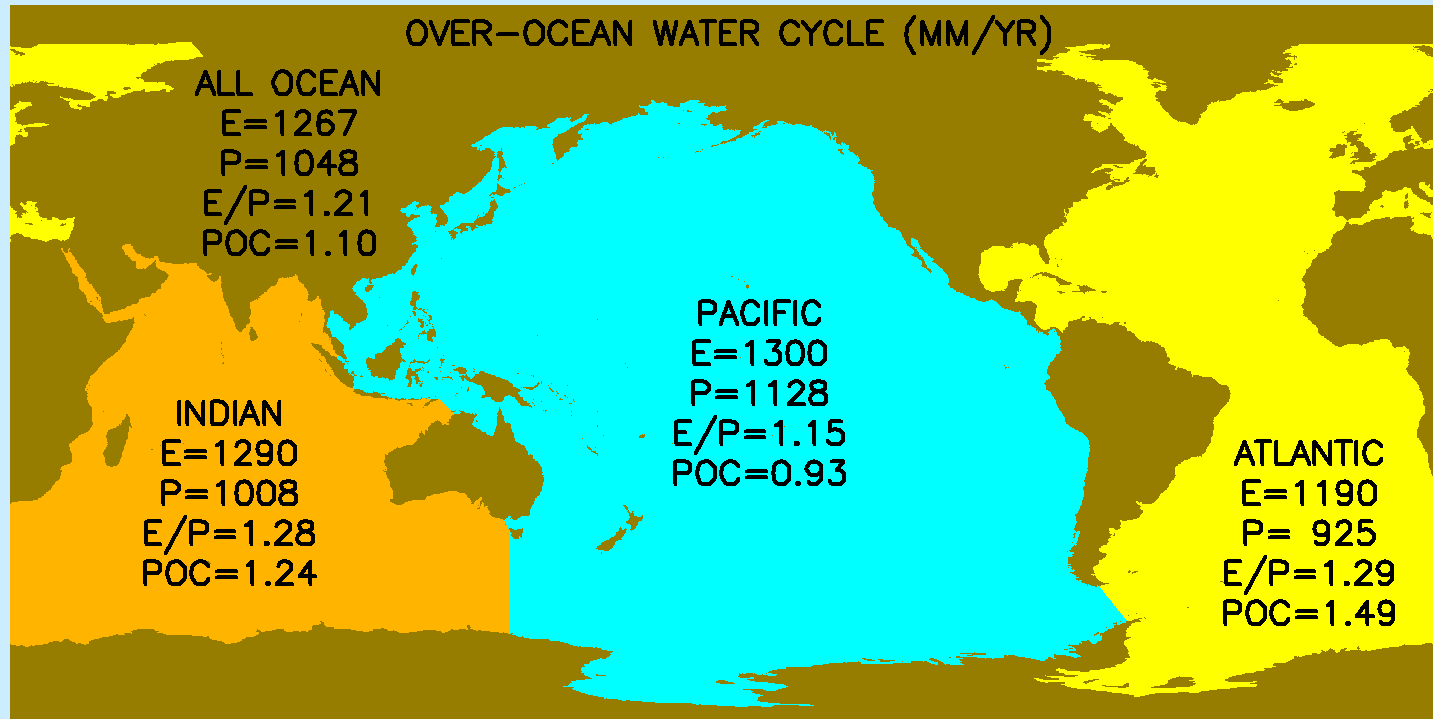
Tim Liu





Regional-Scale Water Balance

20-year basin-wide averages



- Our evaporation ratios (E/P) are more consistent from basin to basin than previous estimates (values from “Physics of Climate” (POC) shown here)
- For a sufficiently large area, evaporation is about 20% larger than precipitation; with the excess finding its way onto land



Trajectory Analysis with Atlas Winds

*Note that particle positions (determined by Atlas winds)
line-up with and move with water vapor*

