The NASA Energy and Water Cycle Study (NEWS) Climatology

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The State of the Global Water and Energy Cycles

Premise: In order to evaluate water and energy cycle consequences of climate change, we must establish the current "state of the global water/energy cycle".

Methods: Use modern, observation-integrating products and associated error-analyses to develop a monthly climatology of W&E cycle components for each continental/oceanic to global scale region.

Outcomes: (1) A benchmark for W&E cycle / climate change studies and model assessments; (2) Constrained energy flux estimates for quantifying the annual cycle of top of the atmosphere, surface, and atmospheric energy balances. (3) Quantitative graphical depictions of the water and energy cycles; (4) Better understanding of where the greatest uncertainties lie and what observations should be targeted for improvement.

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Water Cycle: Primary Data Sources

Variable	Dataset Name	Contributing RS Instruments
Precipitation	GPCP v. 2.2 MERRA CMAP	SSMI, SSMIS, GOES-IR, TOVS, AIRS, TRMM
Evapotranspiration	Princeton MERRA GLDAS	AIRS, CERES, MODIS, AVHRR, MSU, HIRS, SSU, AMSU, SSMI, SSMIS, ERS1/2, QuikSCAT, GOES-IR, TOVS, TRMM
Runoff	U. Washington Dai and Trenberth MERRA GLDAS	TRMM, GOES-IR, TOVS, SSM/I, ERS, ATOVS
Terrestrial and Oceanic Water Storage Change	GRACE CSR RL05 (Chambers)	GRACE
Atmospheric Convergence	QSCAT MERRA PWMC	QuikSCAT, TRMM, GRACE, MSU, HIRS, SSU, AMSU, AIRS, SSMI, ERS1/2, MODIS, GOES-IR
Atmospheric Water Storage Change	(Fetzer)	AIRS, AMSR-E
Ocean Evaporation	SeaFlux v. 1.0 Princeton MERRA	SSMI, AVHRR, AMSR-E, TMI, WindSat

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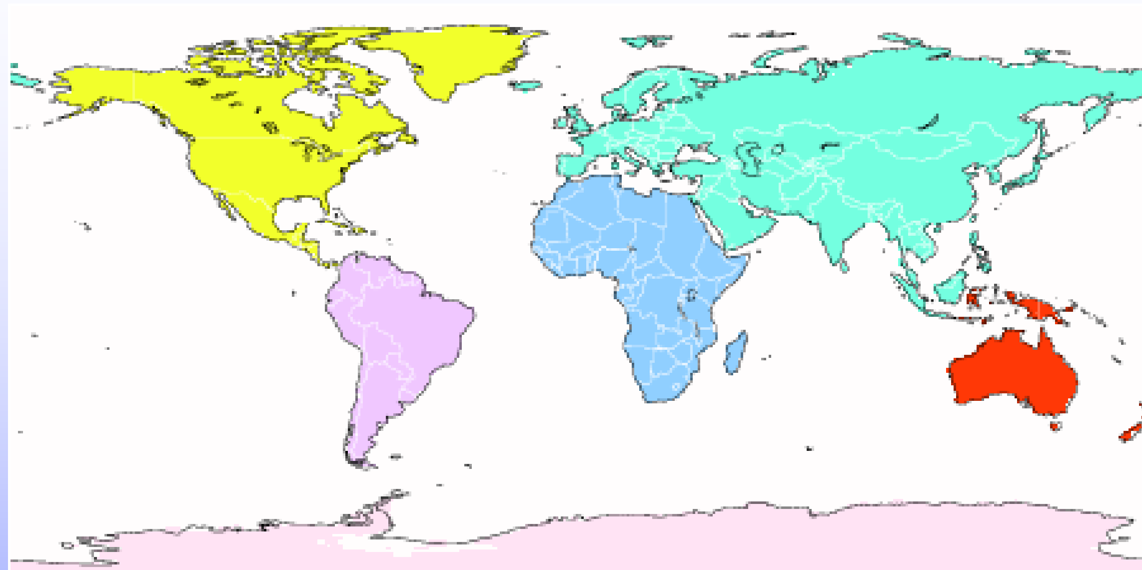
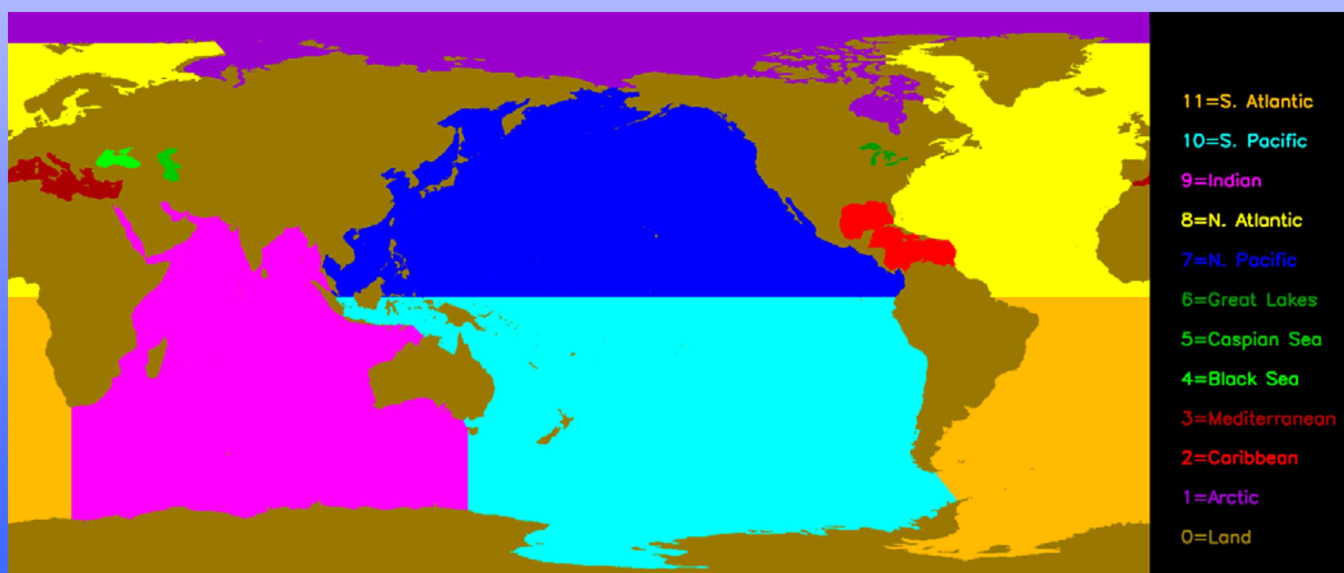
Continents and Ocean Basins





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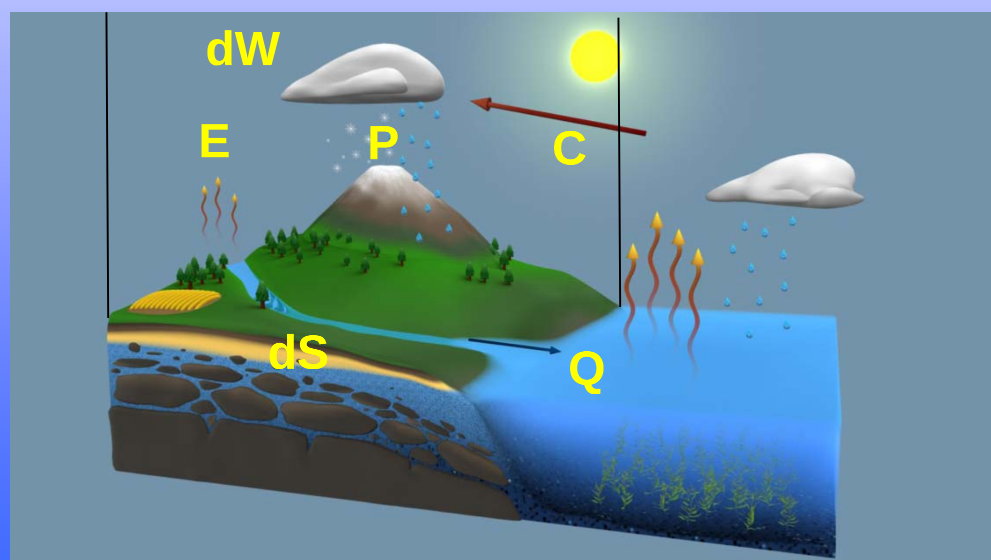
Budget Equations

CONTINENTS

Monthly/Sub-Annual	Annual Mean	
$dS = P - E - Q$	$dS = 0$ $P - E = Q$	(3)
$dW = C - P + E$	$dW = 0$ $C = P - E$	(4)
$dS + dW = C - Q$ • Follows from (3) and (4)	$Q = C$	(5)



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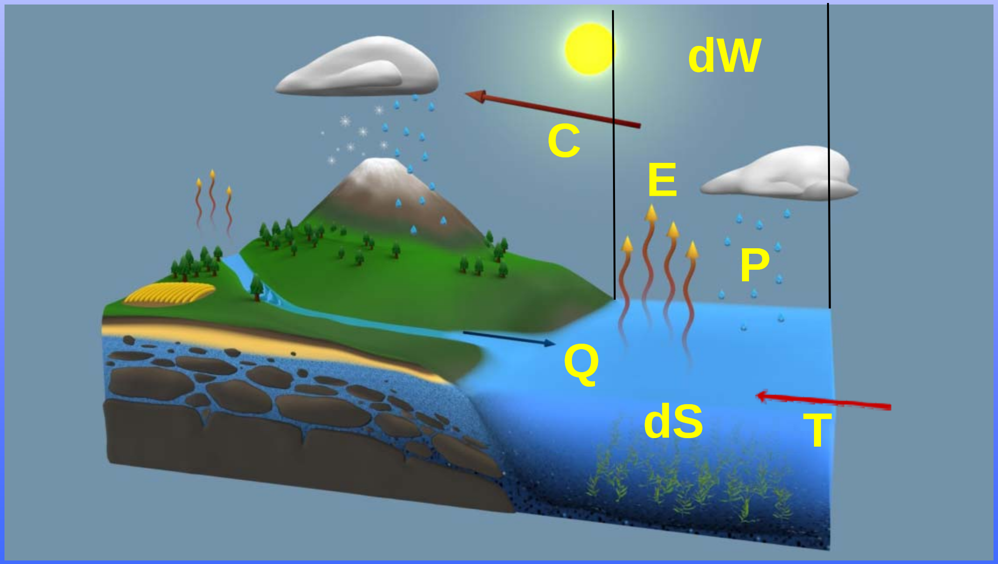
Budget Equations

OCEAN BASINS

Monthly/Sub-Annual	Annual Mean	
$dS = P - E + Q + T$	$dS = 0$ $E = P + Q + T$	(6)
• We do not have estimates of T		
$dW = C - P + E$	$dW = 0$ $C = P - E$	(7)
$dS + dW = C + Q + T$ • Follows from (6) and (7)	$C = -Q - T$	(8)



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Budget Equations

WORLD LAND and WORLD OCEAN

Monthly/Sub-Annual	Annual Mean	
$dS_L + dW_L = -dS_O - dW_O$ • Annual means follow from (3), (4), (6), and (7)	$dS_L = 0$ $dS_O = 0$ $dW_L = 0$ $dW_O = 0$	(9)
$Q_L = Q_O$ • We do not have an independent estimate of Q_O	$Q_L = Q_O$	(10)
$C_L = -C_O$	$C_L = -C_O$	(11)
$T = 0$	$T = 0$	(12)
$dS_O = P_O - E_O + Q_O$ • Follows from (6) and (12)	$E_O = P_O + Q_O$	(13)
$dS_L + dW_L = C_L - Q$ • Identical to (5)	$Q_L = C_L$	(14)
$dS_O + dW_O = C_O + Q$ • Follows from (8) and (12)	$Q_O = -C_O$	(15)
$dW_L + dW_O = E_L + E_O - P_L - P_O$ • Follows from (4), (7), and (11)	$P_L - E_L = E_O - P_O$	(16)

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Budget Equations

WORLD

Monthly/Sub-Annual	Annual Mean	
$C_W = 0$	$C_W = 0$	(17)
$dS_W = -dW_W$	$dS_W = 0$	(18)
$dS_W = P_W - E_W$	$P_W - E_W = 0$	(19)
$dW_W = E_W - P_W$ • Follows from (17) and (18)	$dW_W = 0$	(20)

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Budget Equations

Water and energy budgets constrain each other at all spatial and temporal scales:

$$E \sim LH$$

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Optimization

- Simultaneous application of multiple constraints
- Some iteration necessary
- Operations performed in IDL

General budget equation:

$$R = \sum_{i=1}^{M} F_i - \sum_{o=1}^{N} F_o$$

"Optimal" solution minimizes the cost function (assuming errors are Gaussian):

$$J = \left(\mathbf{F} - \mathbf{F_{obs}}\right)^{\mathbf{T}} \mathbf{S_{Fobs}^{-1}} \left(\mathbf{F} - \mathbf{F_{obs}}\right) + \frac{\left(R - R_{obs}\right)^2}{\sigma_R^2}$$

Minimum occurs when:

$$\mathbf{F} = \mathbf{F_{obs}} + \mathbf{S_F K^T S_{Robs}^{-1}} \left(\mathbf{R_{obs}} - \mathbf{K F_{obs}}\right)$$

$$\mathbf{S_F} = \left(\mathbf{K^T S_{Robs}^{-1} K} + \mathbf{S_{Fobs}^{-1}}\right)^{-1}$$

R = storage change
F = flux (in and out)
$\mathbf{S_{Fobs}}$ = error covariances of all observed fluxes
$\mathbf{S_{Robs}}$ = error covariances of all observed storage changes
K = Jacobian of **R** wrt component fluxes
$\mathbf{S_F}$ = error covariance for component fluxes after optimization

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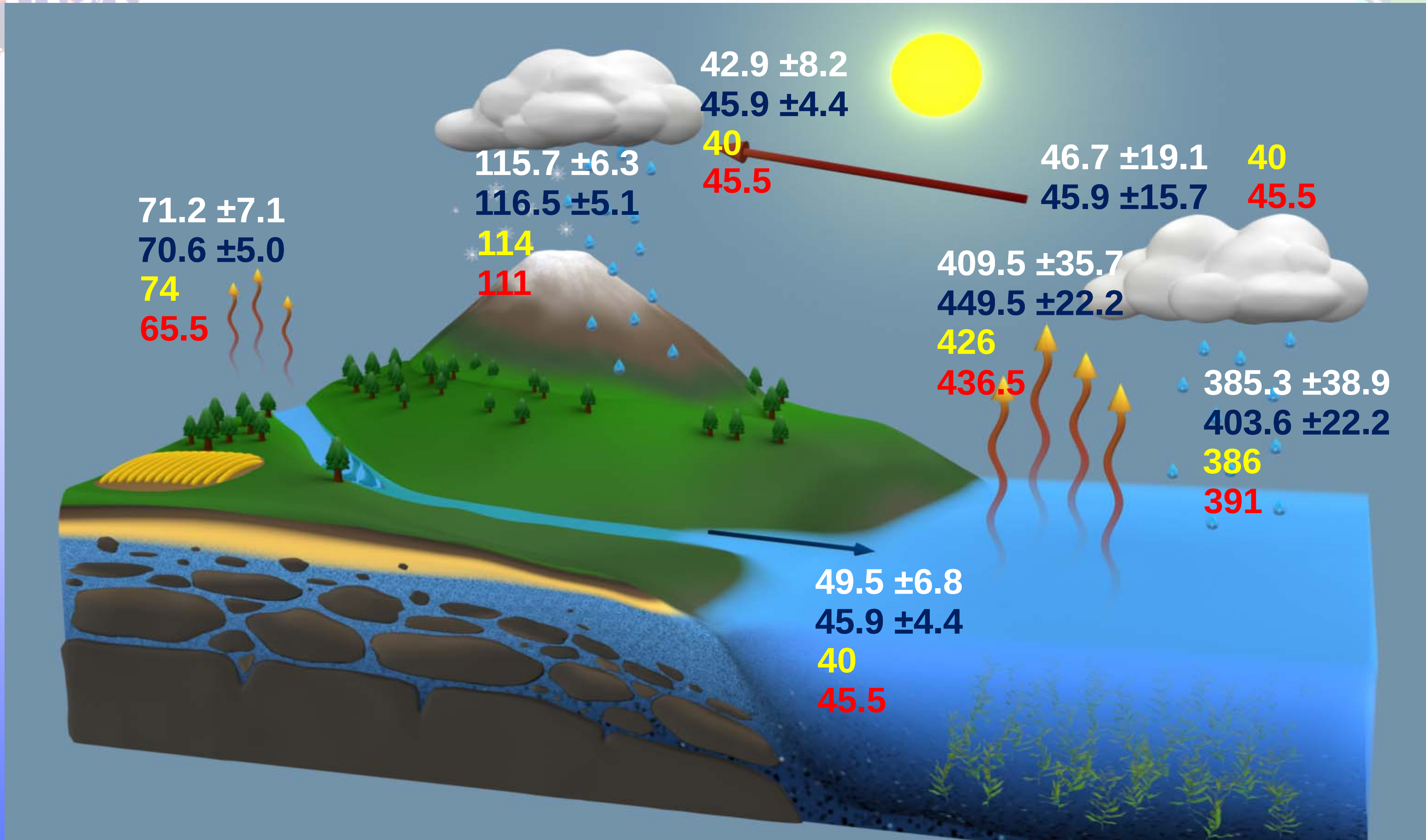
Global, Mean Annual Water Cycle



Global mean water fluxes (1,000 km^3/yr) at the start of the 21st century

Best guess estimates from observations and data integrating models

When water balance is enforced, uncertainty decreases

Trenberth et al. (2011) for comparison

Oki and Kanae (2006) for comparison

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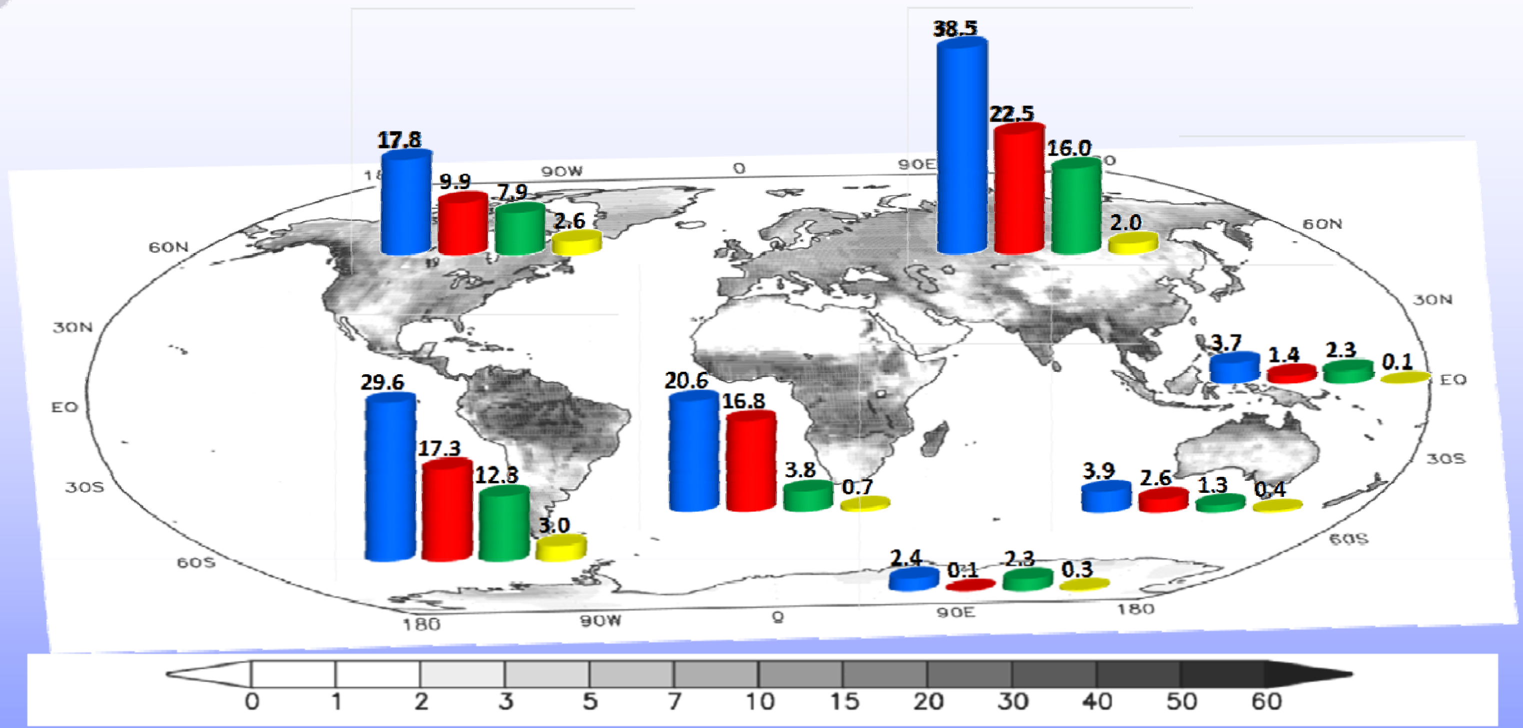
Continental Mean Annual Water Fluxes



Water budget constrained/optimized results: Precipitation (blue), evapotranspiration (red), runoff (green), and annual amplitude of terrestrial water storage (yellow) in 1,000 km^3/yr. Background shows GRACE-based amplitude of the annual cycle of terrestrial water storage (cm).

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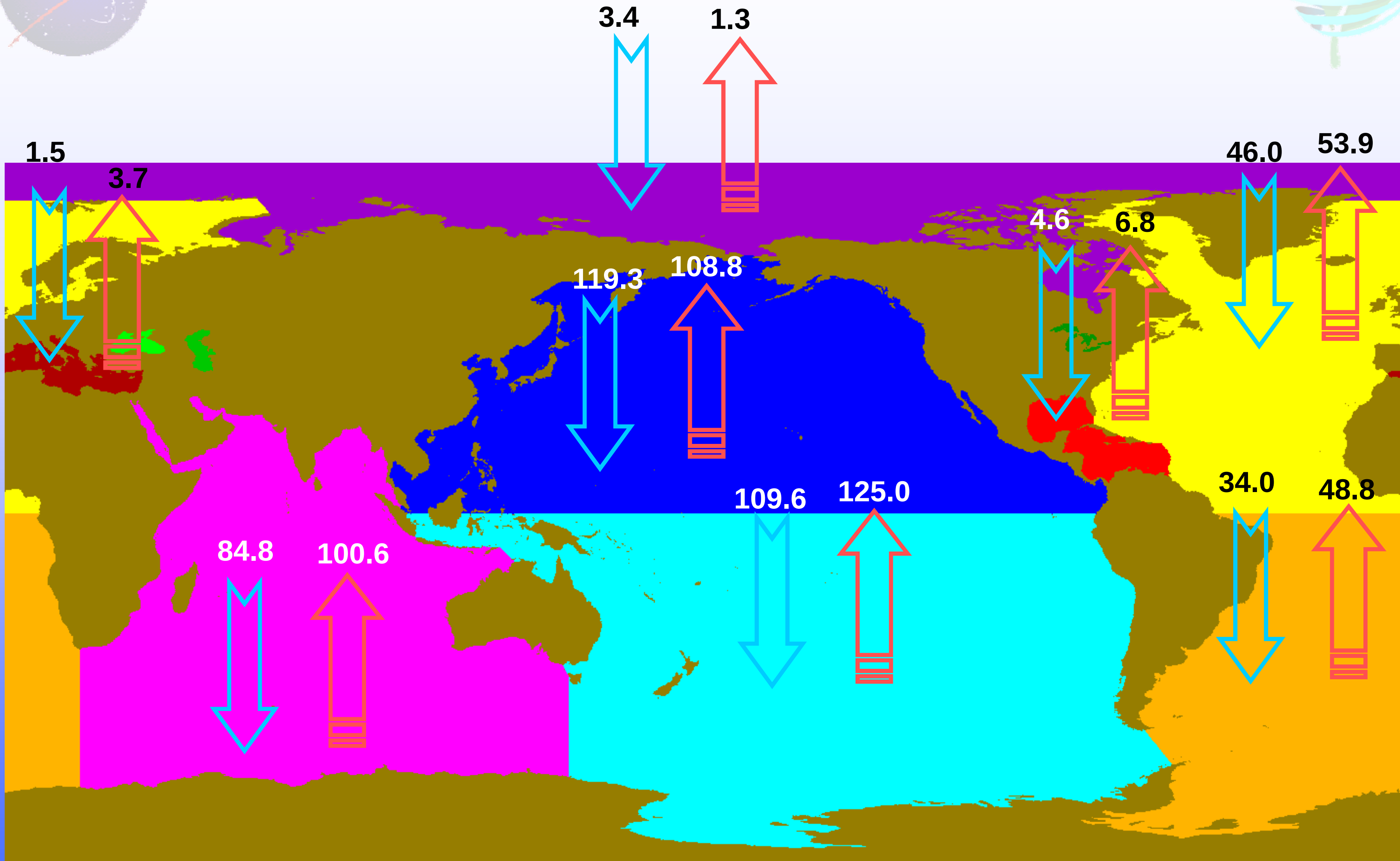
Optimized Oceanic Mean Annual Water Fluxes



Precipitation (downward arrows) and evaporation (upward arrows) in 1,000 km^3/yr.

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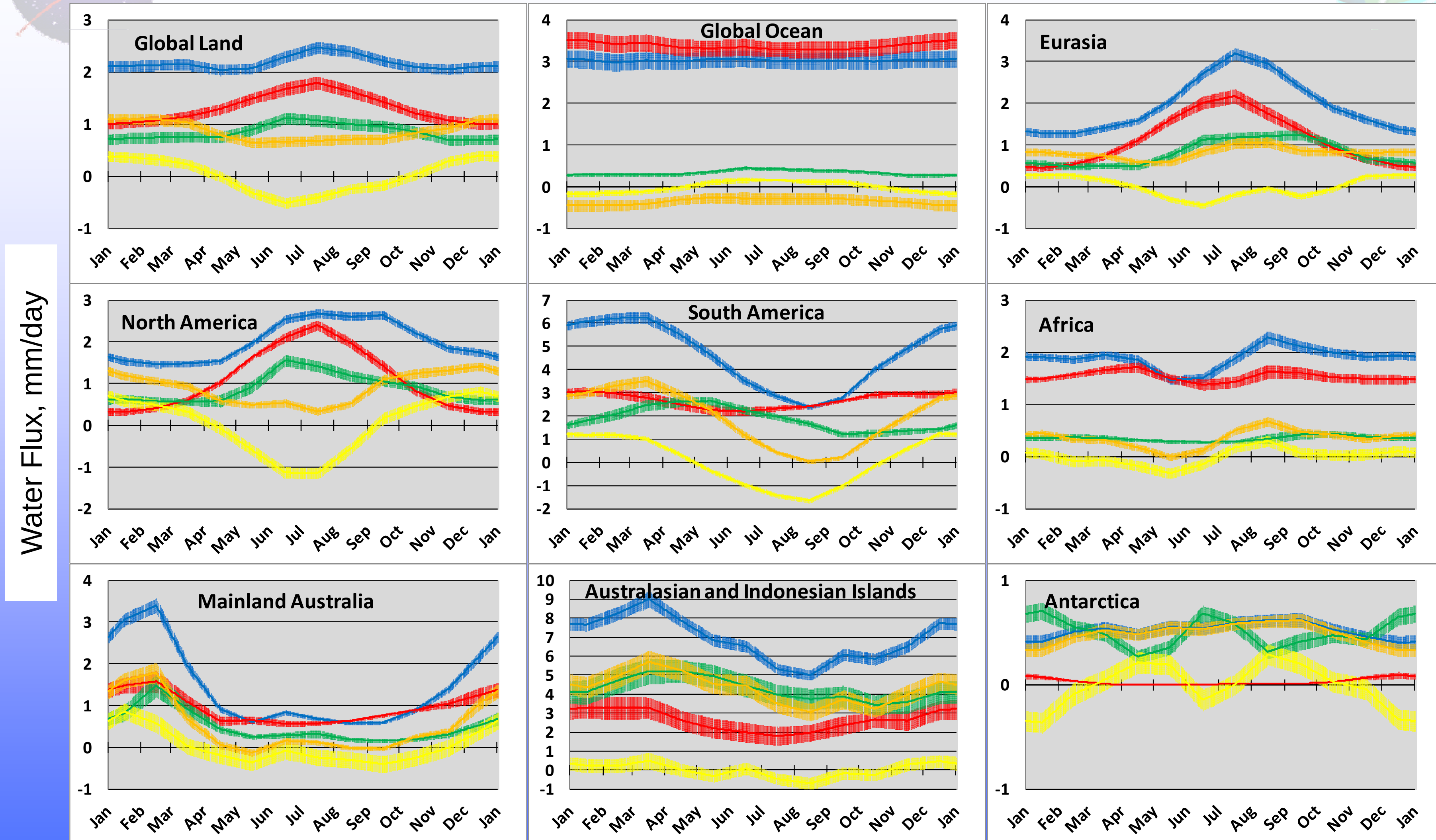
Optimized Mean Monthly Water Cycle



Mean monthly precipitation (blue), evapotranspiration (red), runoff (green), atmospheric convergence (orange), and month-to-month change in terrestrial water storage (yellow), in mm/day). Shading indicates uncertainty range.

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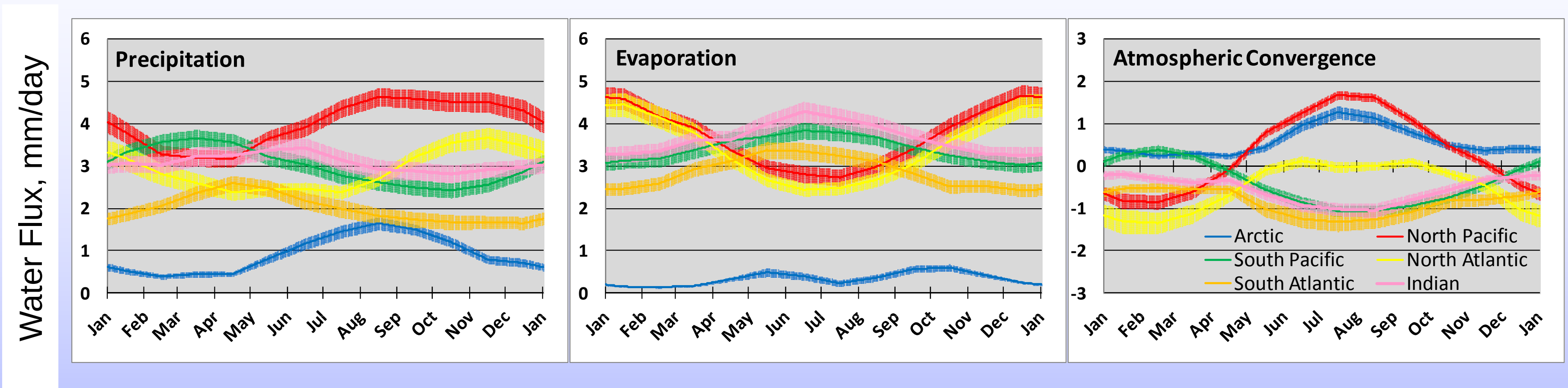
Optimized Mean Monthly Water Cycle



Mean monthly precipitation, evaporation, and atmospheric convergence over the major ocean basins: Arctic (blue), North Pacific (red), South Pacific (green), North Atlantic (yellow), South Atlantic (orange), and Indian (pink). Shading indicates uncertainty range.

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How Well Can We Close the Annual Surface Water Budget?

	Expected Closure Error	Best Guess Residual	Expected Error after Optimization
North America	8.6%	11.0%	6.4%
South America	8.0%	5.0%	5.7%
Eurasia	12.5%	5.1%	8.7%
Africa	8.1%	2.1%	5.7%
Australia Mainland	15.0%	7.6%	9.4%
Australasian and Indonesian Islands	19.5%	12.5%	9.9%
Antarctica	32.4%	*0.0%*	17.2%
World Land	10.1%	4.3%	7.2%
World Ocean	13.8%	6.6%	7.8%

Note the residual after optimization is ~0% in all cases.

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The State of the Global Water and Energy Cycles

• The NEWS W&E Cycle Climatology Team used modern, observation-integrating products and associated error-analyses to develop a monthly climatology of W&E cycle components for each continental/oceanic to global scale region.

• Over most regions and time periods, the original observation-based water budget residual was within the uncertainty range expected based on individual error estimates.

• An optimization process was applied to force closure of the terrestrial, atmospheric, and oceanic water budgets, and the energy budget simultaneously, at mean annual and monthly, global and continental/basin scales. Adjustments were generally smaller than the expected errors.

• The largest adjustments were in the ocean evaporation estimates (~+10%), attributed mainly to energy cycle closure. Adjustments to ocean precipitation (~+5%) were consistent with GPCP error estimates and recent studies (Behrangi et al., 2012; 2014).

• Despite having denser observing networks, residuals tended to be larger over North America and Eurasia than over Africa and South America. This may reflect continuing difficulty observing and modeling cold land processes.

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