Documentation for the VS-Lite Model, version 2.2

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November 22, 2011

1 New Features and Relation to Past Model Versions

There is one new features of the VS-Lite model in version 2.2: the option to run the "Leaky Bucket" hydrology at a sub-monthly timestep (hereafter referred to as "substepping"). The model may be run without the substepping option, in which case it is equivalent to the VS-Lite model version 2.1 previously archived on the WDCA-Paleo software library (http://www.ncdc.noaa.gov/paleo/softlib/softlib.html). As with previous versions, VS-Lite version 2.2 is also compatible with the freeware Matlab-clone, Octave 3.2.4 s(www.octave.org).

The original Leaky Bucket model of hydrology requires monthly input climate data, but actually updates soil moisture at a sub-monthly timestep to account for the nonlinearity of the soil moisture response (*Huang et al.* (1996)). Without the substepping, the Leaky Bucket model authors found that a single step for the entire month can cause the soil to dry out too quickly (Nicholas Graham, Konstantine Georgakakos, personal communication, March 2011.) Past versions of the VS-Lite model code did not include the option for sub-stepping. Version 2.2 with the substepping option bases tree-ring width growth on the instantaneous soil moisture computed at the end of each month. In general, comparisons of the model output with and without substepping show that using substepping tends to add more "drag" to the modeled hydrological system, so that the substepping tends to curb the largest rates of change in the system compared to the implementation without substepping (see Figure 1). Note that if the initial soil moisture input to the model is less than zero and thus unphysical, the model sets the initial value to a default value of 0.2 v/v.

The VS-lite v2.2 model has been validated with leaky bucket temporal substepping using all the same tests used and described and implemented by *Tolwinski-Ward et al.* (2011a) and *Tolwinski-Ward et al.* (2011b) to validate the earlier model version. The differences in simulations performed with and without substepping appear quite minor in the test networks examined; results are provided Tables 3-6 and Figures 2-12 below (Tables and Figures are numbered to correspond with numbering of results in *Tolwinski-Ward et al.* (2011a)).

A script called vslite_bayes_param_cal.m for Bayesian calibration of the VS-Lite v2.2 model parameters has also been developed and archived with separate documentation at the WDCA-Paleo software library (http://www.ncdc.noaa.gov/paleo/softlib/softlib.html).

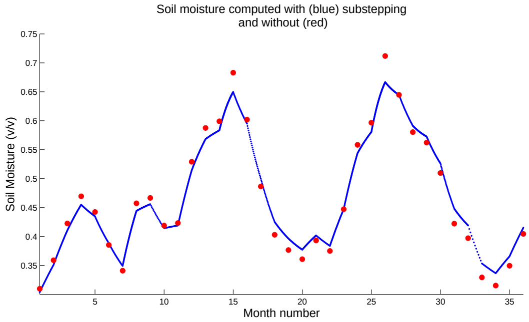

Figure 1: Three years of soil moisture simulated at one site with the same input climate, for the Leaky Bucket implementations with substepping turned "on" (blue) and "off" (red).

2 Acknowledgements

I gratefully acknowledge Nick Graham for pointing out the substepping in the original Leaky Bucket model code, and for sharing his own implementation of the Leaky Bucket code.

References

Huang, J., H. M. van den Dool, and K. P. Georgankakos (1996), Analysis of model-calculated soil moisture over the United States (1931-1993) and applications to long-range temperature forecasts, *J. Clim.*, *9*, 1350–1362.

Tolwinski-Ward, S., M. Evans, M. Hughes, and K. Anchukaitis (2011a), An efficient forward model of the climate controls on interannual variation in tree-ring width, *Clim. Dyn.*, *36*, 2419–2439, doi:10.1007/s00382-010-0945-5.

Tolwinski-Ward, S., M. Evans, M. Hughes, and K. Anchukaitis (2011b), Erratum to: An efficient forward model of the climate controls on interannual variation in tree-ring width, *Clim. Dyn.*, *36*, 2441–2445, doi:10.1007/s00382-011-1062-9.

Table 2: Fraction of observed signal variances at frequencies of $1/5\ \mathrm{yr}^{-1}$ and lower at each site; correlation and significance of bristlecone pine simulations with observed chronologies. Low-frequency signals are given by 5-year filtering of the signals; high-frequency signals are the residuals. Low-freq. p-values are corrected for effective number of degrees of freedom. Sites marked "UFB" are at the upper forest border. **Highlighted rows are results for VS-Lite v2.2 with substepping turned "on", while white rows are previous results for simulations with VS-Lite v2.1.**

Site	Abbrv.	Low Freq. Var. Frac.	Low-freq.	High-freq.
Pearl Peak (UFB)	PRL	0.64	0.55 ($p < 0.01$)	0.12 ($p \approx 0.3$)
Pearl Peak (UFB)	PRL	0.64	0.57 ($p < 0.01$)	0.10 ($p \approx 0.3$)
Sheep Mountain (UFB)	SHP	0.48	0.69 ($p < 0.001$)	0.31 ($p < 0.002$)
Sheep Mountain (UFB)	SHP	0.48	0.69 ($p < 0.001$)	0.31 ($p < 0.002$)
Mount Washington (UFB)	MWA	0.51	0.51 ($p < 0.02$)	0.12 ($p \approx 0.2$)
Mount Washington (UFB)	MWA	0.51	0.49 ($p < 0.03$)	0.16 ($p \approx 0.1$)
Cottonwood Lower	CWL	0.60	0.21 ($p \approx 0.3$)	0.35 ($p < 0.001$)
Cottonwood Lower	CWL	0.60	0.21 ($p \approx 0.3$)	0.34 ($p < 0.001$)
Methuselah Walk	MWK	0.45	0.42 ($p \approx 0.06$)	0.32 ($p < 0.002$)
Methuselah Walk	MWK	0.45	0.42 ($p \approx 0.06$)	0.29 ($p < 0.01$)
Patriarch Lower	PAL	0.55	0.08 ($p \approx 0.7$)	0.28 ($p < 0.01$)
Patriarch Lower	PAL	0.55	0.09 ($p \approx 0.7$)	0.25 ($p < 0.01$)

Table 3: Mean percentage of sites, across an ensemble of 100 simulations, whose simulations correlate significantly with observed tree-ring width chronologies at two significance levels in the M08 network. Results shown for simulations by principal components regression calibrated at each site, simulations by VS-Lite with parameters calibrated at each site, and simulations by VS-lite with a single, "global" parameter set calibrated on the network as a whole. Errors represent 1 standard deviation in the percentages simulated significantly across ensemble members. **Highlighted rows are results for simulations using VS-Lite v2.2 with substepping turned "on", and white rows show previous results with VS-Lite v2.1.**

	M08 Network (N = 282)					
	PC Regr., site-by-site		VS-Lite, site-by-site		VS-Lite, global	
	Calibration	Validation	Calibration	Validation	Calibration	Validation
$p < 0.01$	73% ± 3%	40% ± 3%	69% ± 2%	59% ± 3%	46% ± 3%	48% ± 3%
$p < 0.01$	73% ± 3%	40% ± 3%	69% ± 2%	60% ± 3%	47% ± 2%	49% ± 3%
$p < 0.05$	83% ± 3%	56% ± 3%	80% ± 2%	71% ± 3%	59% ± 3%	61% ± 3%
$p < 0.05$	83% ± 3%	56% ± 3%	80% ± 2%	71% ± 3%	59% ± 2%	61% ± 3%

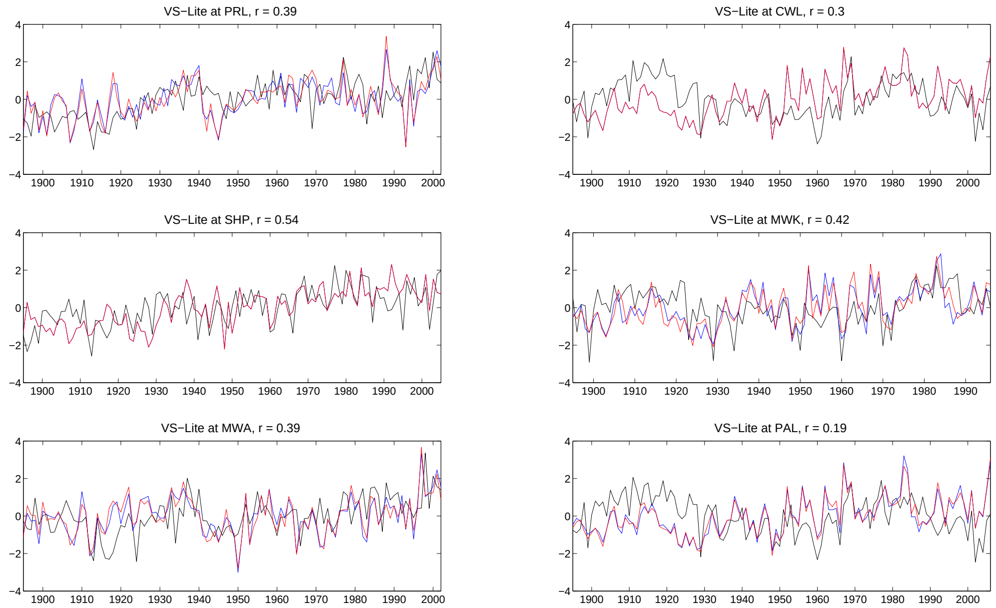

Figure 2: Great Basin bristlecone pine chronologies, observed (black line), simulated with VS-Lite v2.1, (blue) and simulated with VS-Lite v2.2 with Leaky Bucket temporal sub-stepping (red). Chronologies from upper forest border sites are displayed in panels at left; chronologies from below treeline are at right.

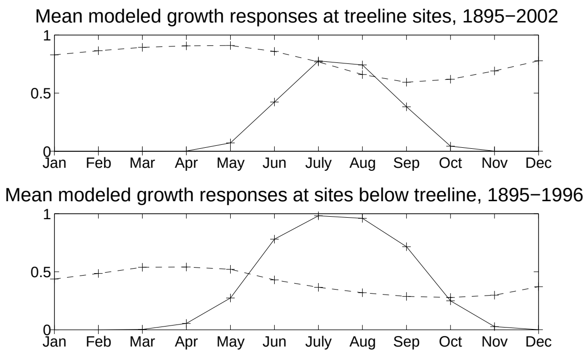

Figure 3: Modeled temperature (solid line) and moisture (dashed) response curves of Great Basin bristlecones at upper forest border (top panel) and below treeline (lower panel) as modeled with VS-Lite v2.2 with Leaky bucket substepping turned "on". The modeled growth response over the growing season is controlled by the pointwise minimum of these two quantities. As in simulations with VS-Lite v2.1, VS-Lite v2.2 with substepping therefore models mainly temperature-limited growth in the upper forest border sites, and more strongly moisture-limited growth below treeline.

Table 4: Correlation and significance of temporal loadings of significant patterns of mean M08 network calibration and validation fields, as simulated by VS-Lite and PC regression, with the corresponding principal components of the observed field. Low and high frequency components are given by a 5-year running filter of the temporal loadings and their residuals, and significance of low-frequency correlations are computed using a 2-sided T-test with the effective number of degrees of freedom estimated by the signal length divided by the length of the low-pass filter. **Highlighted rows are results for simulations using VS-Lite v2.2 with substepping turned "on", and white rows show previous results with VS-Lite v2.1.**

		Low frequency		High frequency	
Model	Pattern Order	Calibration	Validation	Calibration	Validation
VS-Lite	1	$0.64, p < 0.01$	$0.59, p = 0.01$	$0.71, p < 0.001$	$0.67, p < 0.001$
VS-Lite	1	$0.64, p < 0.01$	$0.59, p = 0.01$	$0.71, p < 0.001$	$0.66, p < 0.001$
VS-Lite	2	$0.42, p = 0.09$	$0.41, p < 0.09$	$0.20, p = 0.07$	$0.20, p = 0.06$
VS-Lite	2	$0.42, p = 0.09$	$0.40, p = 0.10$	$0.19, p = 0.07$	$0.19, p = 0.07$
PC Reg	1	$0.82, p < 0.001$	$0.71, p < 0.01$	$0.83, p < 0.001$	$0.74, p < 0.001$
PC Reg	2	$0.51, p < 0.05$	$0.39, p \approx 0.12$	$0.54, p < 0.001$	$0.37, p < 0.001$

Table 5: Mean percentage of sites, across an ensemble of 100 simulations, whose simulations correlate significantly with observed tree-ring width chronologies at two significance levels in the 5N network. Results shown for simulations by principal components regression calibrated at each site, simulations by VS-Lite with parameters calibrated at each site, and simulations by VS-lite with a single, "global" parameter set calibrated on the network as a whole. Errors represent 1 standard deviation in the percentages simulated significantly across ensemble members. **Highlighted rows are results for simulations using VS-Lite v2.2 with substepping turned "on", and white rows show previous results with VS-Lite v2.1.**

	5N Network (N = 66)					
	PC Regr., site-by-site		VS-Lite, site-by-site		VS-Lite, global	
	Calibration	Validation	Calibration	Validation	Calibration	Validation
$p < 0.01$	69% ± 5%	17% ± 3%	41% ± 5%	25% ± 5%	21% ± 5%	20% ± 5%
$p < 0.01$	69% ± 5%	17% ± 3%	42% ± 5%	27% ± 5%	24% ± 5%	21% ± 5%
$p < 0.05$	85% ± 6%	31% ± 4%	60% ± 4%	42% ± 5%	37% ± 5%	36% ± 5%
$p < 0.05$	85% ± 6%	31% ± 4%	60% ± 4%	43% ± 5%	38% ± 5%	36% ± 5%

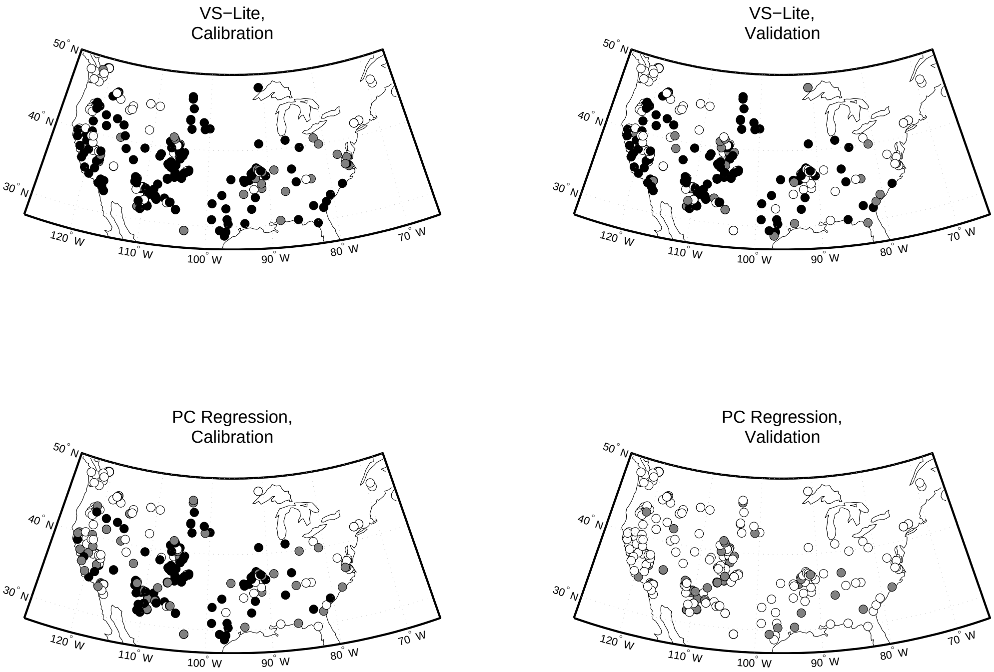

Figure 4a: Mean validation-interval significance of correlations of ring width simulations with observations over a 100-member ensemble of simulations of the M08 network, simulated with VS-lite v2.2 with substepping turned "on". Ensemble members differ in their randomized calibration intervals. Black circles: $p < .01$, gray circles: $p < .05$, white circles: $p > .05$.

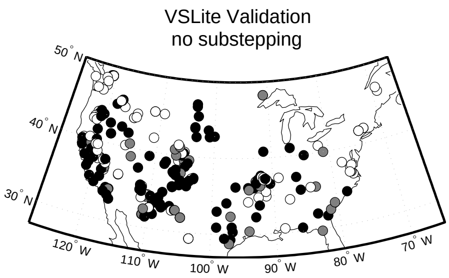

Figure 4b: Mean validation-interval significance of correlations of ring width simulations with observations over a 100-member ensemble of simulations of the M08 network, simulated with VS-lite v2.1 (left) and v2.2 with substepping turned "on" (right). Ensemble members differ in their randomized calibration intervals. Black circles: $p < .01$, gray circles: $p < .05$, white circles: $p > .05$.

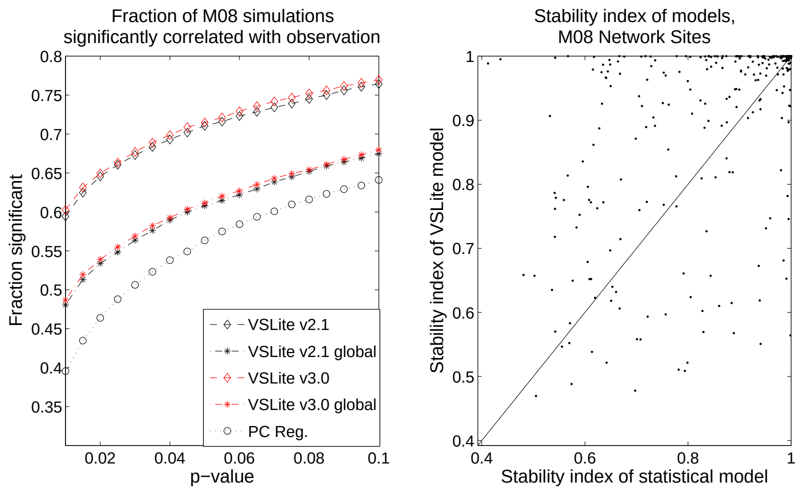

Figure 5: Performance indices of modeling by VS-Lite and principal components regression on the M08 Network. Left panel plots the fraction of network sites whose simulations correlate significantly with observations at a range of p-values for three different simulation approaches. Previous results are plotted in black for comparison; results for simulations using VS-Lite v2.2 with substepping turned "on" are plotted in red. Right panel plots the stability index (eqn. 3) of simulations by corrected VS-Lite code versus PC regression, with one indicating perfect stability of simulations from the calibration to validation periods, and zero representing complete instability. 203 out of 282 points fall above $y = x$ (compare to 202 out of 282 for simulations using VS-lite v2.1).

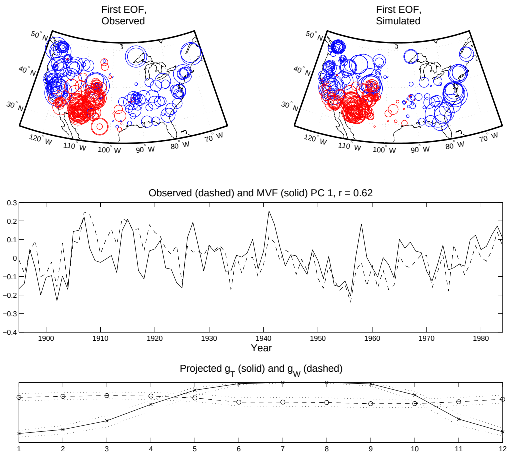

Figure 6a: Top: first pattern in observed (left) and simulated (right) data, M08 network, 1895-1984, for simulations with VS-Lite v2.1. Center: time series associated with first observed (dashed) and simulated (solid) EOF patterns. Bottom: mean over simulated years of the mean validation field temperature and moisture response functions, projected onto the first simulated MVF EOF. Dashed lines give the 95% confidence bands derived from percentiles of the repeated experiments under randomized calibration intervals.

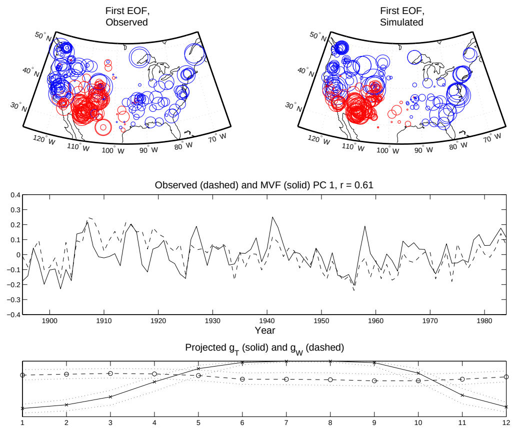

Figure 6b: Top: first pattern in observed (left) and simulated (right) data, M08 network, 1895-1984, for simulations with VS-Lite v2.2 with sub-stepping turned "on". Center: time series associated with first observed (dashed) and simulated (solid) EOF patterns. Bottom: mean over simulated years of the mean validation field temperature and moisture response functions, projected onto the first simulated MVF EOF. Dashed lines give the 95% confidence bands derived from percentiles of the repeated experiments under randomized calibration intervals.

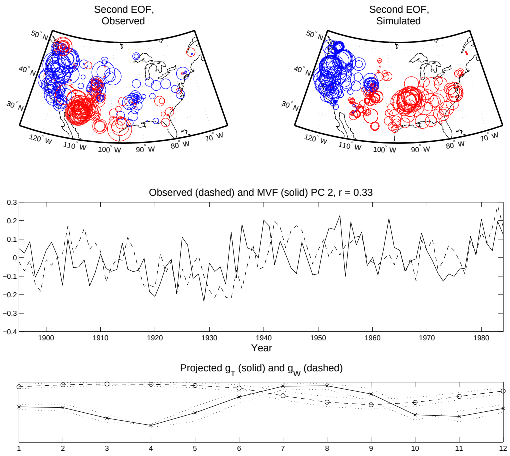

Figure 7a: As in previous figure simulated with VS-Lite v2.1, except displaying results for the second pattern.

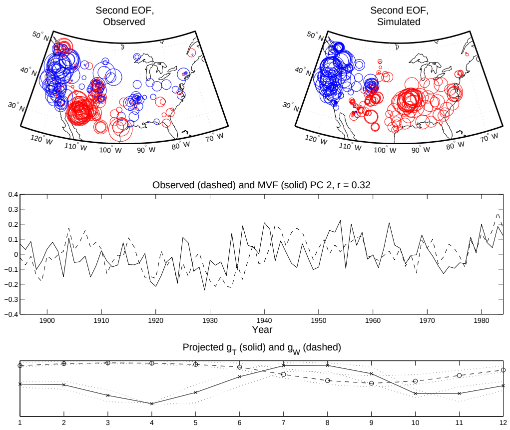

Figure 7b: As in previous figure with simulations from VS-lite v2.2 with substepping turned "on", except displaying results for the second pattern.

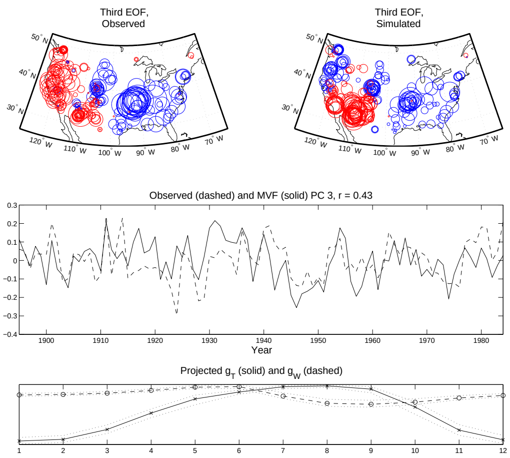

Figure 8a: As in previous figure simulated with VS-Lite v2.1, except displaying results for the third pattern.

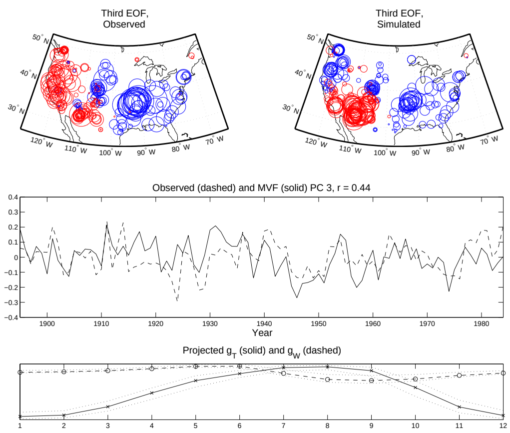

Figure 8b: As in previous figure with simulations from VS-lite v2.2 with substepping turned "on", except displaying results for the third pattern.

Table 6: Correlation and significance of temporal loadings of significant patterns of mean 5N network calibration and validation fields, as simulated by VS-Lite and PC regression, with the corresponding principal components of the observed field. Low and high frequency components are given by a 5-year running filter of the temporal loadings and their residuals, and significance of low-frequency correlations are computed using a 2-sided T-test with the effective number of degrees of freedom estimated by the signal length divided by the length of the low-pass filter. **Highlighted rows are the updated results.**

		Low frequency		High frequency	
Model	Pattern Order	Calibration	Validation	Calibration	Validation
VS-Lite	1	$0.76, p < 0.001$	$0.74, p < 0.001$	$0.46, p < 0.001$	$0.37, p < 0.001$
VS-Lite	1	$0.77, p < 0.001$	$0.74, p < 0.001$	$0.46, p < 0.001$	$0.38, p < 0.001$
VS-Lite	2	$0.81, p < 0.001$	$0.73, p < 0.001$	$0.66, p < 0.001$	$0.63, p < 0.001$
VS-Lite	2	$0.83, p < 0.001$	$0.76, p < 0.001$	$0.67, p < 0.001$	$0.64, p < 0.001$
PC Reg	1	$0.60, p < 0.01$	$0.42, p = 0.09$	$0.37, p < 0.001$	$0.09, p = 0.4$

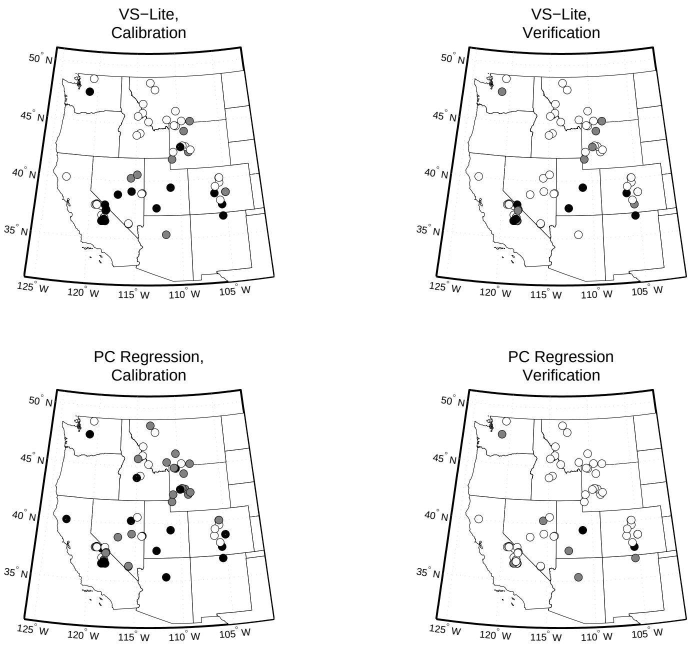

Figure 9a: Mean validation-interval significance of correlations of ring width simulations with observations over a 100-member ensemble of simulations of the 5N network, simulated with VS-lite v2.2 with substepping turned "on". Ensemble members differ in their randomized calibration intervals. Black circles: $p < .01$, gray circles: $p < .05$, white circles: $p > .05$.

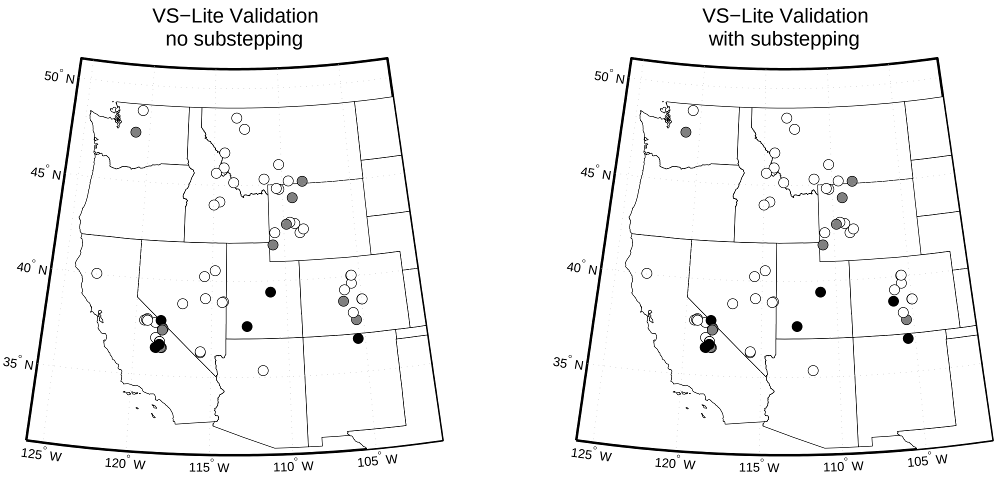

Figure 9b: Mean validation-interval significance of correlations of ring width simulations with observations over a 100-member ensemble of simulations of the 5N network, simulated with VS-lite v2.1 (left) and v2.2 with substepping turned "on" (right). Ensemble members differ in their randomized calibration intervals. Black circles: $p < .01$, gray circles: $p < .05$, white circles: $p > .05$.

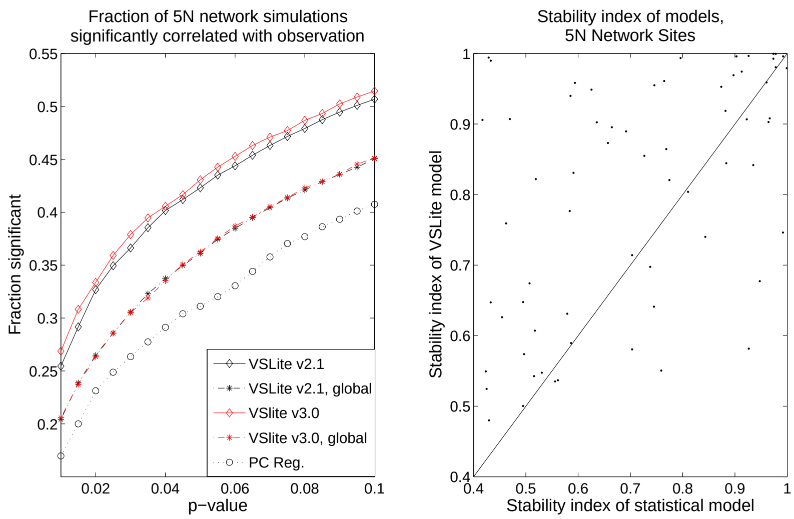

Figure 10: Performance indices of modeling by VS-Lite and principal components regression on the 5N network. Left panel plots the fraction of network sites whose simulations correlate significantly with observations at a range of p-values for three different simulation approaches. Previous results are plotted in black for comparison; results for simulations using VS-Lite v2.2 with substepping turned "on" are plotted in red. Right panel plots the stability index (eqn. 3) of simulations by corrected VS-Lite code versus PC regression, with one indicating perfect stability of simulations from the calibration to validation periods, and zero representing complete instability. 48 out of 66 points fall above $x = y$ (compare to 42 out of 66 with previous results using VS-Lite v2.1).

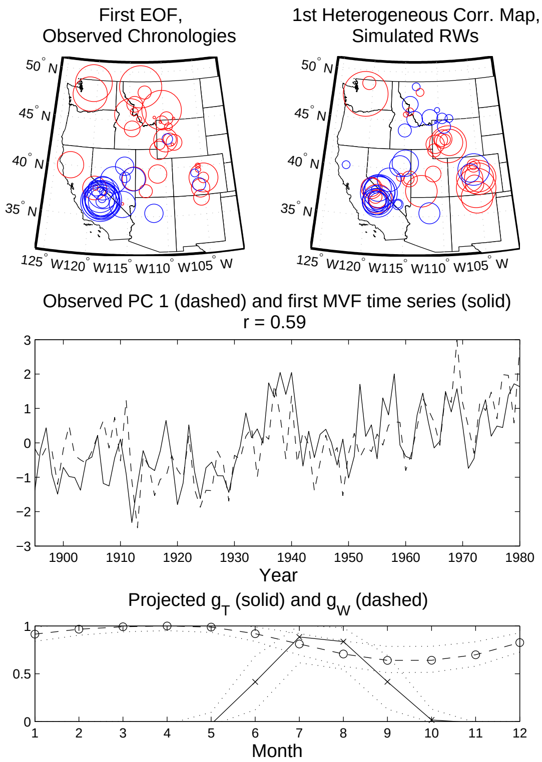

Figure 11a: Top left: first pattern in observed data, 5N network, 1895-1980, for simulations with VS-Lite 2.1. Top right: Simulated data projected on first pattern of covariance in the observed network. Center: time series associated with first observed pattern and first pattern of covariance in simulated network. Bottom: mean over simulated years of the mean validation field temperature and moisture response functions projected onto the first pattern of observed covariance. Dashed lines give the 95% confidence bands derived from percentiles of the repeated experiments under randomized calibration intervals.

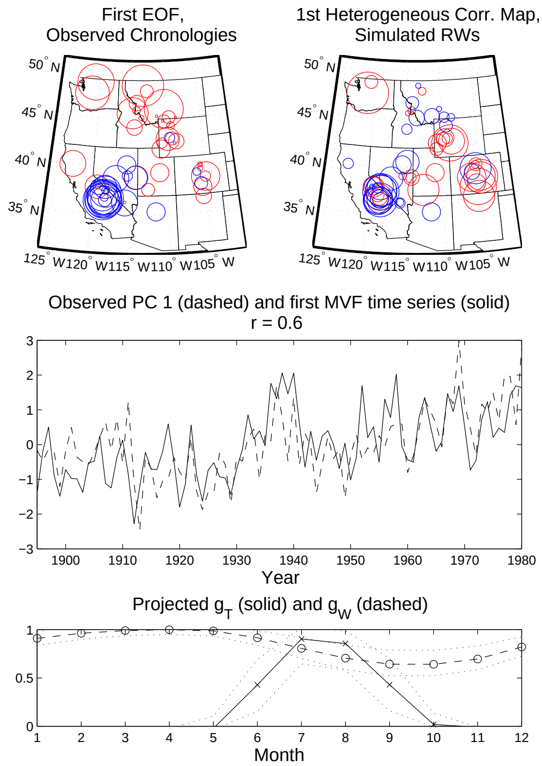

Figure 11b: Top left: first pattern in observed data, 5N network, 1895-1980, for simulations with VS-Lite 3.0 and substepping turned "on". Top right: Simulated data projected on first pattern of covariance in the observed network. Center: time series associated with first observed pattern and first pattern of covariance in simulated network. Bottom: mean over simulated years of the mean validation field temperature and moisture response functions projected onto the first pattern of observed covariance. Dashed lines give the 95% confidence bands derived from percentiles of the repeated experiments under randomized calibration intervals.

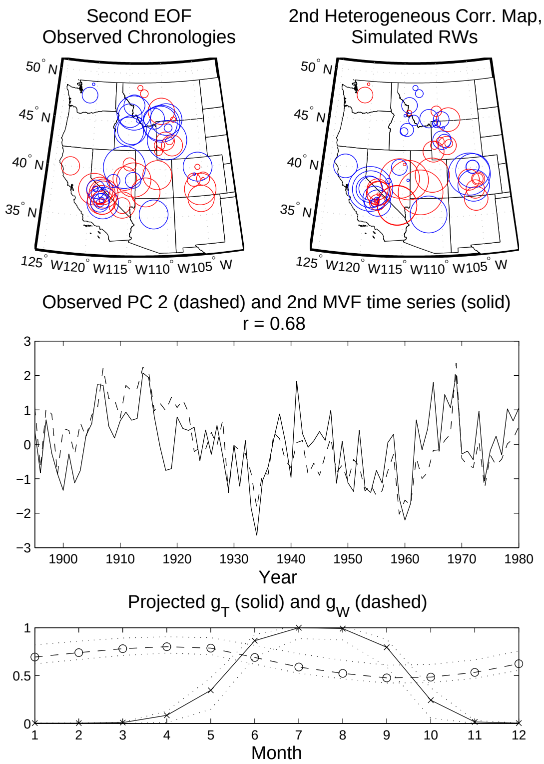

Figure 12a: As in previous figure with simulations from VS-Lite v2.1, except displaying results for the second pattern.

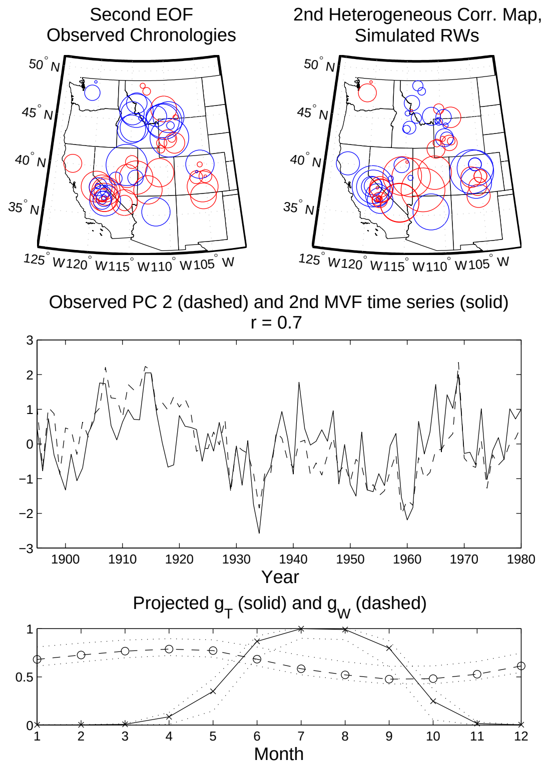

Figure 12b: As in previous figure with simulations from VS-Lite v2.2 with substepping turned "on", except displaying results for the second pattern.