Application of a Subgrid Orography Scheme to a Global Climate Model

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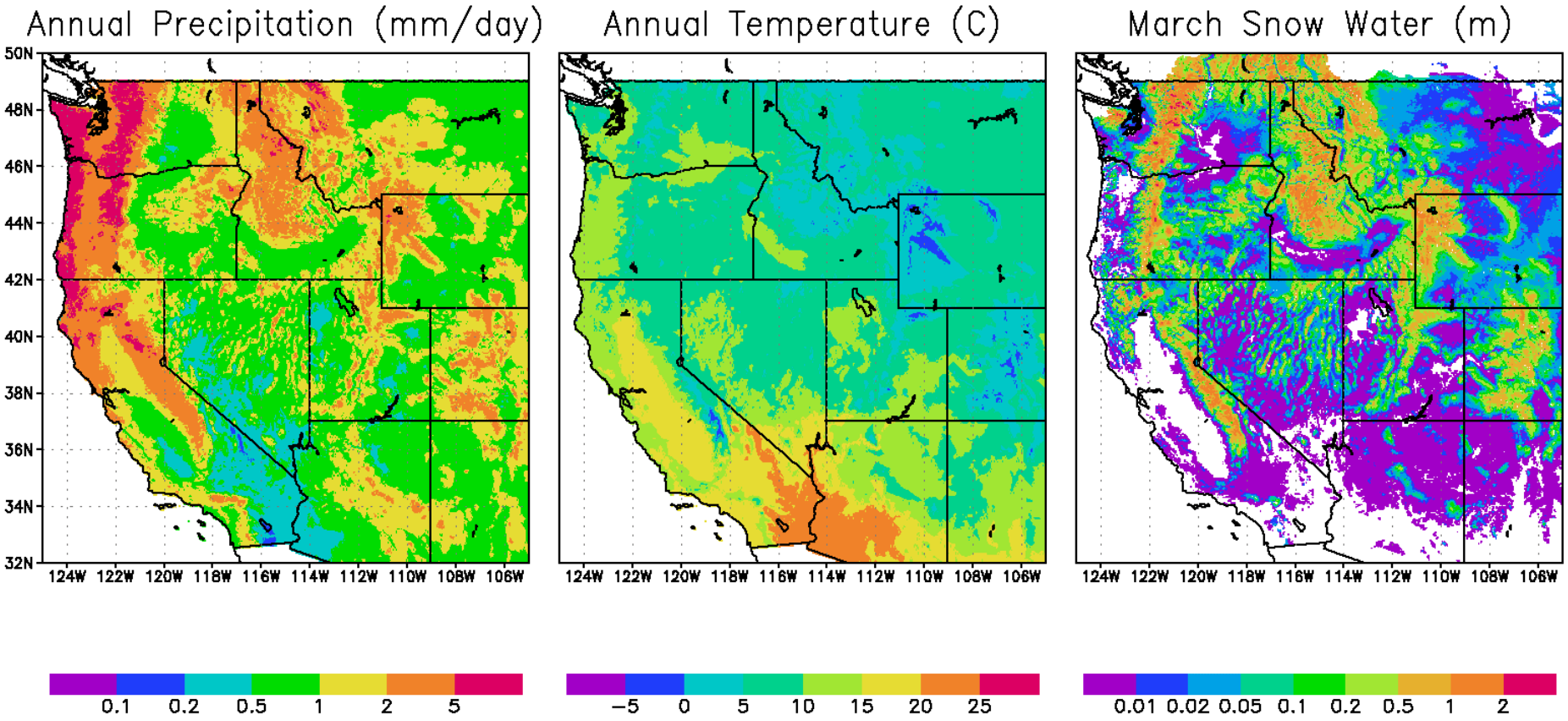
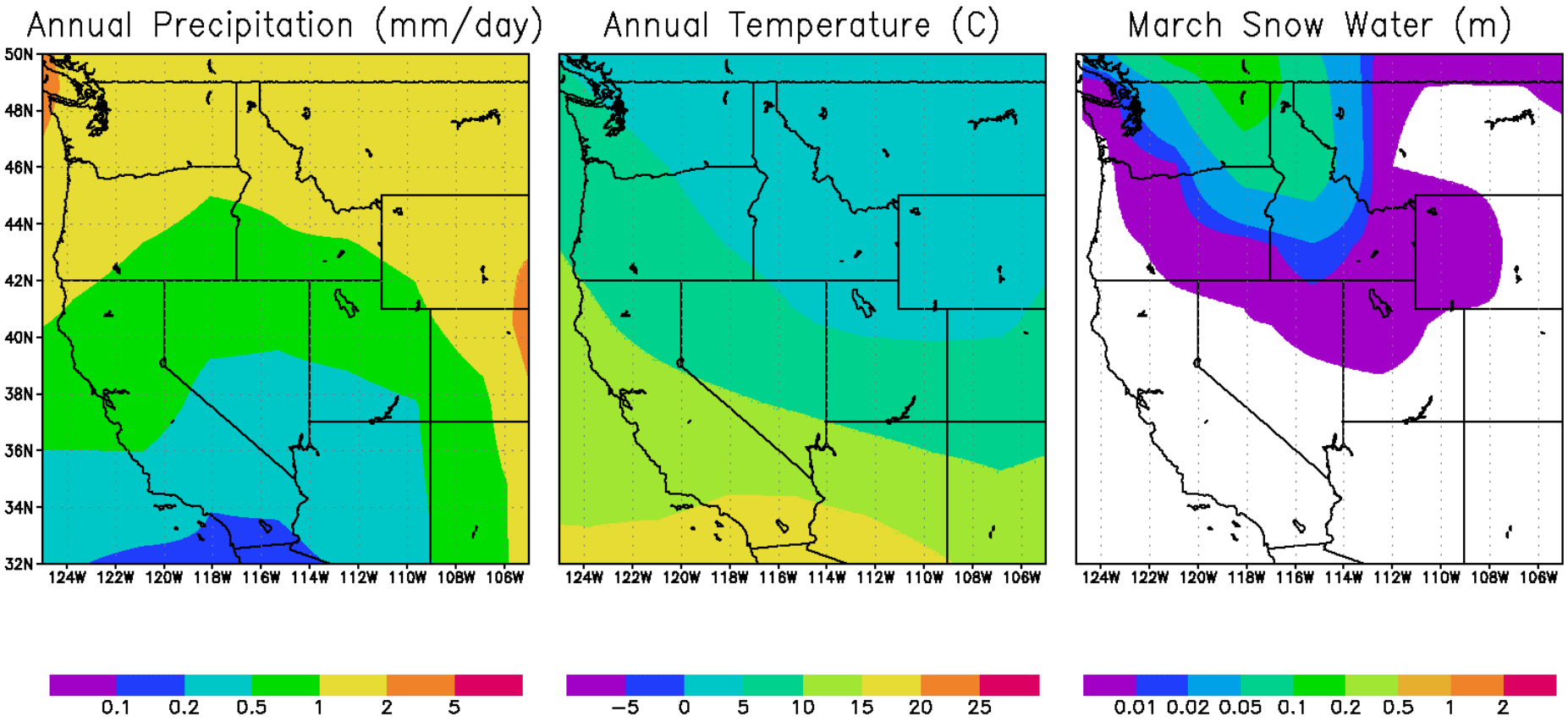
Motivation

- Current global climate models provide horizontal resolution of about 250 km.
- In regions with complex terrain climate much of the spatial variability of climate (temperature, precipitation, and snow water) occurs on scales below 10 km.
- Current global climate simulations fail to adequately resolve the spatial structure of climate necessary for impact asssessment.
- The grid size of global climate models is not expected to reach 10 km for twenty years.
- Downscaling methods (regional climate modeling, statistical downscaling, high-resolution time slices) offer advantages but also have serious limitations.
- A subgrid orography scheme developed in a regional climate model can be applied to a global model.

Observed Climatology



Simulated Climatology T42 Resolution



Moore's Law

If we assume

•computer power doubles every 2 years

•operations per simulated day increase 8-fold for a doubling in horizontal resolution

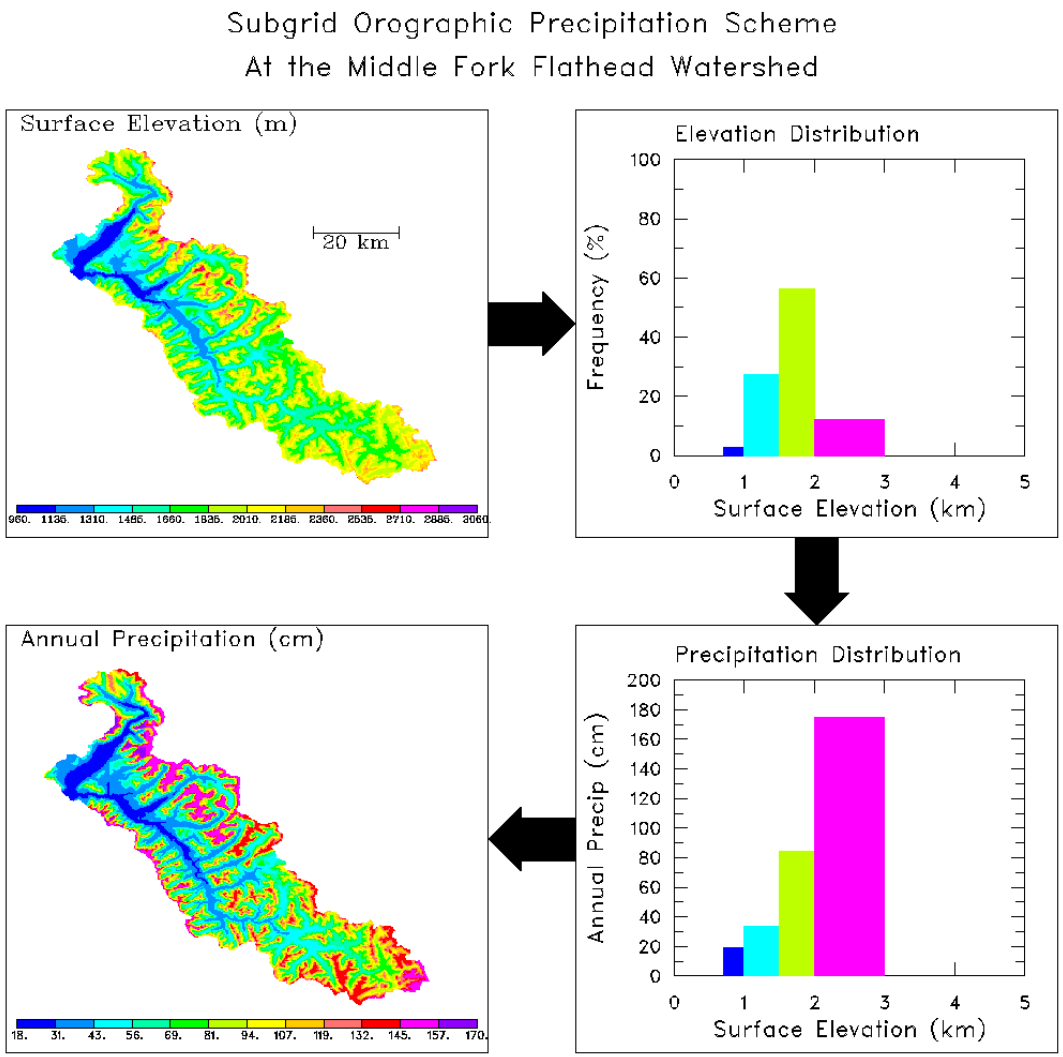
km	640	320	160	80	40	20	10
year	1988	1994	2000	2006	2012	2018	2024

then the typical grid size of global climate models will not reach that required for complex terrain (10 km) until 2024.

Downscaling Methods

- High resolution time slice
  - +global higher (100 km) resolution
  - -limited time sample
- Variable-resolution global simulation
  - +higher resolution in selected region
  - +feedback between small scales and large scales in selected region
  - -high resolution restricted to the selected region
  - -subgrid parameterizations may not apply to all resolutions
- Regional climate modeling
  - +high resolution in selected region
  - -neglects feedback between region and globe
- Statistical
  - +low computational cost
  - +corrects for biases
  - -limited by density of stations
  - -regressions may not be applicable to future climate

Subgrid Scheme



Classify surface elevation in grid cell into a modest set of elevation classes.

For each elevation class use an airflow model to estimate the height rise of parcels traversing the grid cell.

Apply conservation of energy and moisture to diagnose the temperature and humidity for each elevation class.

Apply column physics to diagnose precipitation

Distribute precipitation in postprocessing according to high resolution surface elevation.

Implementation

A purely diagnostic approach produces an excessive orographic signature. A prognostic approach works better.

$$\frac{\partial X_n}{\partial t} = A(\overline{X}) + D(\overline{X}) + Q_n(X_n) + \frac{X_n^* - X_n}{t}$$

X = temperature, humidity
τ=orographic timescale

$$X_n^*(z) = \overline{X}(z - h_n)$$

orography forcing profile

$$h_n = \min(z_n - \overline{z_s}, \frac{U}{N})$$

height of air parcels

- Applies to all column physics
  - clouds
  - radiative transfer
  - vertical mixing
  - surface physics

Mass, moisture, and energy conservation

Multiply conservation equation for class n by the fractional area f_n and the layer mass m_{kn} and sum over all classes

$$\sum_n f_n m_{kn} \frac{\partial X_{kn}}{\partial t} = \sum_n f_n m_{kn}(A_{kn} + D_{kn} + Q_{kn}) + \frac{1}{\tau}\sum_n f_n m_{kn}(X^*_{kn} - X_{kn})$$

Conservation of mass, energy and moisture requires the following conditions:

(1) $\sum_n f_n = 1$

(2) $\sum_n f_n m_{kn} = \overline{m}_k$

(3) $\sum_n f_n m_{kn} A_{kn} = \overline{m}_k \overline{A}_k$

(4) $\sum_n f_n m_{kn} D_{kn} = \overline{m}_k \overline{D}_k$

(5) $\sum_n f_n m_{kn} Q_{kn} = \overline{m}_k \overline{Q}_k$

(6) $\sum_n f_n m_{kn} X^*_{kn} = \overline{m}_k \overline{X}_k$

(7) $\sum_n f_n m_{kn} X_{kn} = \overline{m}_k \overline{X}_k$

Experiment Design

CCM3.10

T42 L30 resolution

Semi-Lagrangian dynamics (Δt=30 minutes)

Arbitrary initialization of land surface model

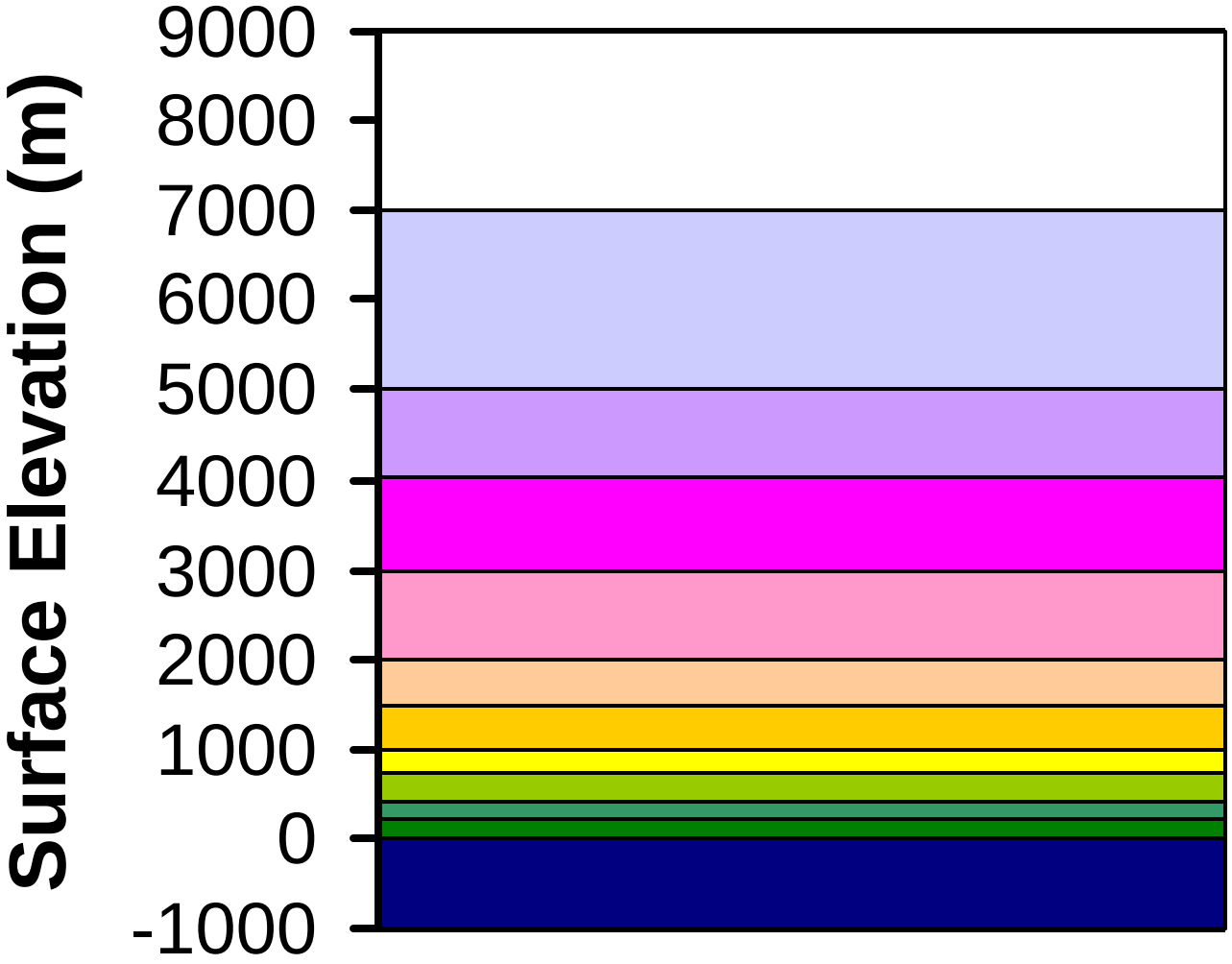
9 year AMIP simulations after 16 month spin up

- 1 elevation class
- 12 classes (τ=10 hr)

Aggregate results to grid cell mean

Distribute results according to 2.5 minute surface elevation

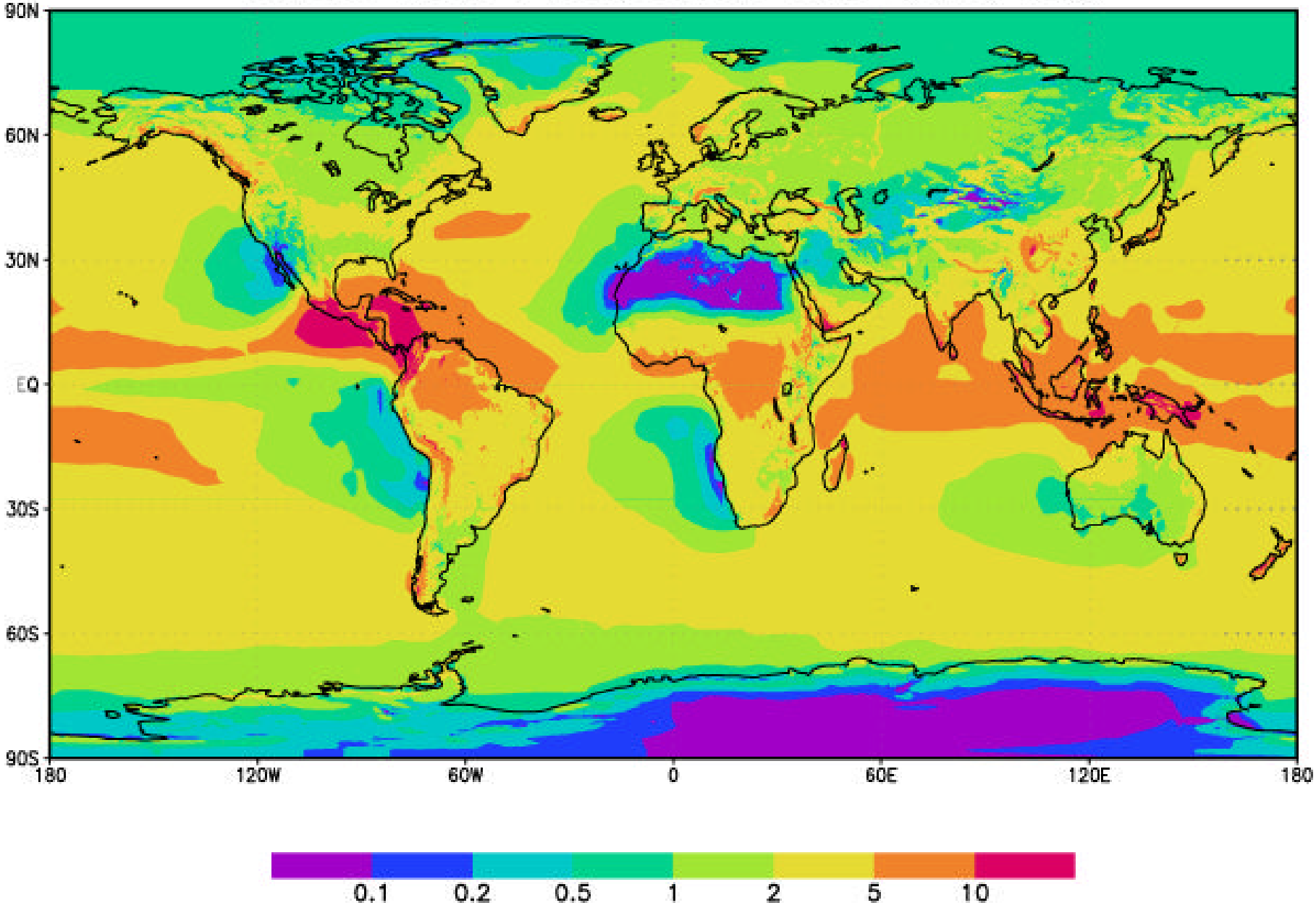
Elevation Classification

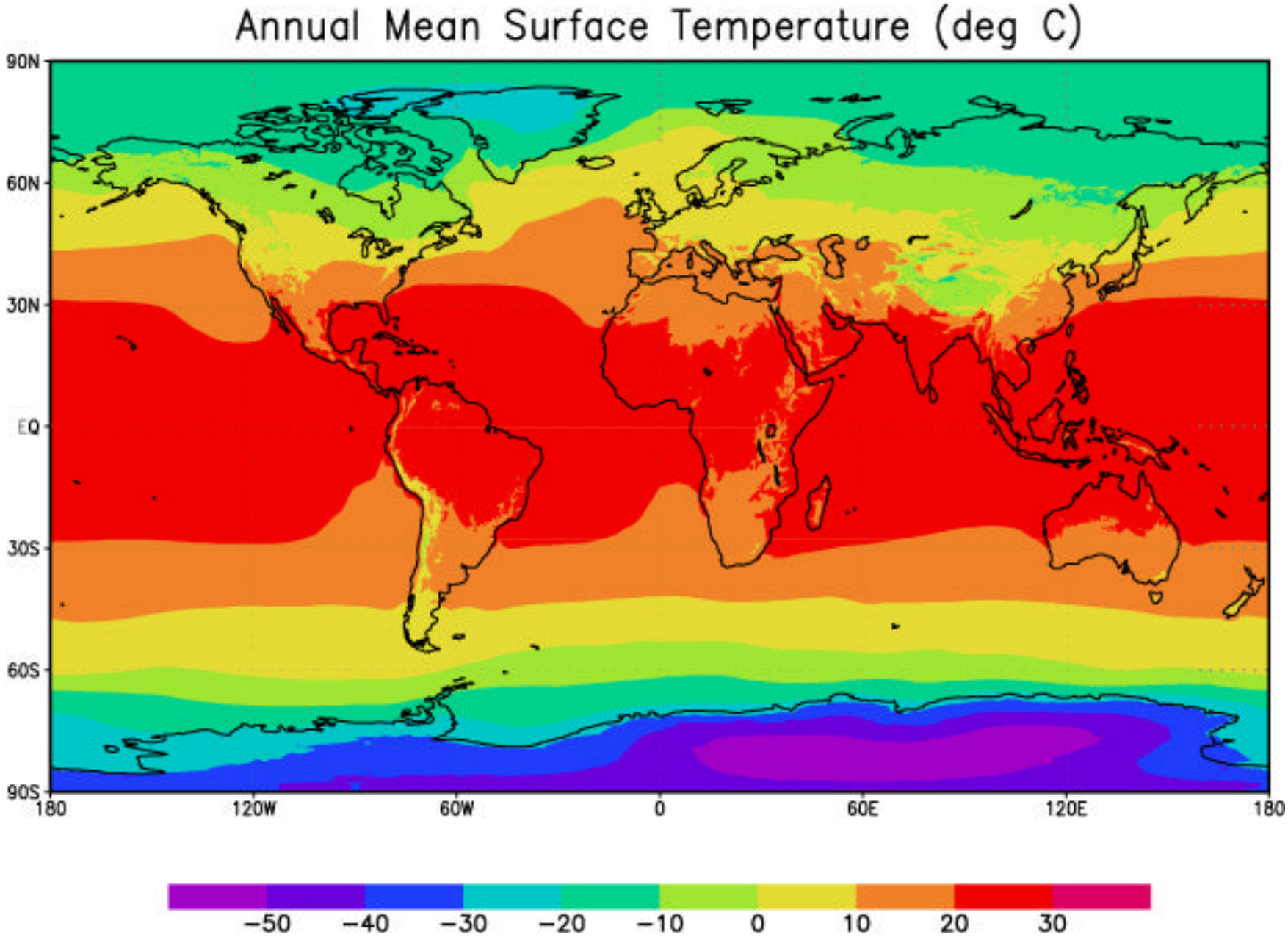


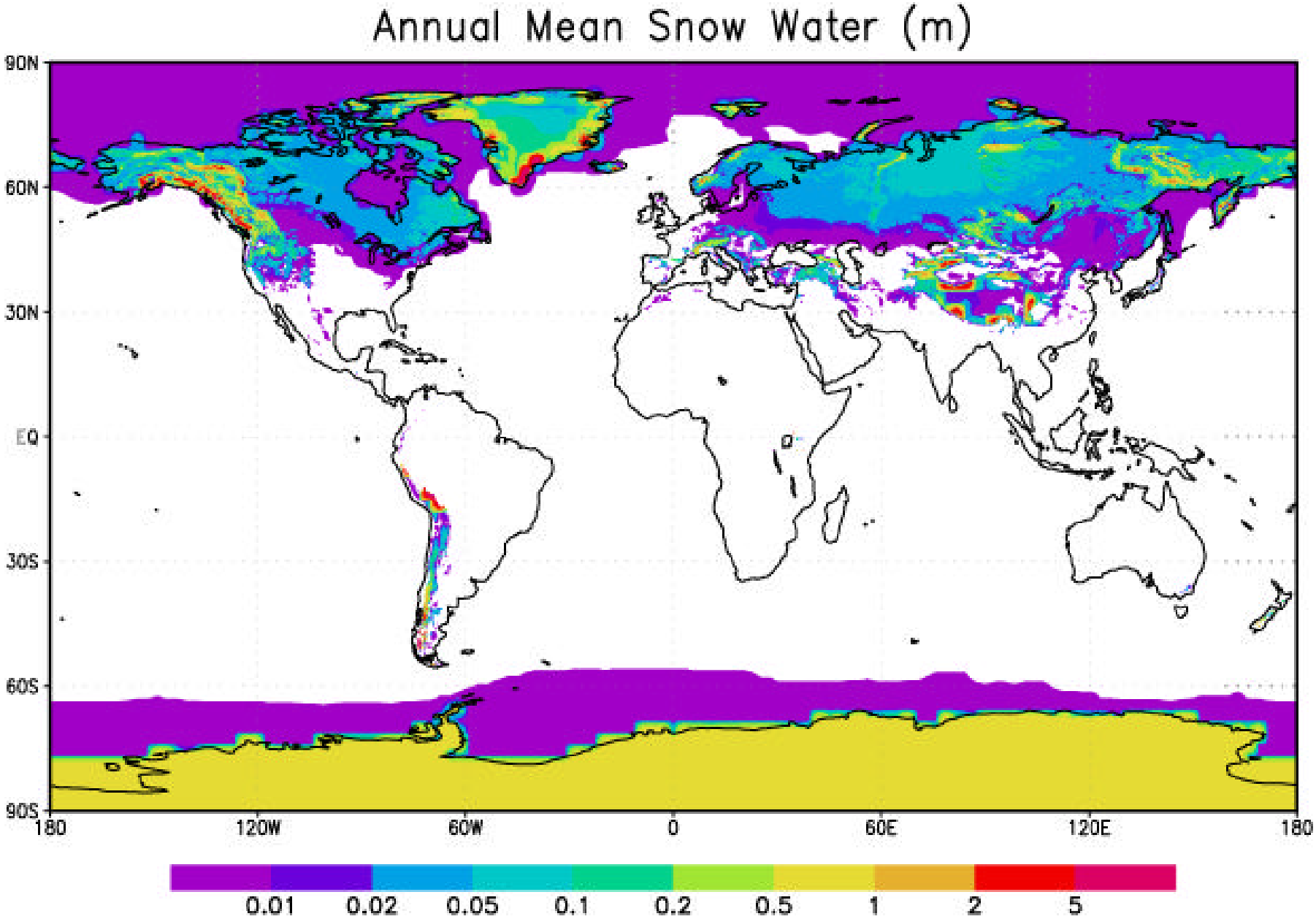
Global Conservation of Moisture and Energy

global annual mean	1 class	12 classes
precip (mm/day)	2.9633	2.9578
evaporation (mm/day)	2.9634	2.9579
solar at TOA (Wm^{-2})	234.7	235.7
infrared at TOA (Wm^{-2})	232.8	234.3
radiative cooling (Wm^{-2})	104.6	105.2
surface sensible and latent heating (Wm^{-2})	106.5	107.1

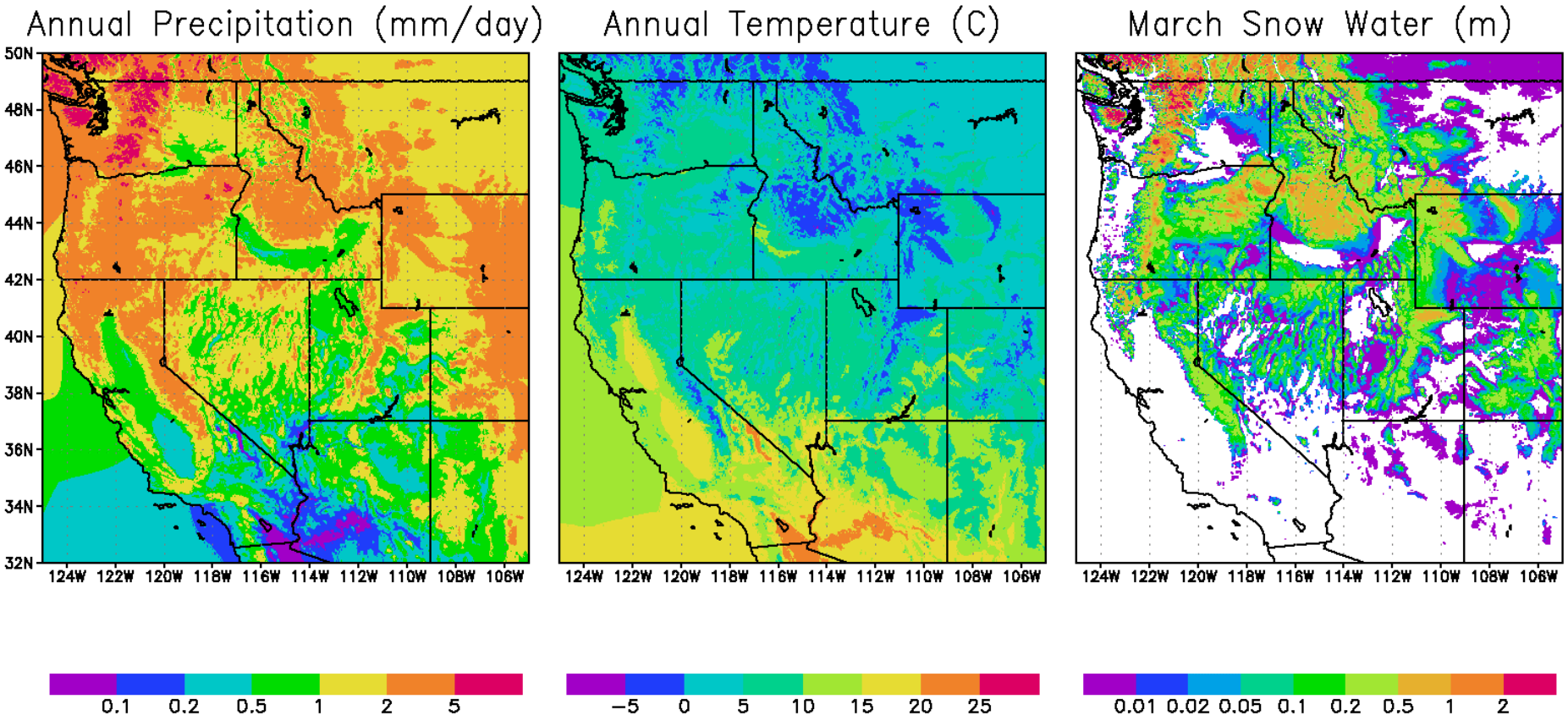
Annual Mean Precipitation Rate (mm/day)




Annual Mean Surface Temperature (deg C)
90N
60N
30N
EQ
30S
60S
90S
180
120W
60W
0
60E
120E
180
−50
−40
−30
−20
−10
0
10
20
30

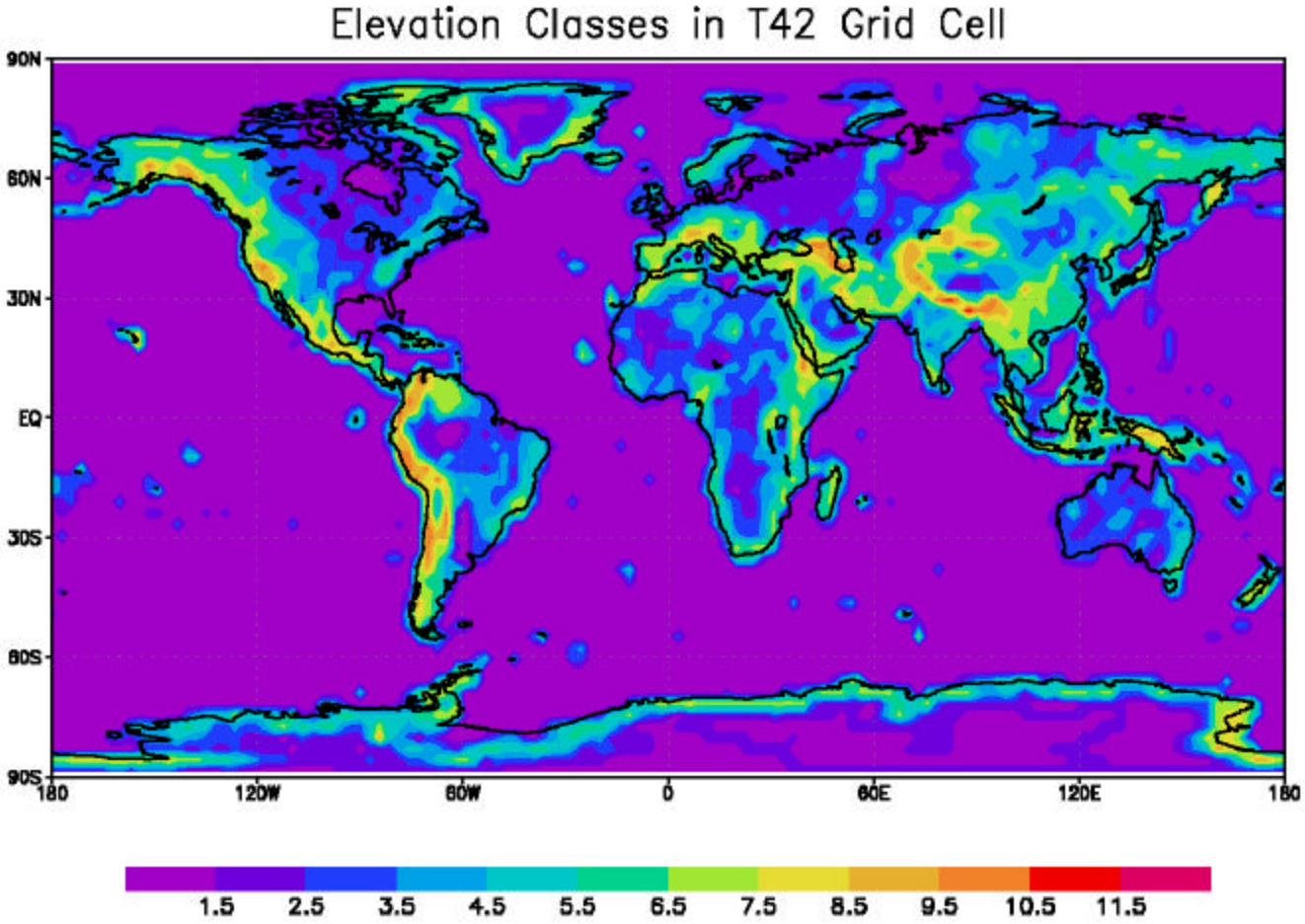

Annual Mean Snow Water (m)
90N
60N
30N
EQ
30S
60S
90S
180
120W
60W
0
60E
120E
180
0.01
0.02
0.05
0.1
0.2
0.5
1
2
5

Simulated Climatology T42 12 Classes

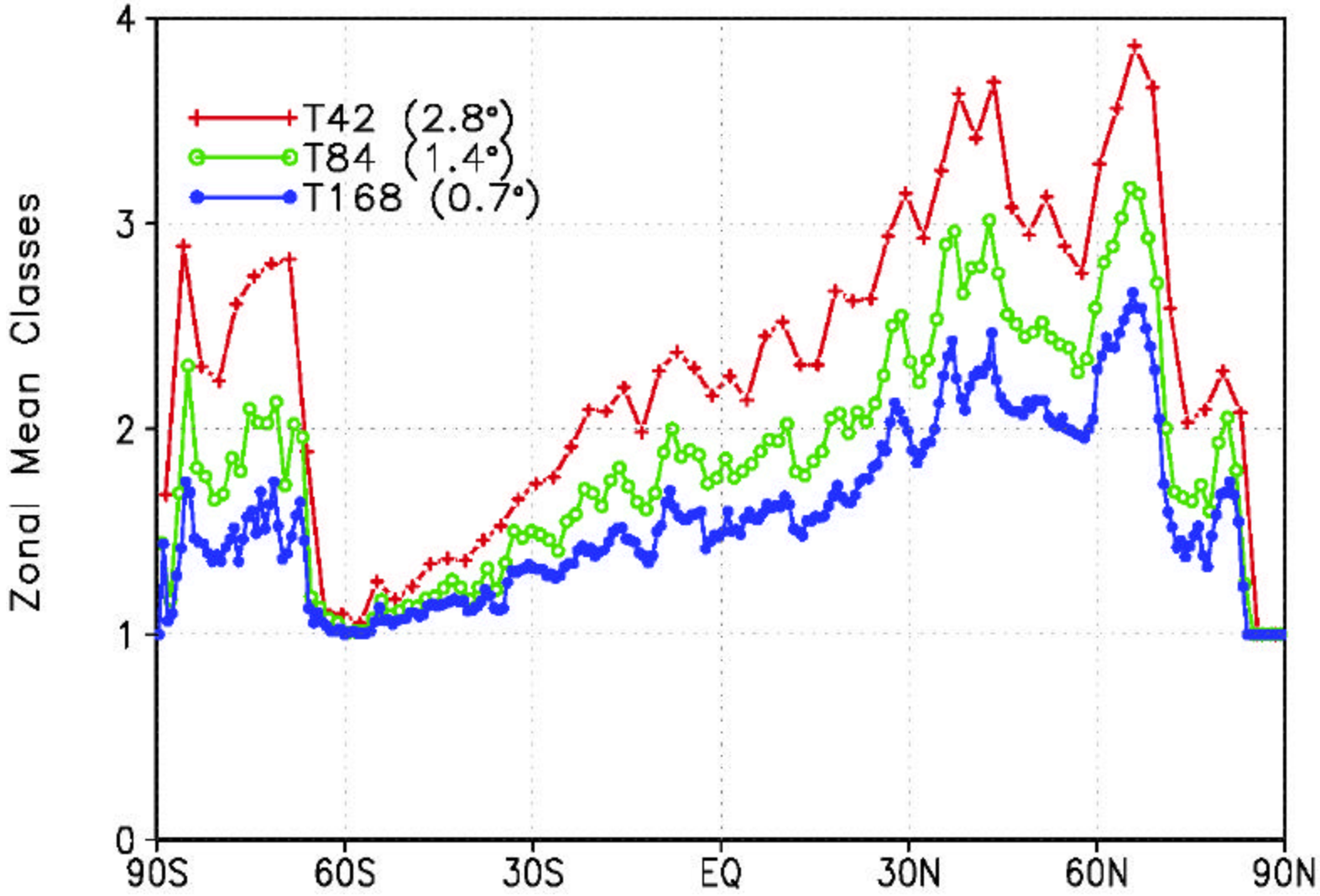


Computational Burden

If the column physics dominates the computations then the computational burden is proportional to the number of elevation classes in each grid cell.



Zonal Mean Computational Burden



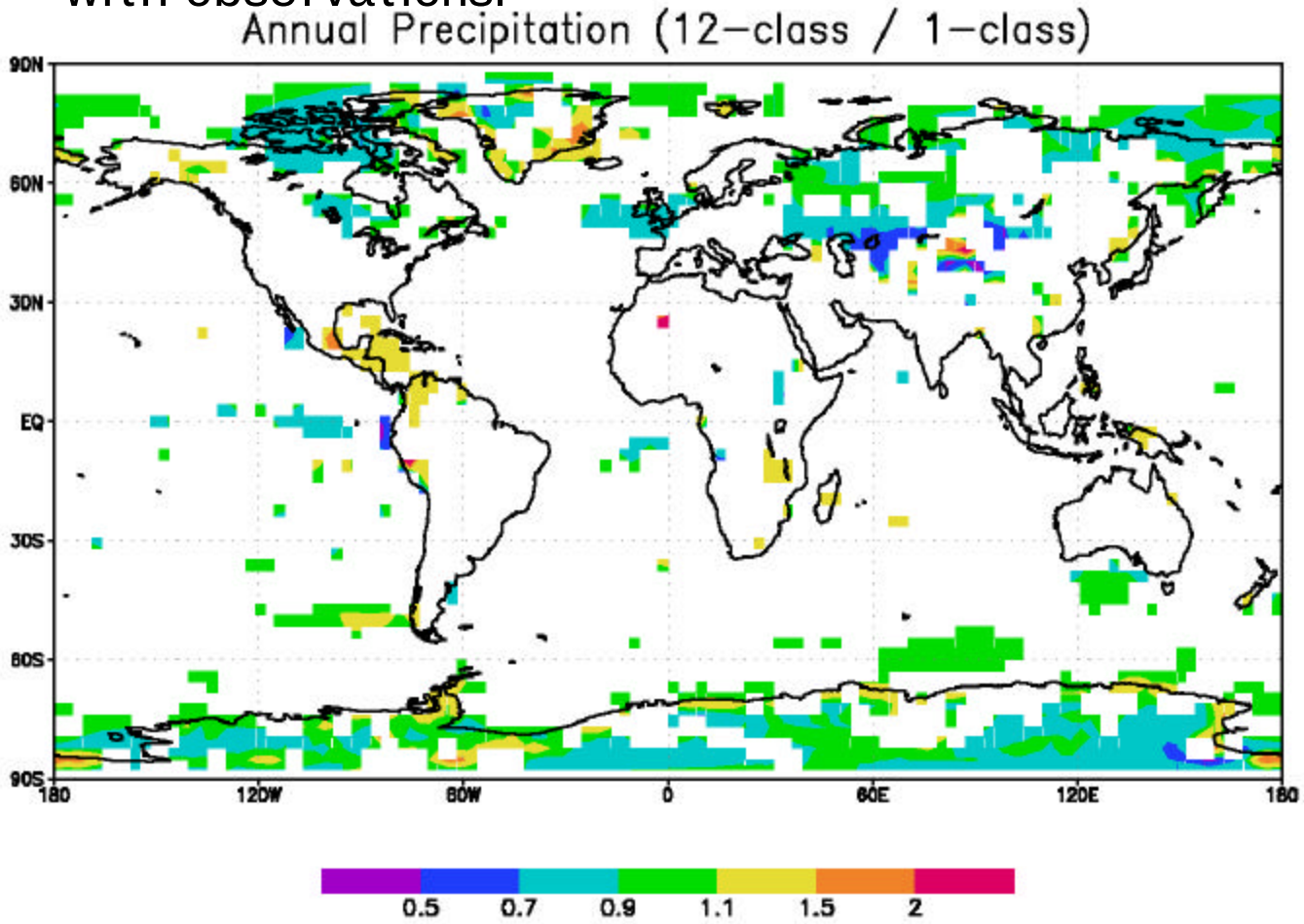
Global Burden

	Spectral Resolution		
	T42	T84	T168
Average classes per cell	2.31	1.86	1.58
Maximum classes in a cell	11	11	11
Maximum zonal mean classes per cell	3.9	3.2	2.7

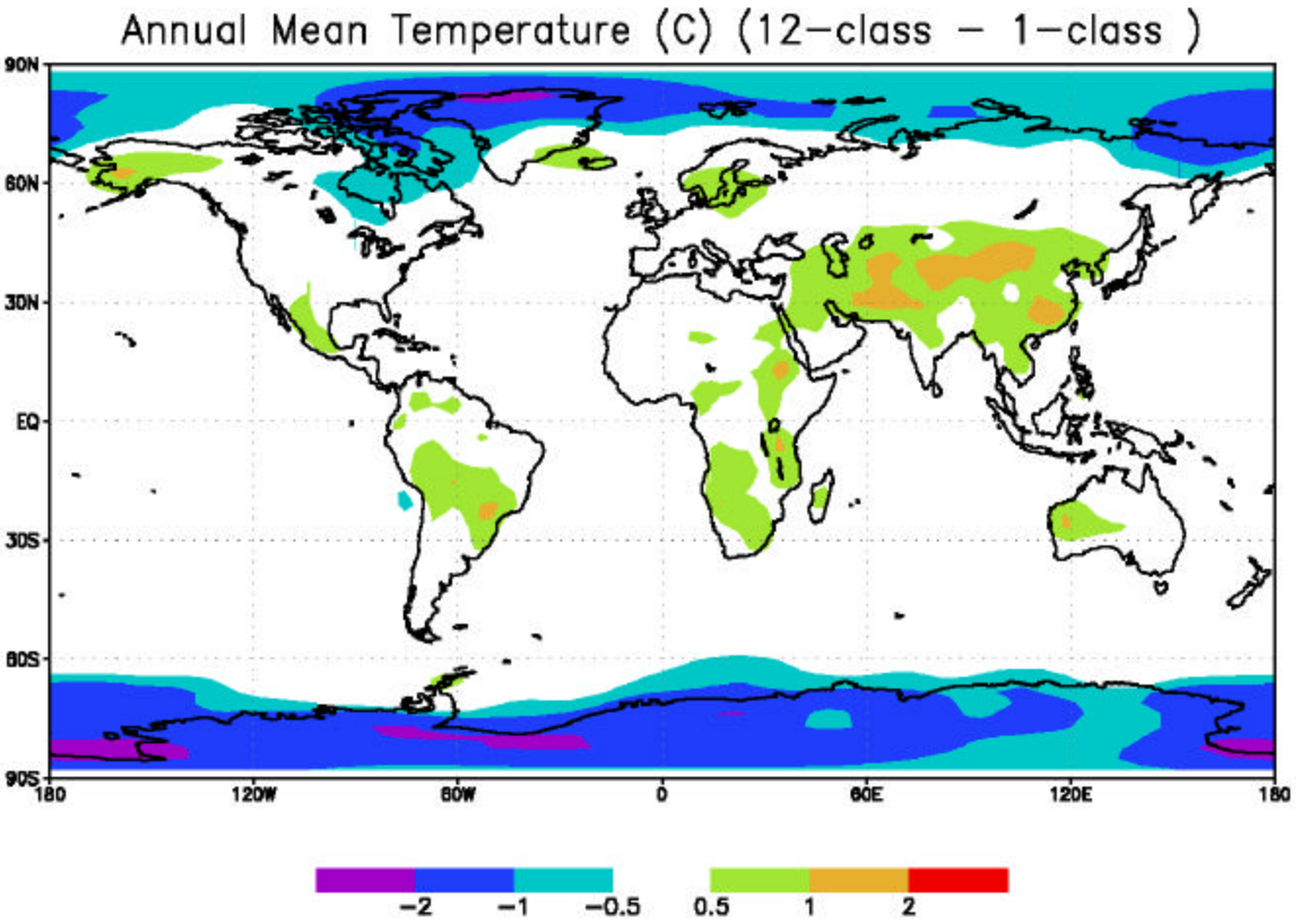
Can the Subgrid Scheme be Treated as an Option?

- Requires negligible impact on grid cell means of most climate variables.
- We've already seen that global mean energy and moisture balances are unaffected.
- If the local grid cell means are also insensitive to the subgrid scheme then tuning of model without subgrid scheme can apply to simulations with the subgrid scheme.

For most grid cells the grid cell mean precipitation rate simulated with the subgrid scheme is not significantly different from that simulated without. For grid cells with significant differences the differences are smaller than the biases compared with observations.



For all grid cells the impact of the subgrid scheme on the grid cell mean temperature is smaller than the temperature bias.



Strengths of Subgrid Scheme

- Provides superior performance for precipitation and snow at lower computational cost.
- Provides high resolution detail without high memory costs.
- Adds computations only in complex terrain.
- Is physically based.
- Does not affect large-scale climatology of most fields.
- Applies to synoptic as well as climatic time scales.
- Computational and climatic impact decreases with increasing resolution.
- Workload distribution is static and hence can be evenly distributed across processors.

Weaknesses of Scheme

- Airflow model is relatively crude.
- Orographic forcing timescale τ is arbitrary.
- Influence of slope and aspect on surface processes is neglected.
- Precipitation in one elevation class does not influence precipitation in other classes.
- Does not treat rainshadows, which require grid size < 100 km.
- Introduces large computational load imbalance.

Future Work

- Explore sensitivity to
  - elevation classification
  - orographic timescale
  - horizontal resolution
- Apply to CCSM-2 as a model option.
- Balance the computational load.