Hydrological and Climatic Effects of Land Cover Changes in Southern United States

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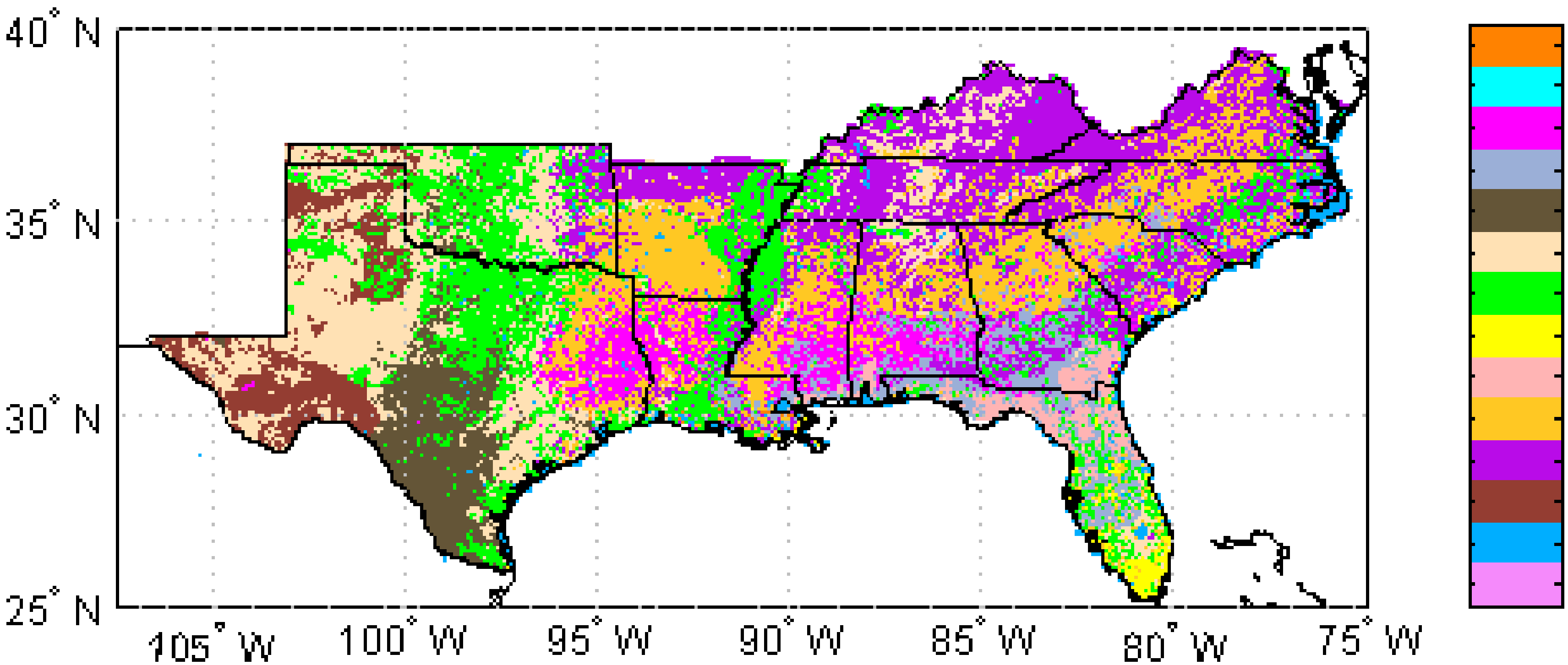
Introduction

Southern U.S. summer fuel model map

(from Burgan et al., 1998)

- 13 states from Atlantic to Taxes, from Florida to Virginia.
- Over 60% (207 million ha) of lands dominated by forest cover.
- Roughly 40% of U.S. timberland (USDA 1988).



A - Annual grasses
B - Dense dead brush
C - Pine grass savanna
D - Southern low pocosins
E - Intermediate brush
F - Perennial grasses
G - Agricultural land
H - Sawgrass
I - Dense live brush
J - Southern pine plantation
K - Hardwoods (summer)
L - Sagebrush-grass mixture

Historical land cover changes in Southern U.S.

- Agricultural exploitation

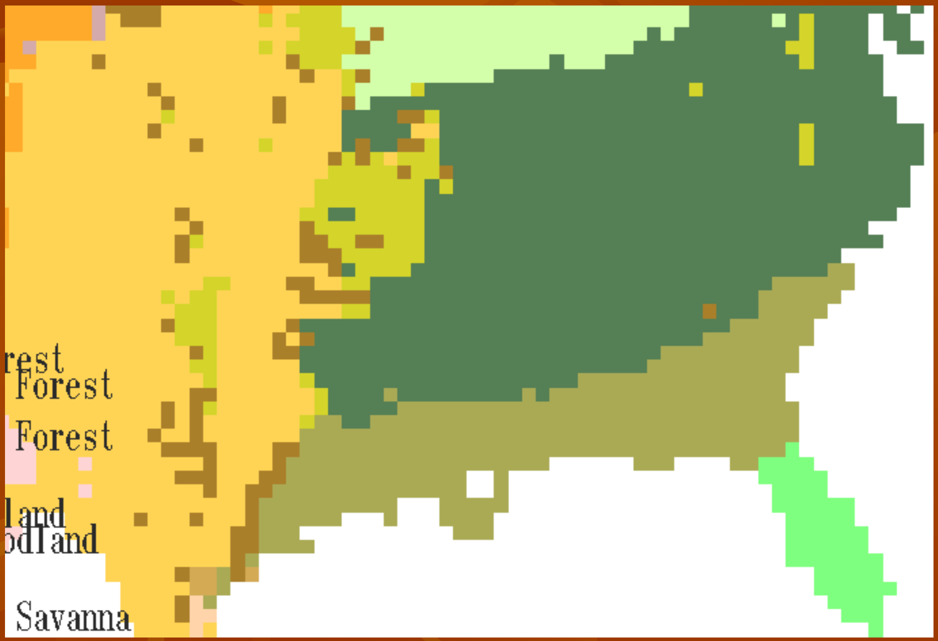
  began in the 17th century and reached peak in the late 19th century.

- Regrowth of southern forests

  a 40 year period after the Great Depression.

Projected vegetation changes due to global warming
(Neilson et al.)

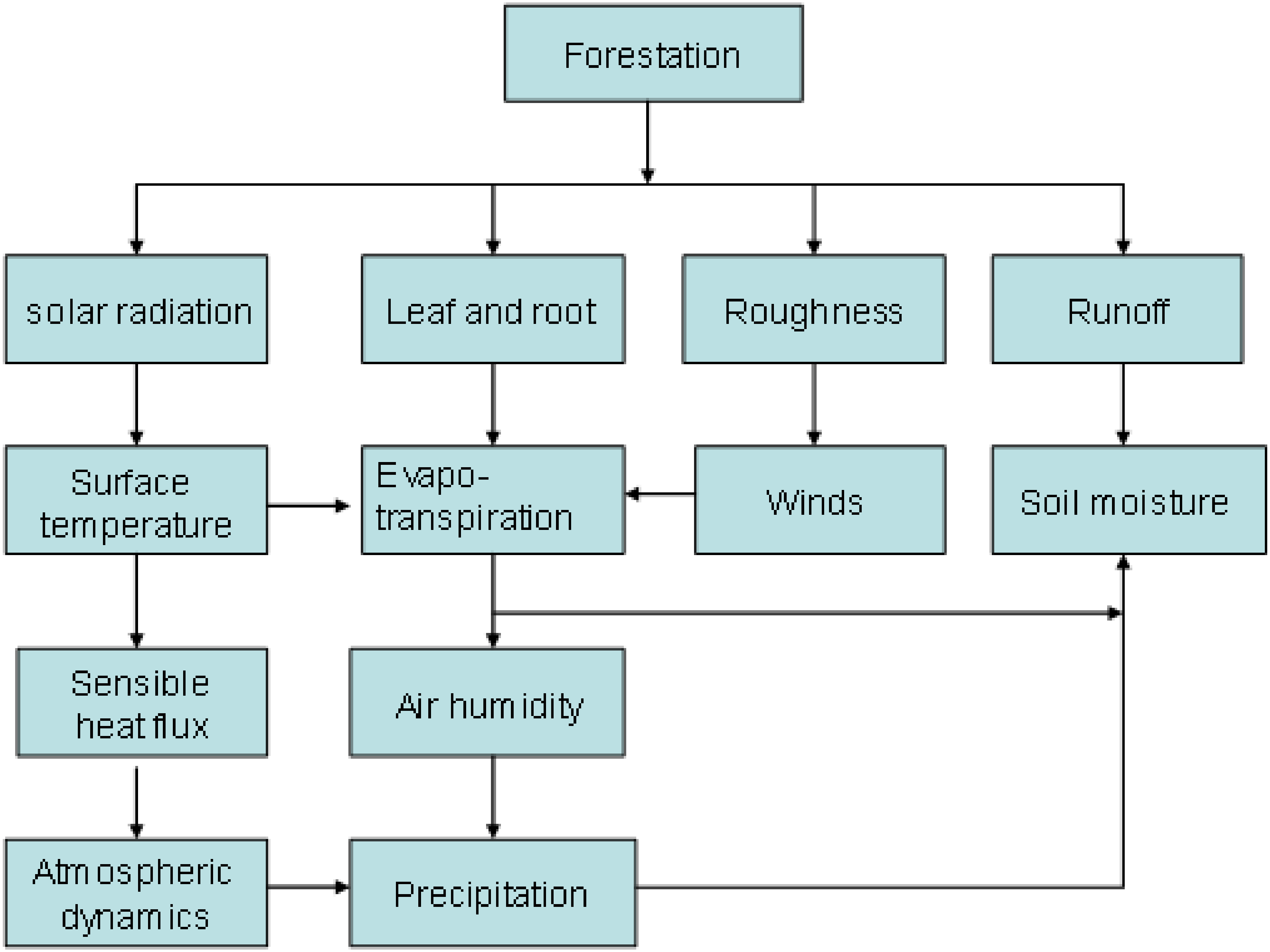
VEG TYPE 1971-2000



VEG TYPE 2045-2075

Some deciduous forests in northern Southeast converted to savanna

Some coastal mixed forests converted to conifer woodland



Forestation
solar radiation
Leaf and root
Roughness
Runoff
Surface temperature
Evapo-transpiration
Winds
Soil moisture
Sensible heat flux
Air humidity
Atmospheric dynamics
Precipitation

Modeling studies

• If the tropical forests in the Amazon were replaced with degraded grassland, evapotranspiration and precipitation would decrease significantly (Shukla et al. 1990)

• Afforestation in Southern U.S. would slightly increase precipitation in the Southeast, while decrease precipitation in western Gulf coastal area (Jackson et al., 2005)

• The northern China forest shelterbelt project is likely to improve overall hydroclimate conditions by increasing precipitation, relative humidity, and soil moisture (Liu et al. 2008)

Climate-forest interaction project

- Investigate the effects of historical land cover changes in southern U.S. on regional climate and hydrology
- Project forest vegetation changes due to global warming and their feedback to climate
- Use NCAR global CSM coupled with GDVM and downscale CSM outputs to the southern U.S. region using regional climate modeling
- A preliminary study of regional climate modeling with current and pre-forest regrowth land cover conditions is presented here with a primary issue of the role of afforestation in water resources

Method

Model

- The National Center for Atmospheric Research (NCAR) regional climate model (RegCM)
- To provide a modeling tool for understanding regional high-resolution spatial patterns of climatic variability
- Driven by observation or global climate model simulations
- By incorporating more detailed schemes of important climate processes in MM4/5

Atmospheric component

$$\sigma = (\pi - \pi_t)/(\pi_s - \pi_t) \qquad \mu = \pi_s - \pi_t \qquad \varepsilon \equiv \frac{1}{g}\frac{dw}{dt}$$

$$\frac{d\mathbf{v}}{dt} = -(1+\varepsilon)\nabla_\sigma \Phi - \alpha \nabla_\sigma p + f\mathbf{k} \times \mathbf{v}$$

$$\frac{\partial T}{\partial t} = -\mathbf{v} \bullet \nabla_\sigma T - \dot{\sigma}\frac{\partial T}{\partial \sigma} + \frac{\alpha}{c_p}[\frac{\partial p}{\partial t} + \mathbf{v} \bullet \nabla_\sigma p + \dot{\sigma}\frac{\partial p}{\partial \sigma}]$$

$$\frac{\partial \mu}{\partial t} + \nabla_\sigma \bullet (\mu \mathbf{v}) + \frac{\partial(\mu\dot{\sigma})}{\partial \sigma} = 0$$

$$\alpha = RT/p$$

$$\frac{\partial \Phi}{\partial \sigma} = -\mu \frac{RT}{p}$$

$$w = \frac{1}{g}(\frac{\partial \Phi}{\partial t_\sigma} + \mathbf{v} \bullet \nabla_\sigma \Phi + \dot{\sigma}\frac{\partial \Phi}{\partial \sigma})$$

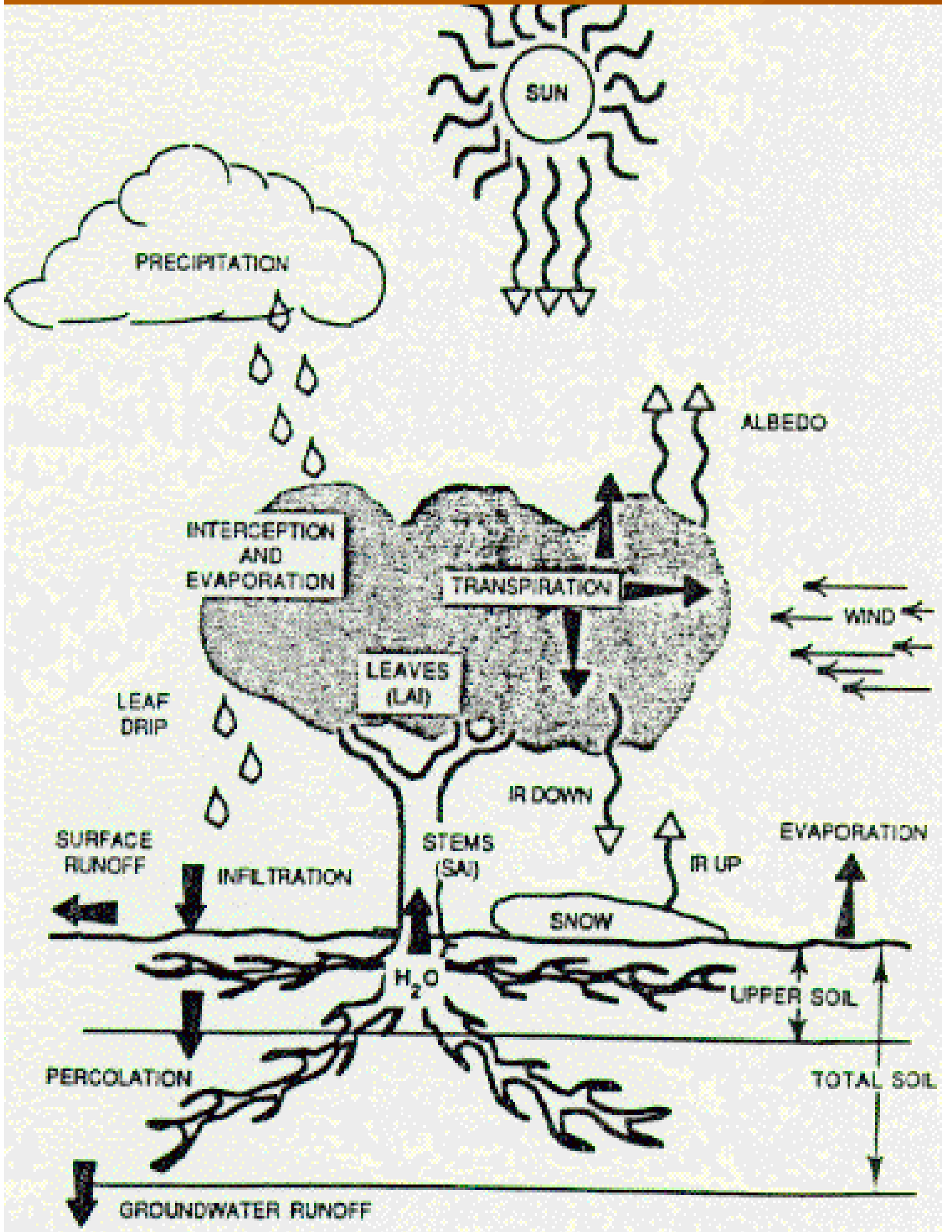
$$\frac{\partial p}{\partial \pi} = 1 + \varepsilon$$

- Conservation of momentum
- Conservation of energy
- Conservation of mass
- Conservation of water
- Equation of state

- Radiation
- Clouds and precipitation
- Planetary boundary-layer
- Land-surface processes

- Speed (3D)
- Temperature
- Pressure
- Humidity
- Air density

Land component



The governing equations for the two temperatures, T_c and T_{gs}, are:

Canopy

$$C_c \frac{\partial T_c}{\partial t} = Rn_c - H_c - \lambda E_c, \tag{1}$$

Ground

$$C_{gs} \frac{\partial T_{gs}}{\partial t} = Rn_{gs} - H_{gs} - \lambda E_{gs}, \tag{2}$$

where

T_c, T_{gs} = temperature, K
Rn_c, Rn_{gs} = absorbed net radiation, W m^{-2}
H_c, H_{gs} = sensible heat flux, W m^{-2}
E_c, E_{gs} = evapotranspiration rate, kg m^{-2} s^{-1}
C_c, C_{gs} = heat capacity, J m^{-2} K^{-1}
λ = latent heat of vaporization, J kg^{-1}.

The governing equations for the two interception water stores are

Canopy

$$\frac{\partial M_c}{\partial t} = P_c - D_c - E_{wc}/\rho_w, \tag{3}$$

Ground Cover

$$\frac{\partial M_g}{\partial t} = P_g - D_g - E_{wg}/\rho_w, \tag{4}$$

where

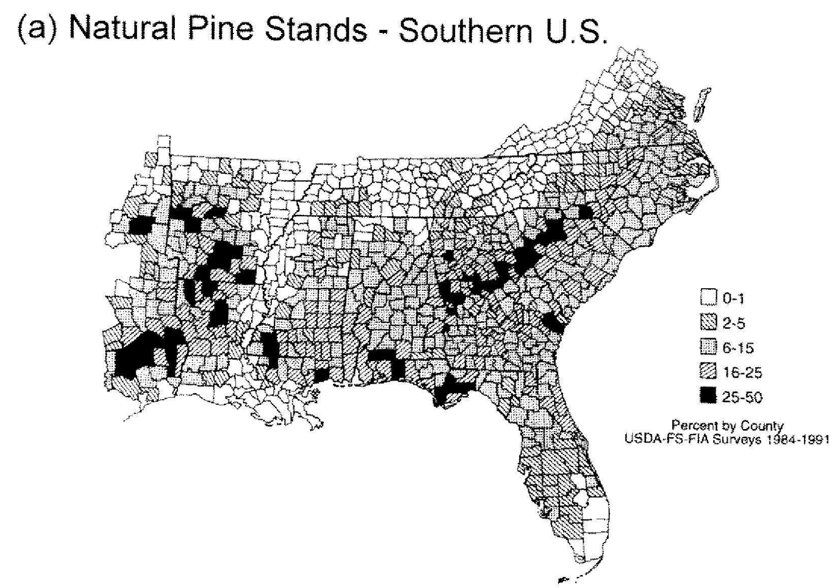
M_c, M_g = water stored on the leaves, m
P_c, P_g = rate of precipitation interception, m s^{-1}
D_c, D_g = water drainage rate, m s^{-1}
E_{wc}, E_{wg} = rate of evaporation of water from the wet portions of the leaves, kg m^{-2} s^{-1}
ρ_w = density of water, kg m^{-3}.

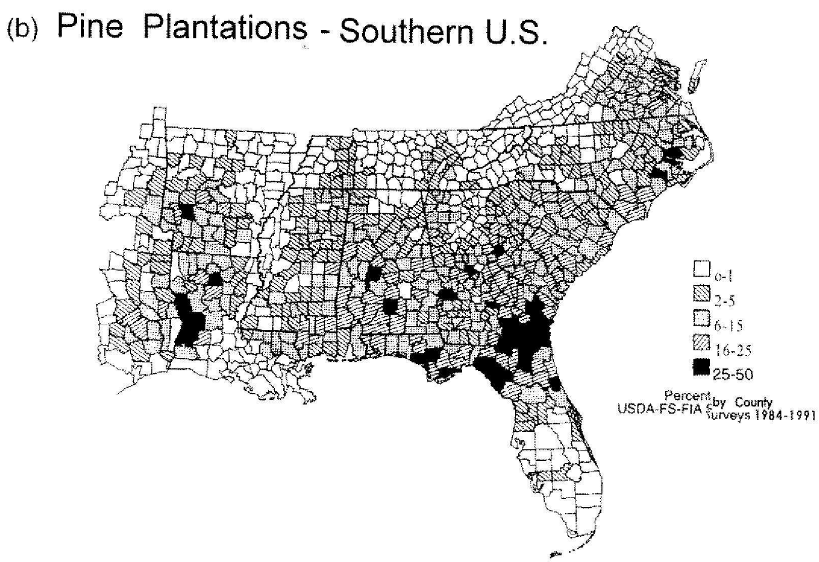
Simulation Setup

- Domain: Continental U.S.
- Resolution: 60 km, 14 atmospheric vertical layers
- Soil: 3 layers
- Integration periods: January and July, 1988-1995
- Simulations: control one with current land cover, and experiment one with farming land

Natural pine and plantation

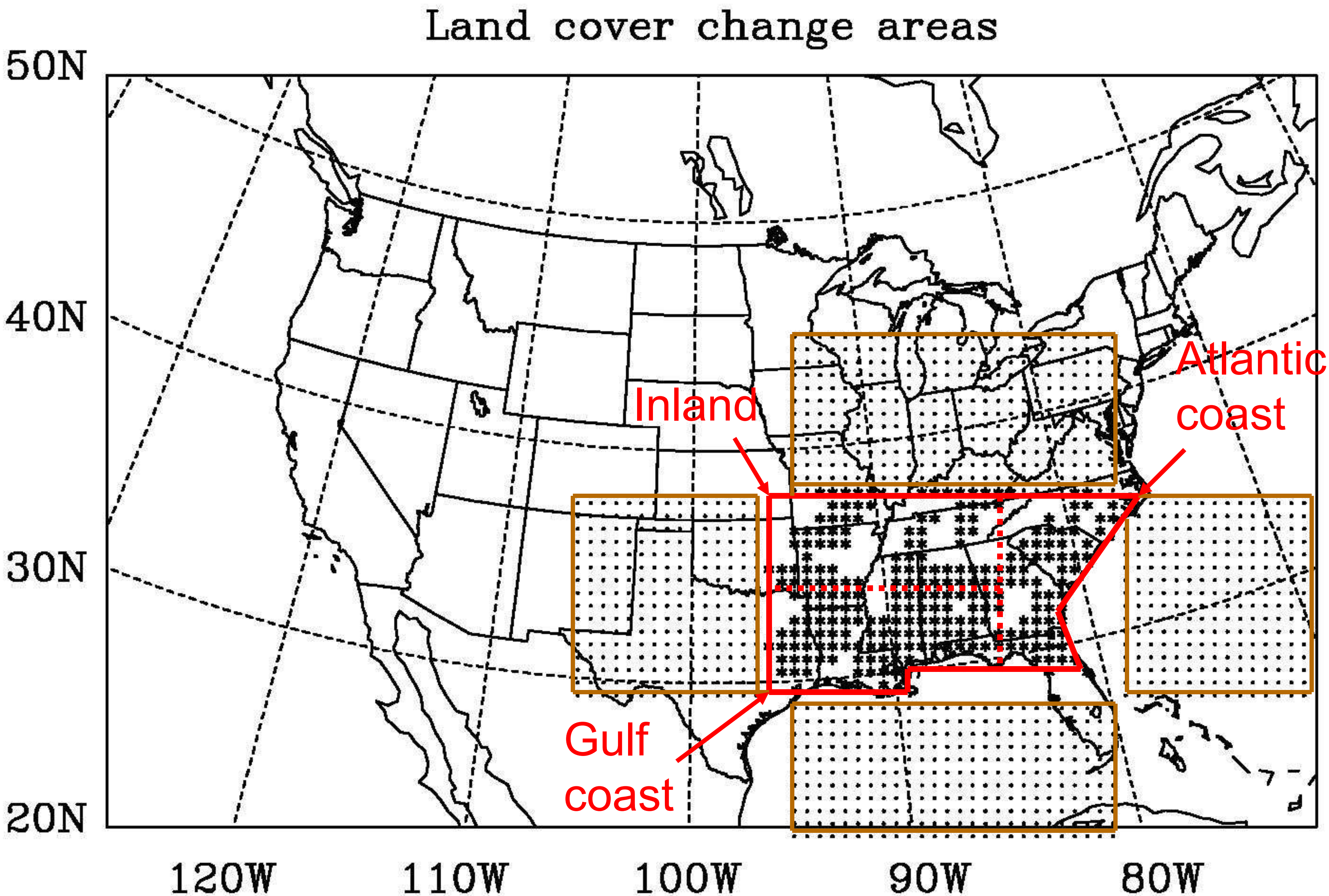
(from Allen et al., 1996)





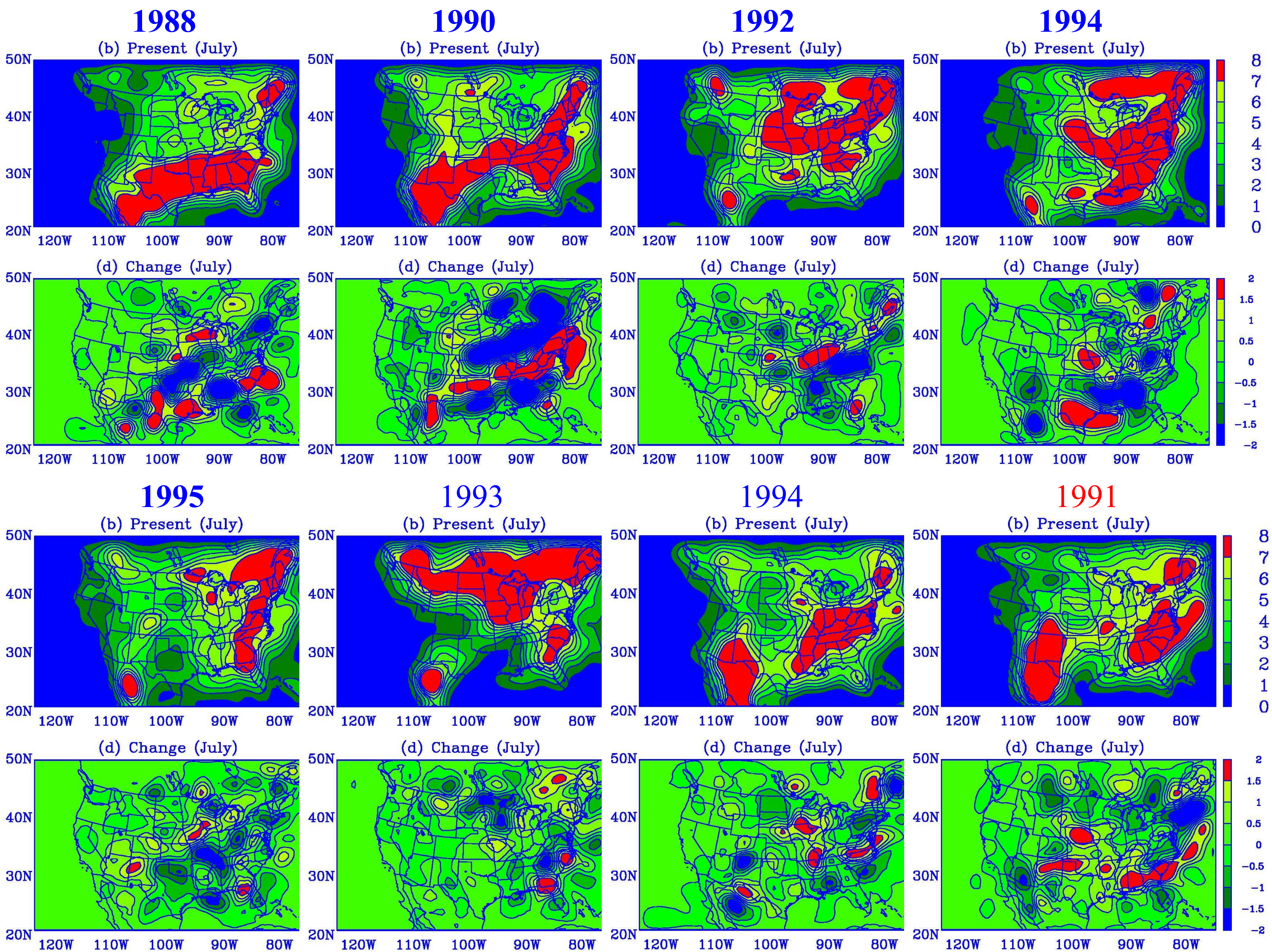
Natural pine forests dominant along the southern Piedmont, selected counties on the southern coastal plain, and upland areas west of the Mississippi River.

Pine plantations dominated in northern Florida and other counties throughout the coastal plain.



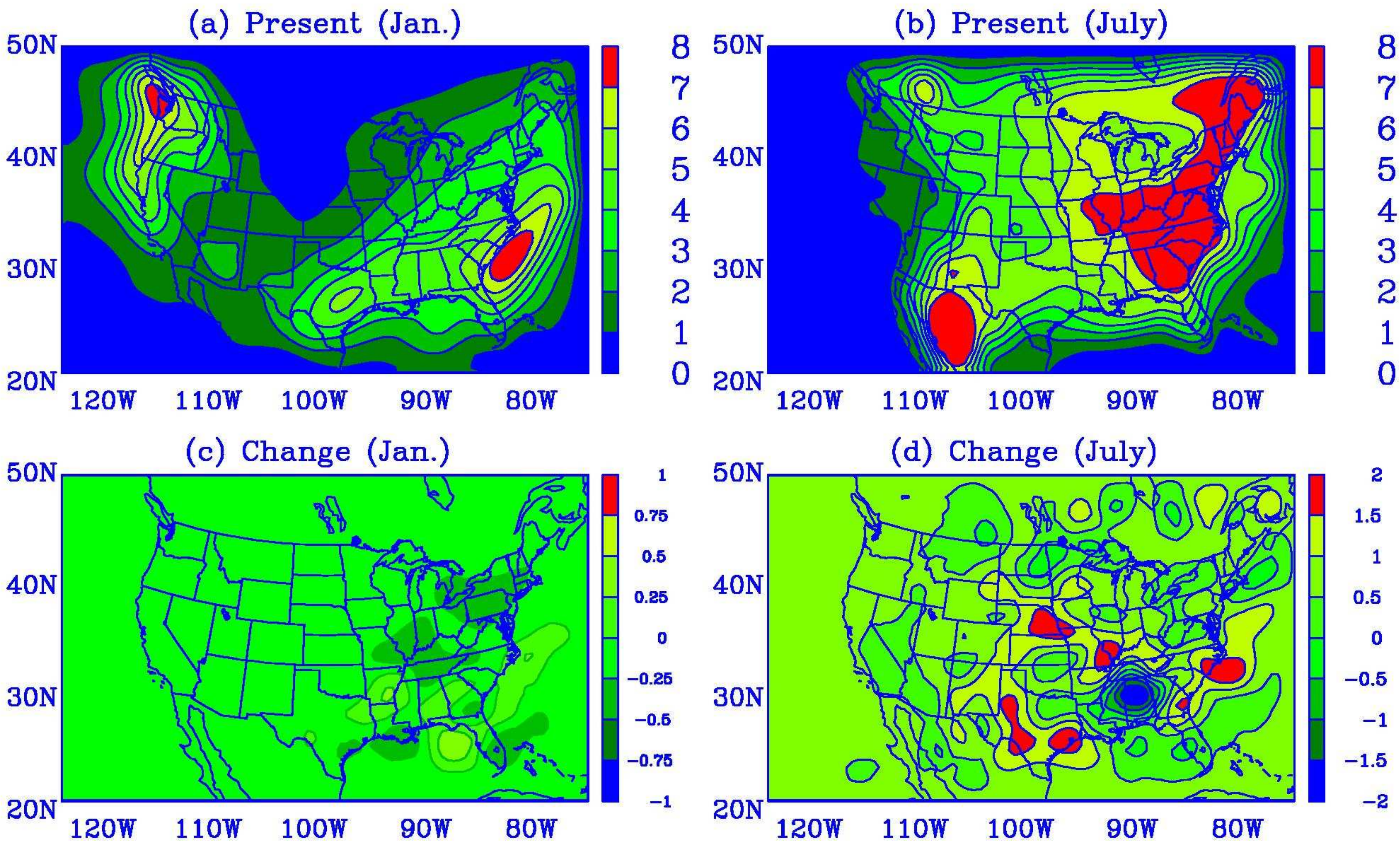
Land cover change areas
50N
40N
30N
20N
120W
110W
100W
90W
80W
Inland
Atlantic
coast
Gulf
coast

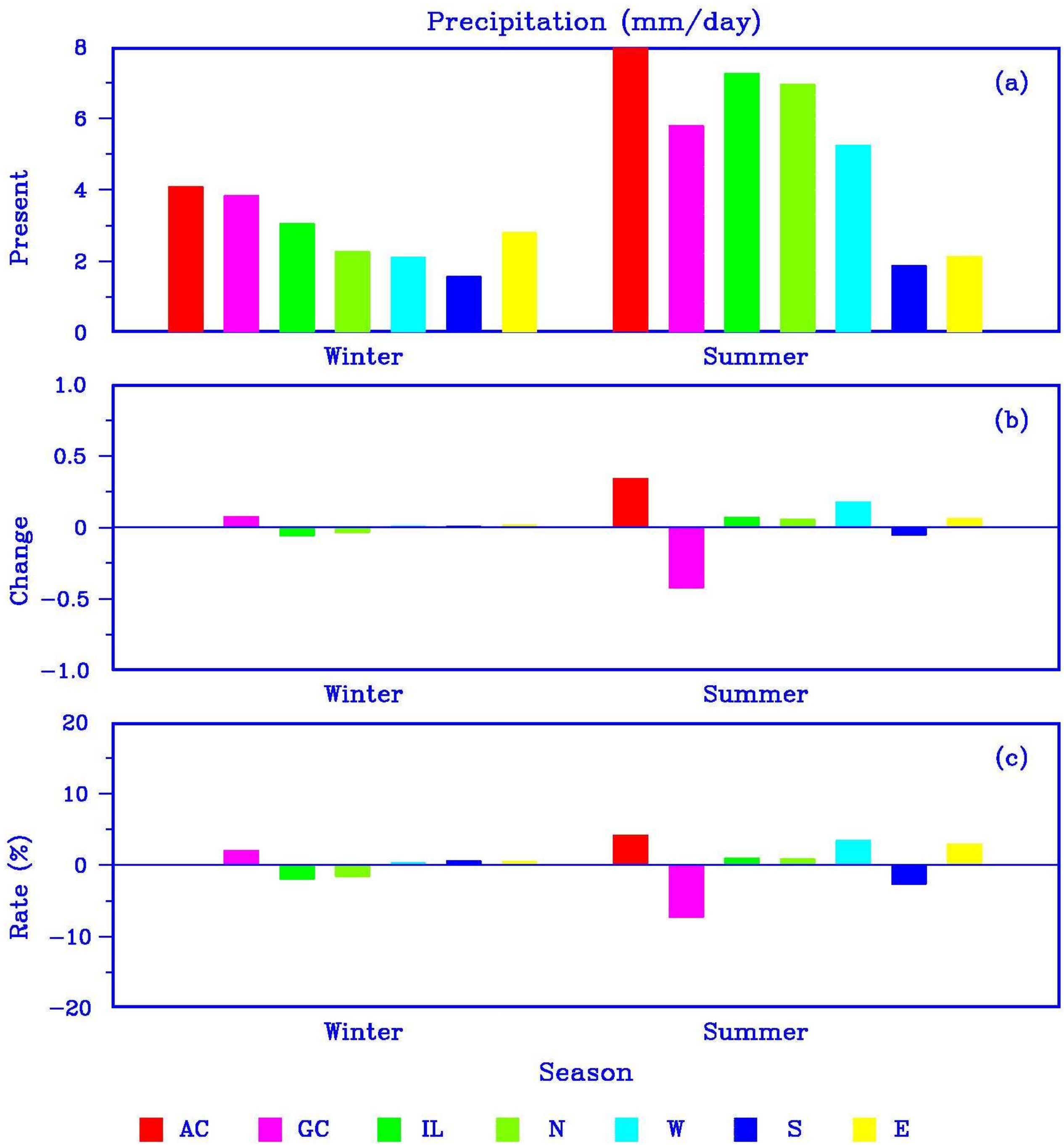
Results



1988
(b) Present (July)
(d) Change (July)
1990
(b) Present (July)
(d) Change (July)
1992
(b) Present (July)
(d) Change (July)
1994
(b) Present (July)
(d) Change (July)
1995
(b) Present (July)
(d) Change (July)
1993
(b) Present (July)
(d) Change (July)
1994
(b) Present (July)
(d) Change (July)
1991
(b) Present (July)
(d) Change (July)
50N
40N
30N
20N
120W
110W
100W
90W
80W
8
7
6
5
4
3
2
1
0
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2

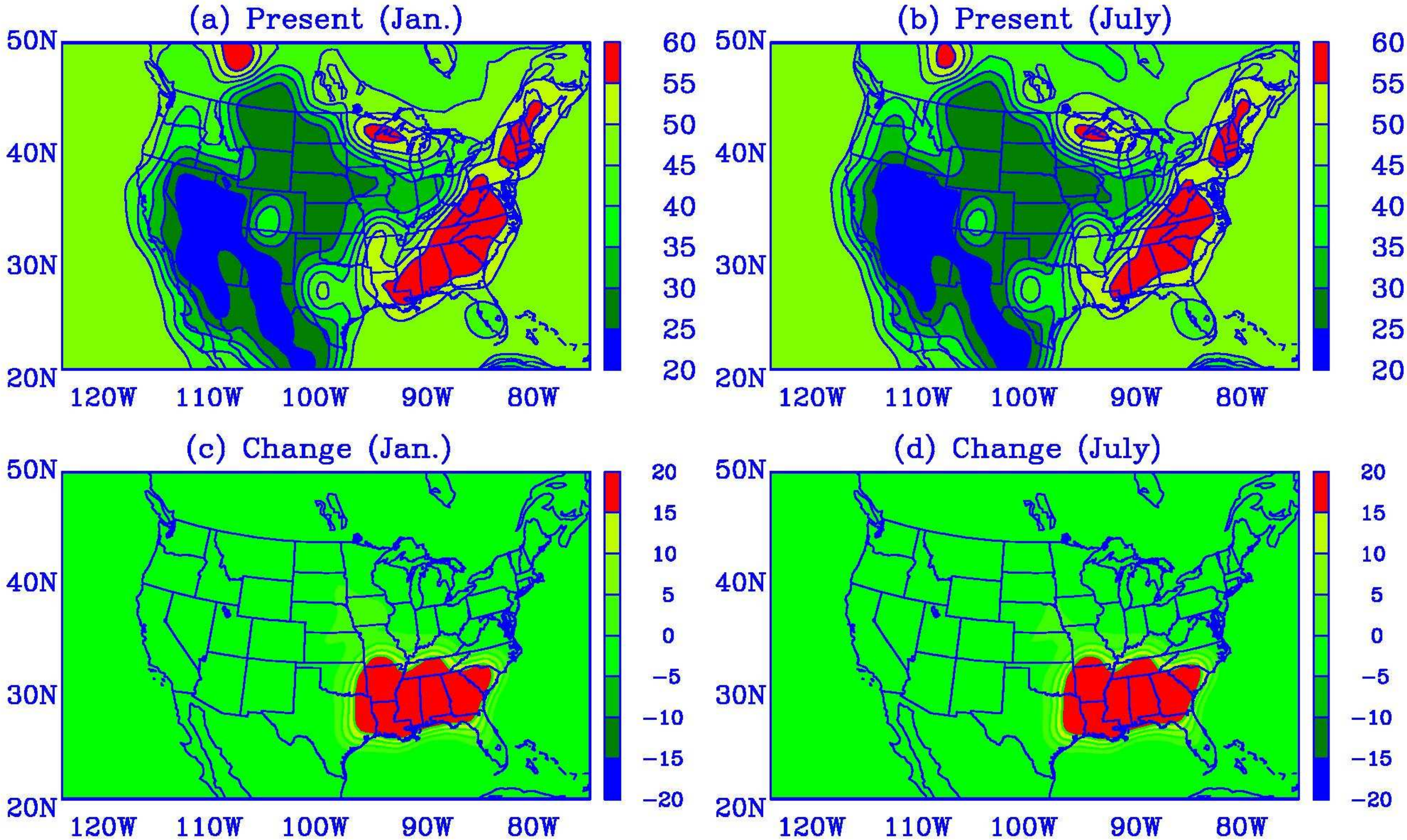
Precipitation (mm/day)

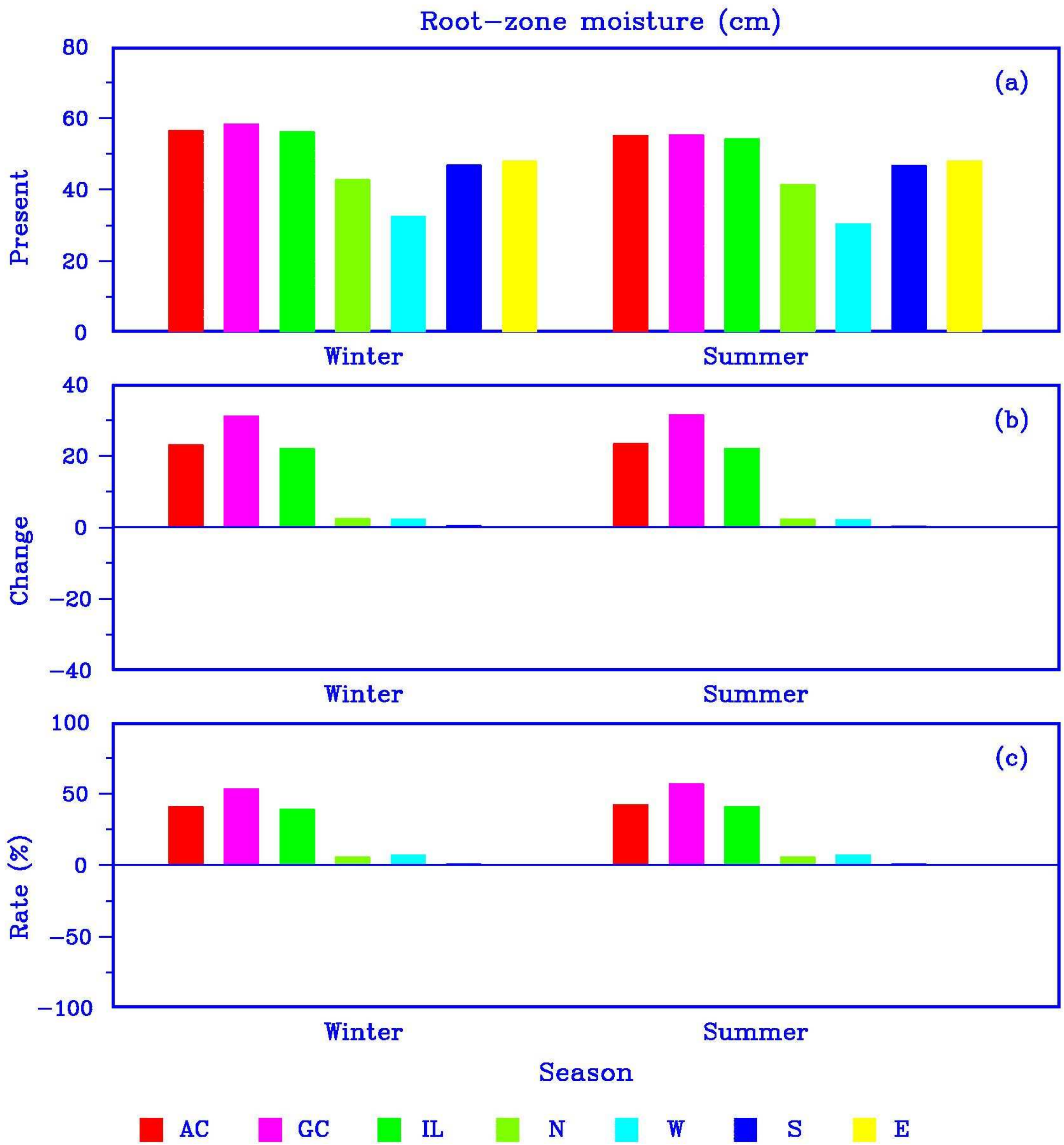




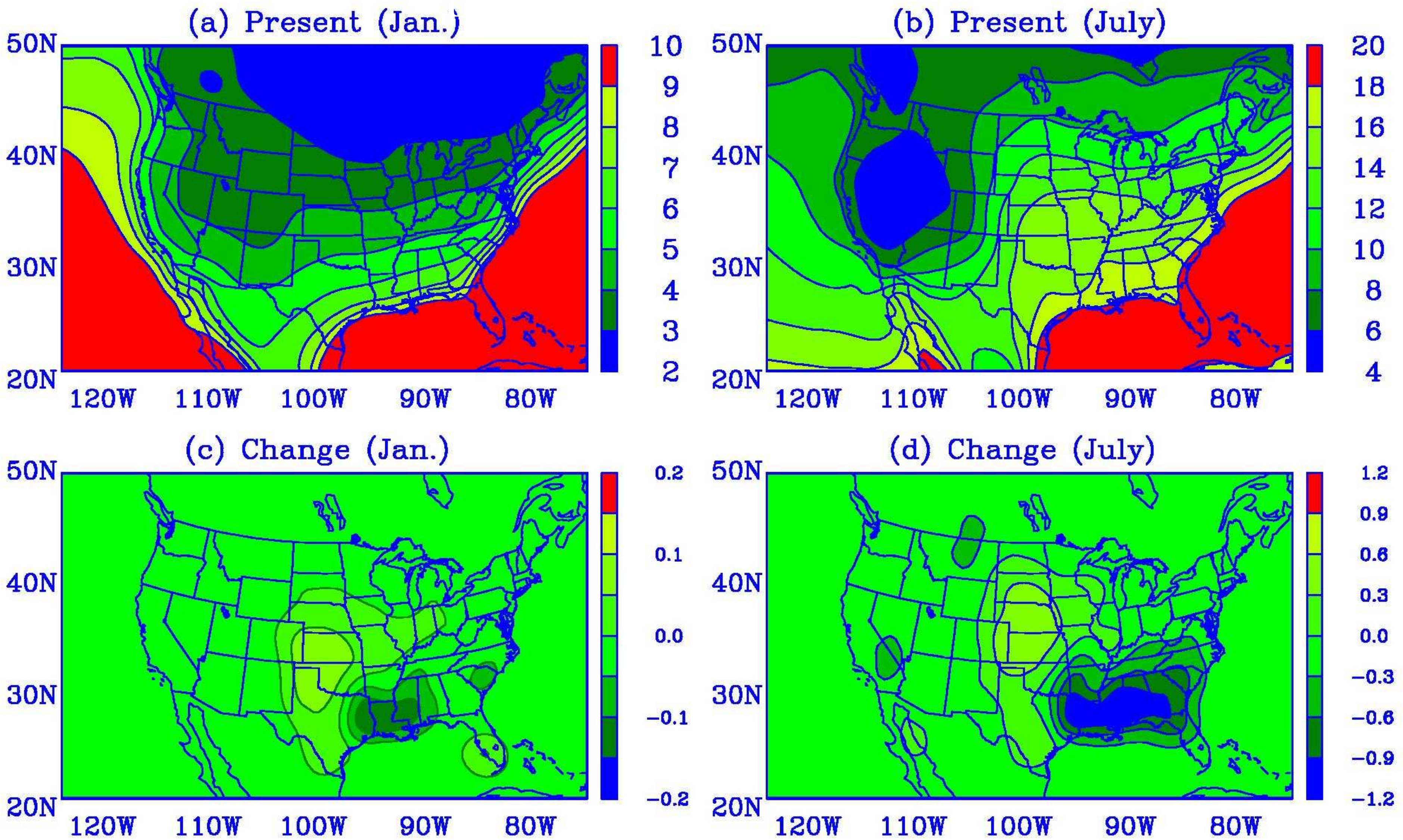
Precipitation (mm/day)
(a)
Present
8
6
4
2
0
Winter
Summer
(b)
Change
1.0
0.5
0
−0.5
−1.0
Winter
Summer
(c)
Rate (%)
20
10
0
−10
−20
Winter
Summer
Season
AC
GC
IL
N
W
S
E

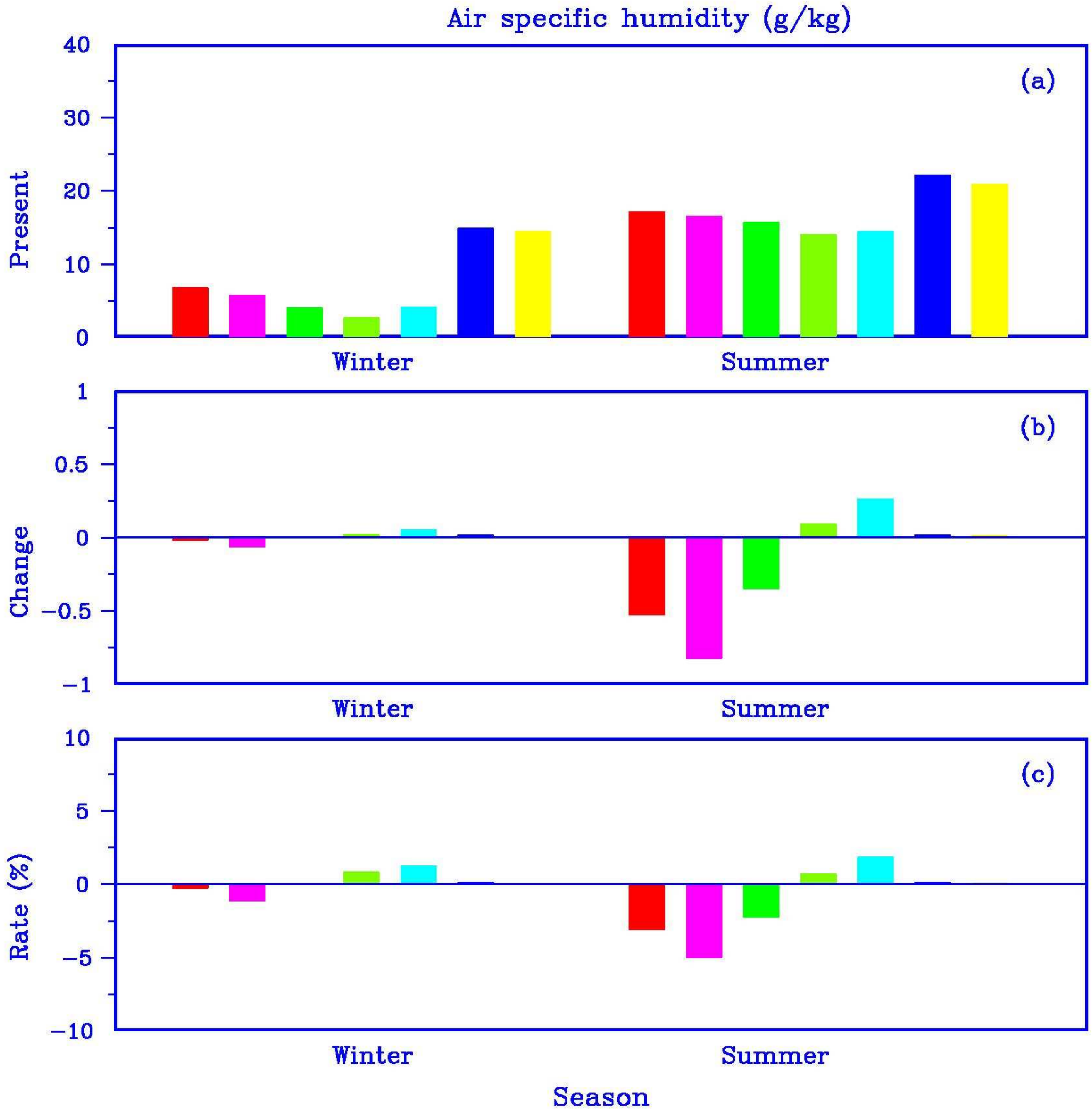
Soil moisture (cm)




Root-zone moisture (cm)
(a)
Present
80
60
40
20
0
Winter
Summer
(b)
Change
40
20
0
−20
−40
Winter
Summer
(c)
Rate (%)
100
50
0
−50
−100
Winter
Summer
Season
AC
GC
IL
N
W
S
E

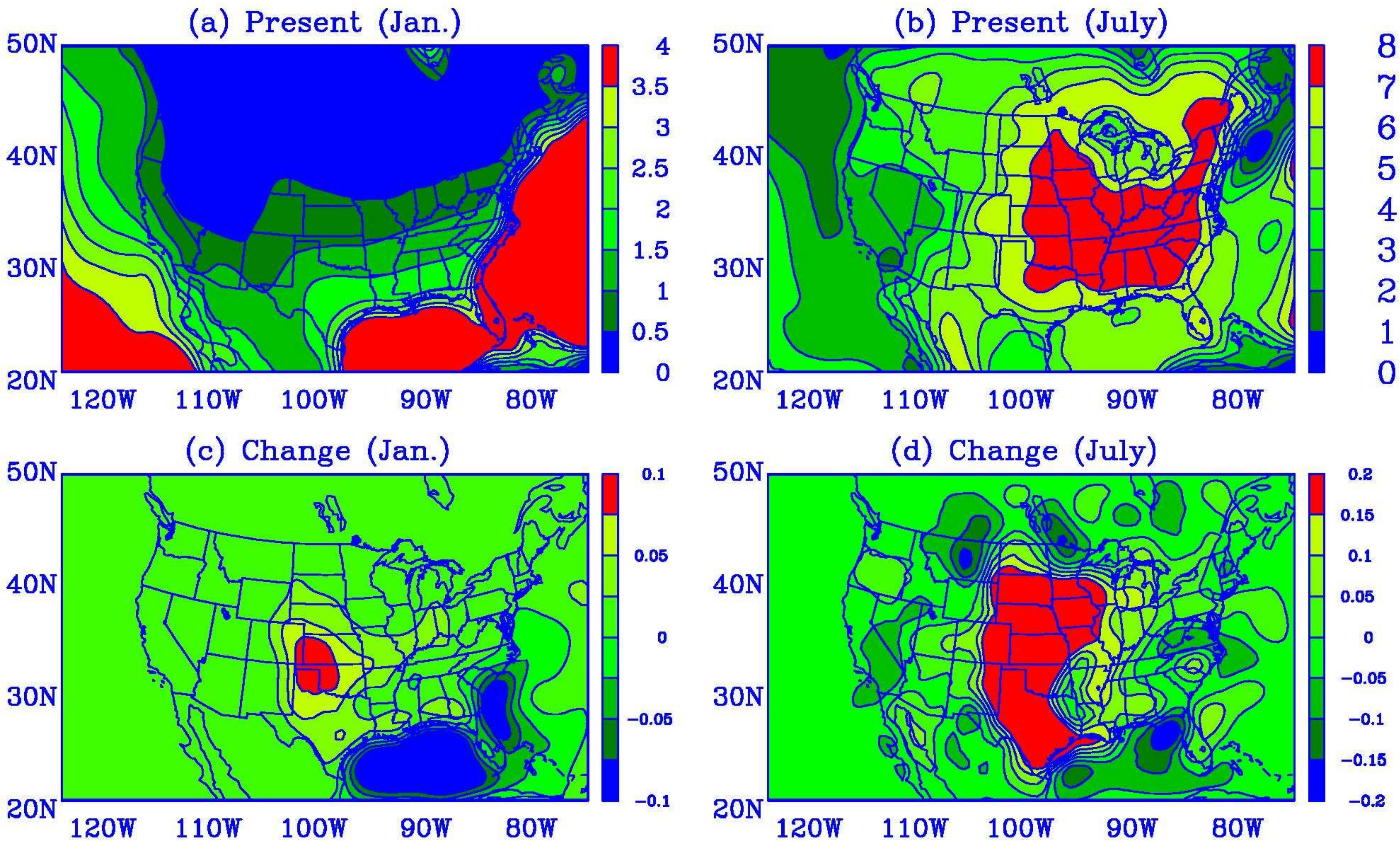
Air specific humidity (g/kg)

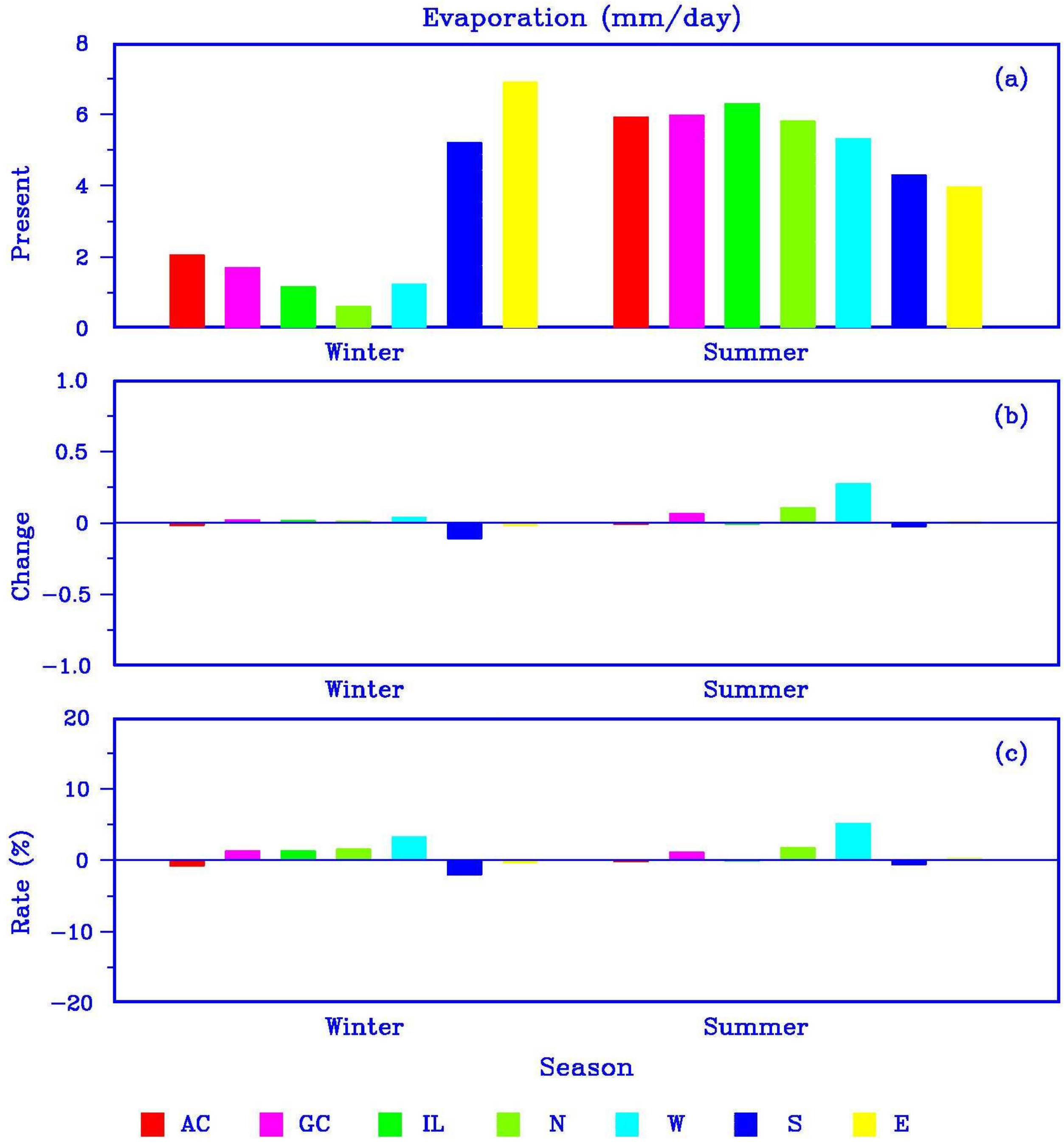




Air specific humidity (g/kg)
(a)
Present
40
30
20
10
0
Winter
Summer
(b)
Change
1
0.5
0
−0.5
−1
Winter
Summer
(c)
Rate (%)
10
5
0
−5
−10
Winter
Summer
Season

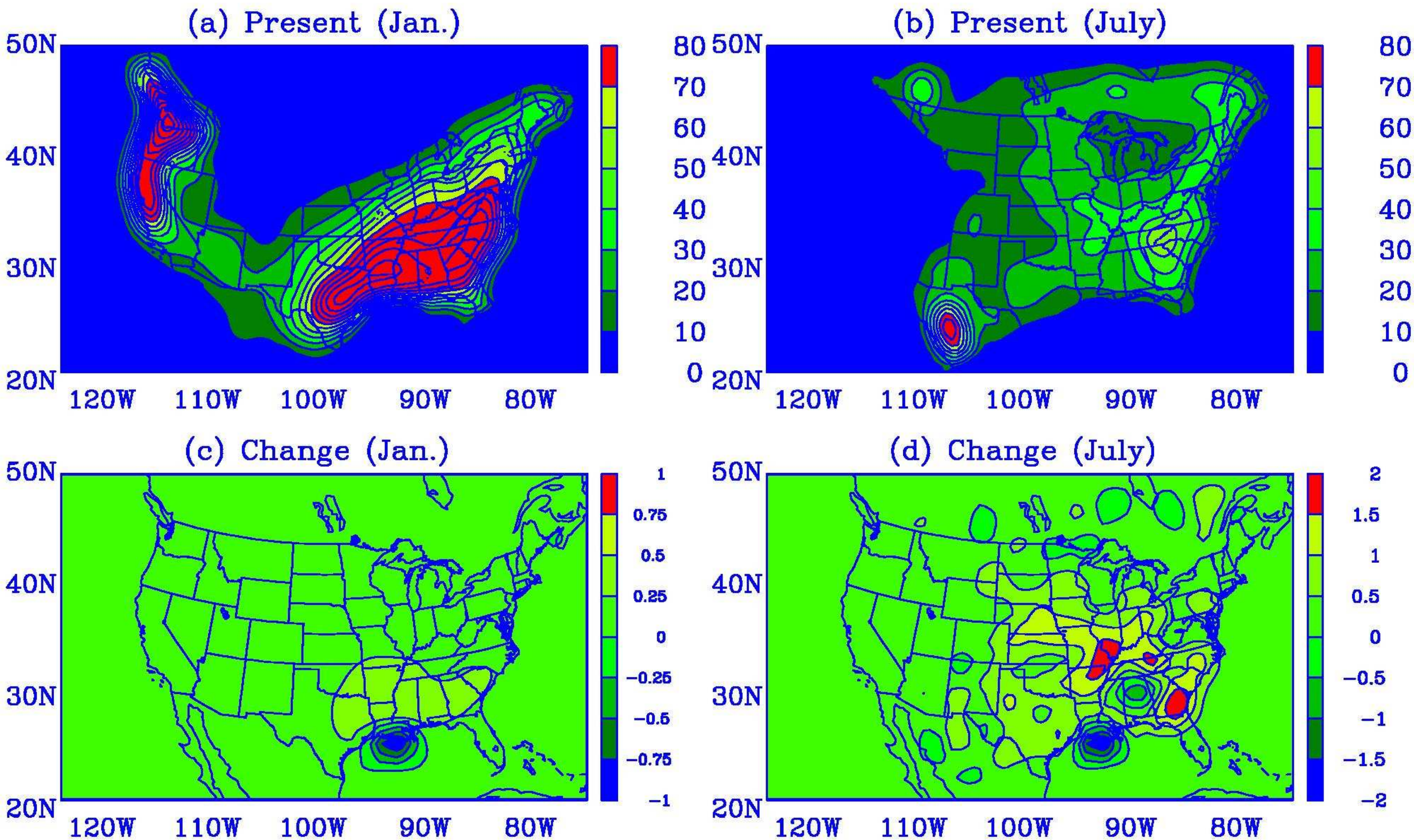
Evapotranspiration (mm/day)



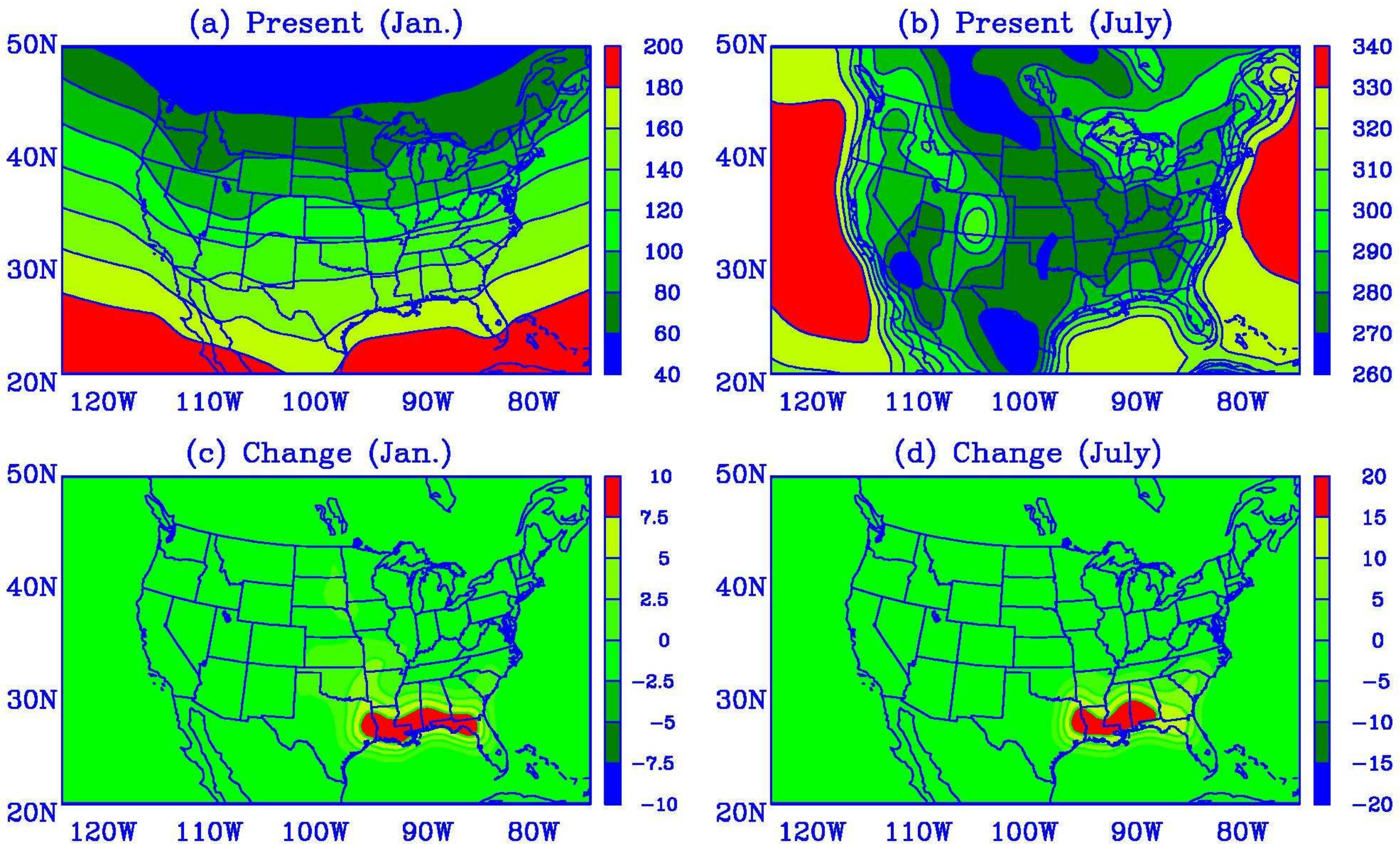


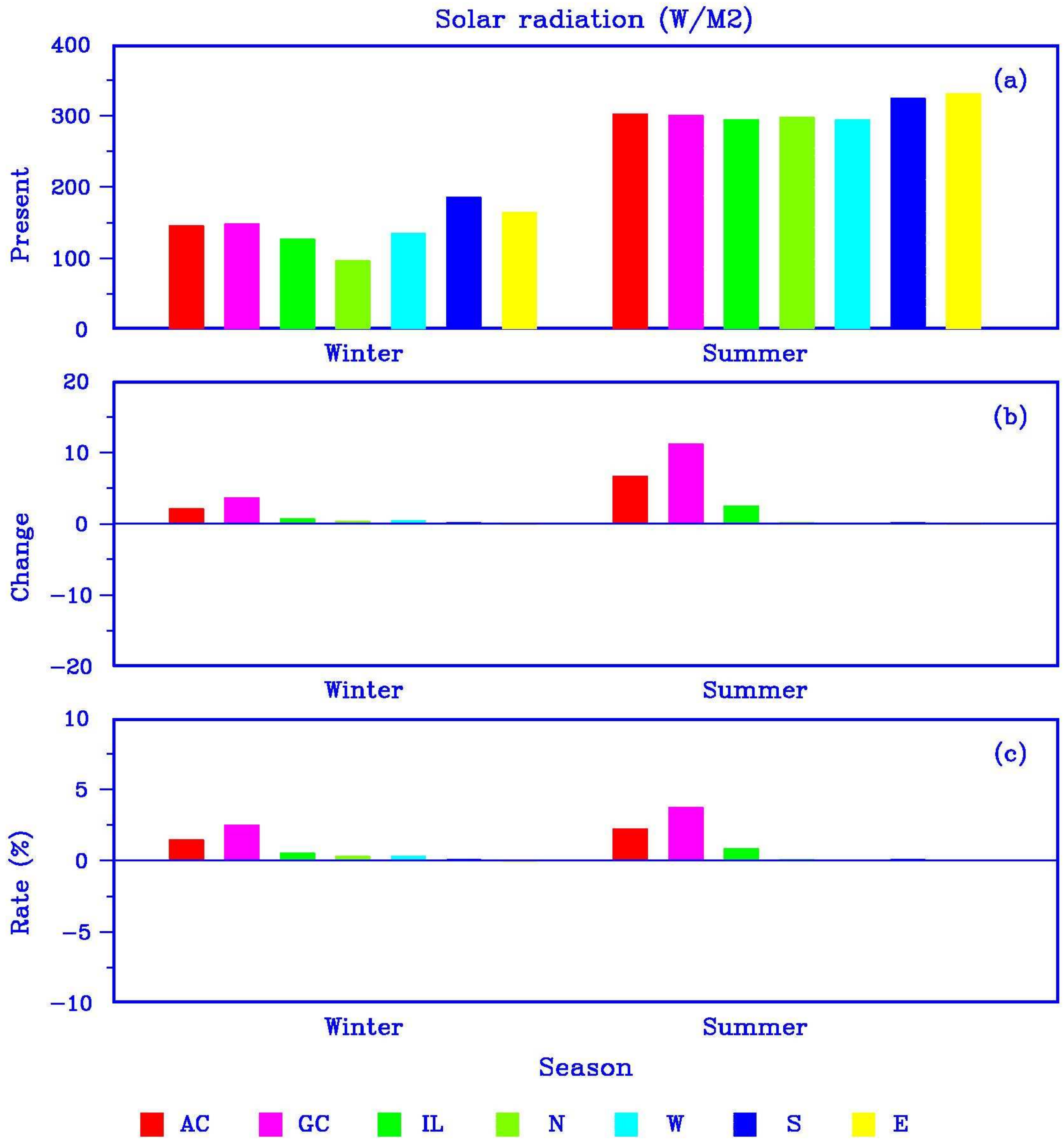
Evaporation (mm/day)
(a)
(b)
(c)
Present
Change
Rate (%)
8
6
4
2
0
1.0
0.5
0
−0.5
−1.0
20
10
0
−10
−20
Winter
Summer
Season
AC
GC
IL
N
W
S
E

Runoff (mm/day)



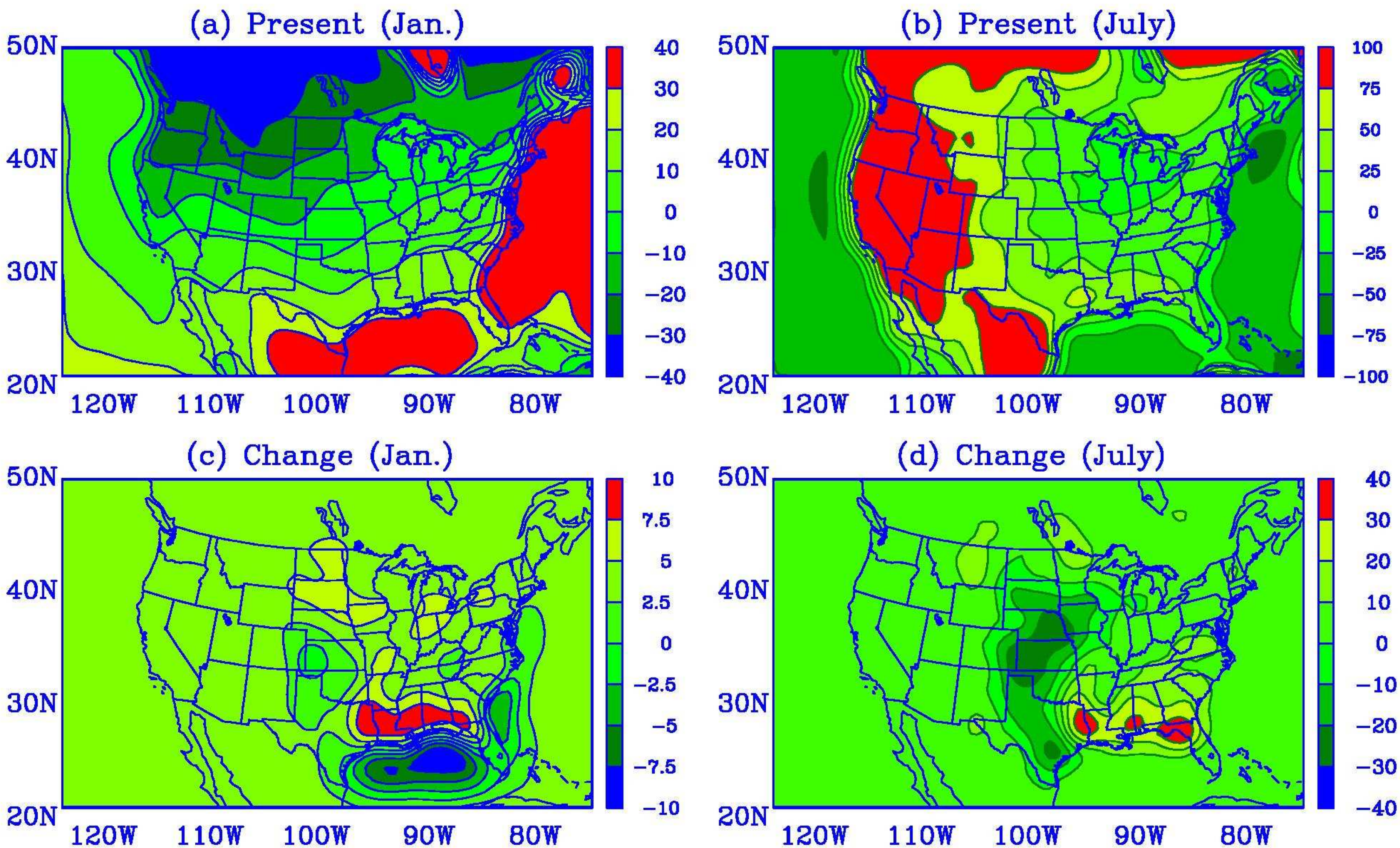
Solar radiation (W/M2)

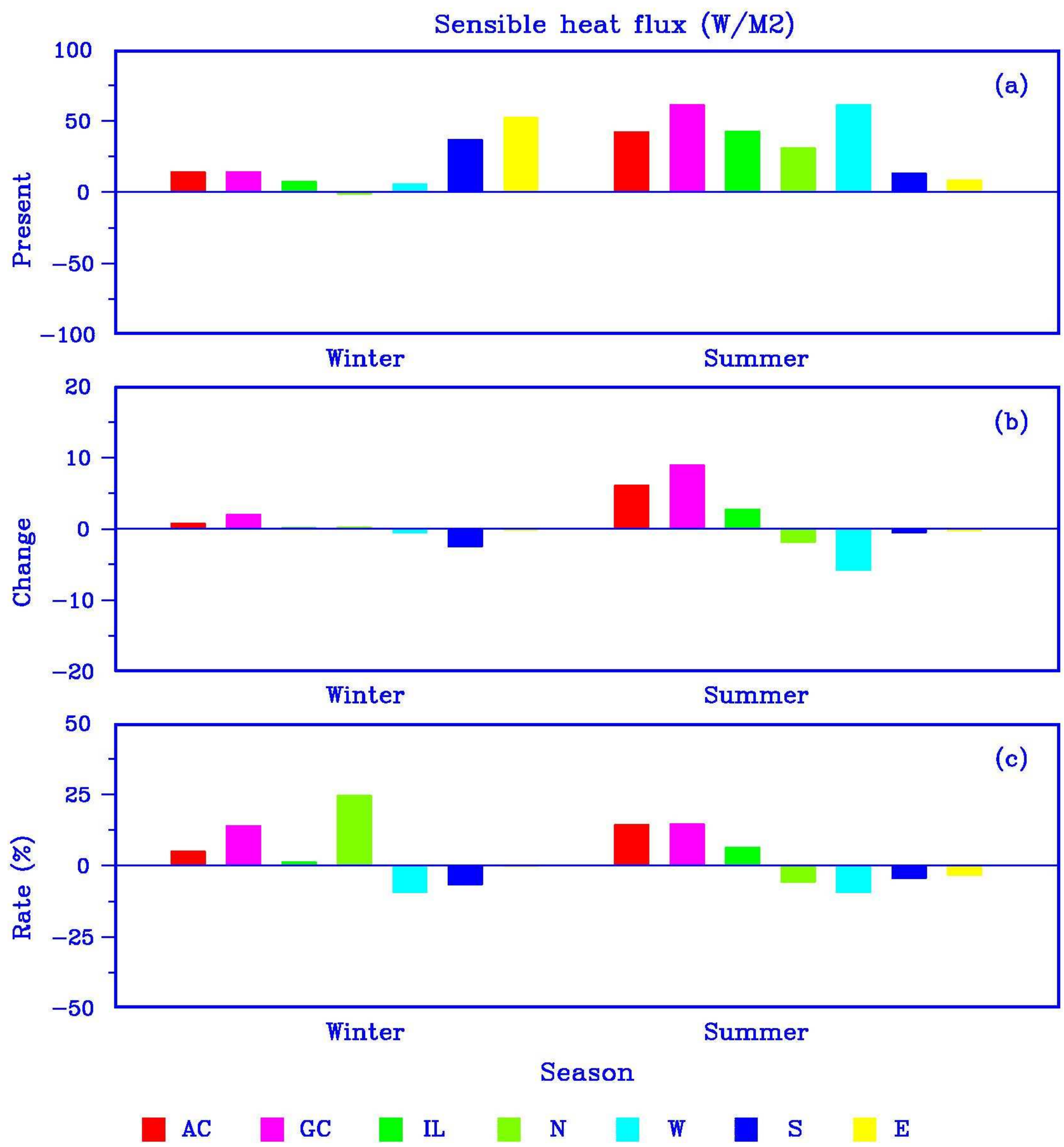




Solar radiation (W/M2)
(a)
(b)
(c)
Present
Change
Rate (%)
400
300
200
100
0
20
10
0
−10
−20
10
5
0
−5
−10
Winter
Summer
Season
AC
GC
IL
N
W
S
E

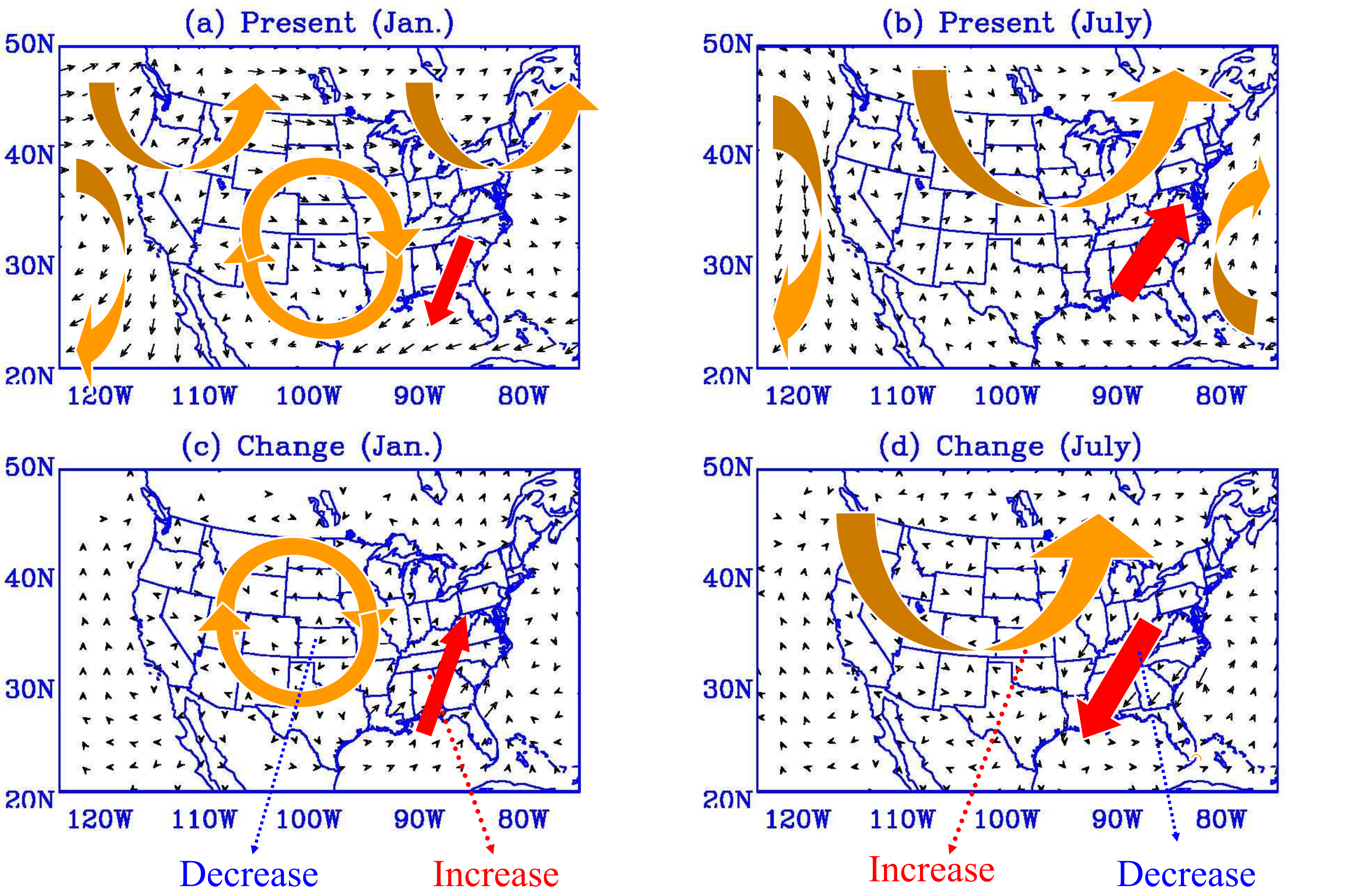
Sensible heat flux (W/M2)



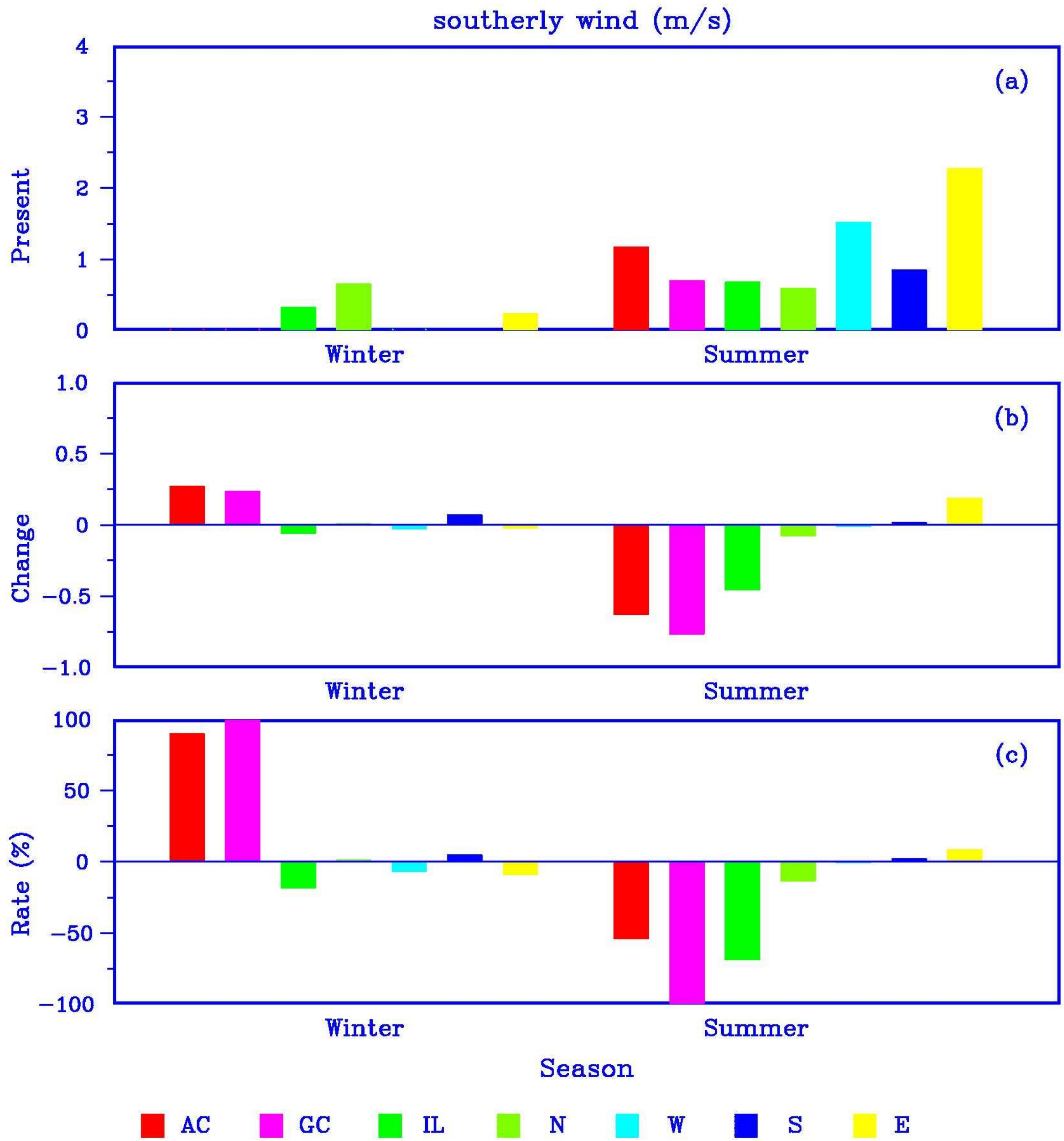


Sensible heat flux (W/M2)
(a)
(b)
(c)
Present
Change
Rate (%)
100
50
0
−50
−100
20
10
0
−10
−20
50
25
0
−25
−50
Winter
Summer
Winter
Summer
Winter
Summer
Season
AC
GC
IL
N
W
S
E

Surface wind field

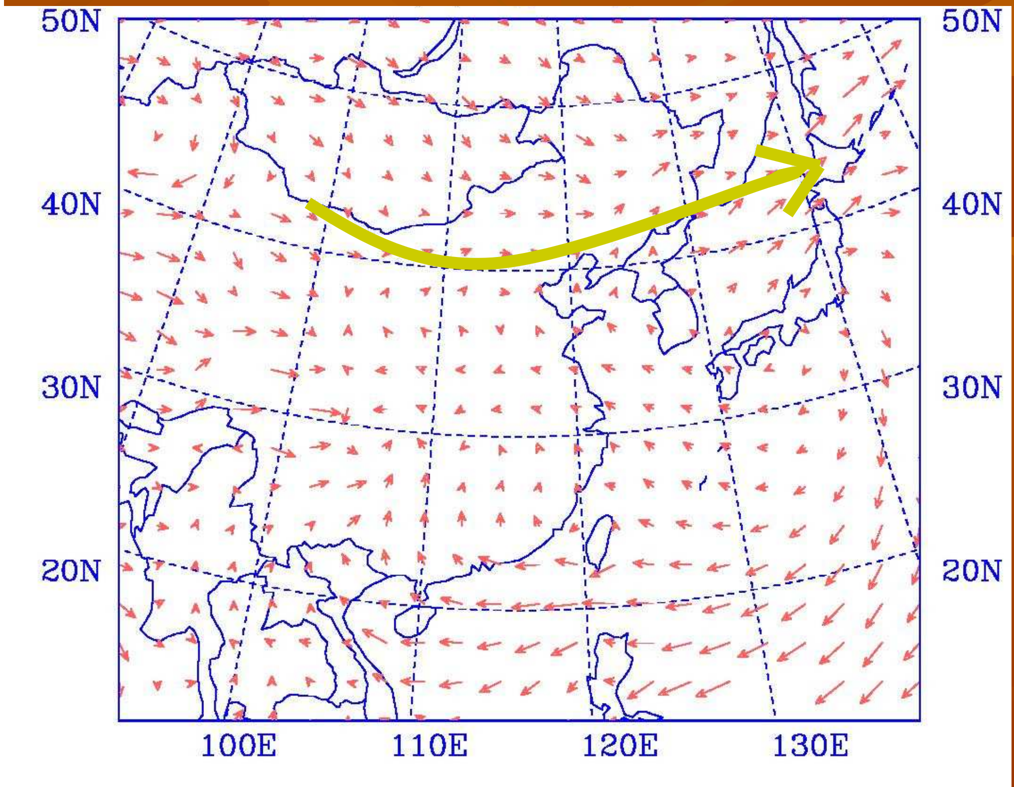


Precipitation change

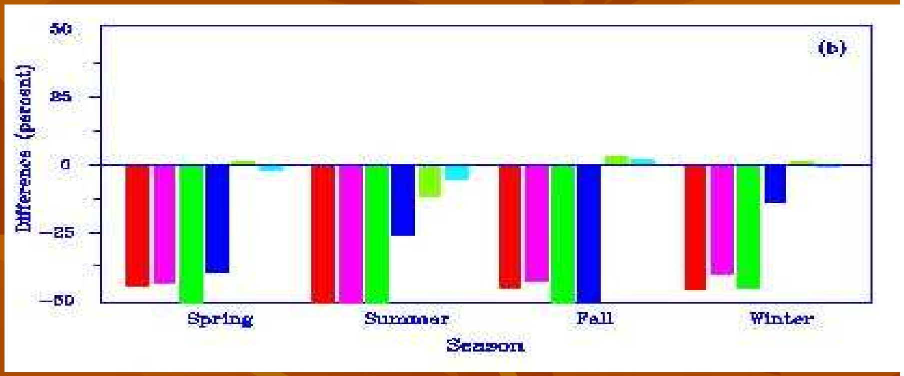

southerly wind (m/s)
(a)
(b)
(c)
Present
Change
Rate (%)
4
3
2
1
0
1.0
0.5
0
−0.5
−1.0
100
50
0
−50
−100
Winter
Summer
Season
AC
GC
IL
N
W
S
E

Comparison with the Northern China Forest Shelterbelt Project (Green Great Wall)

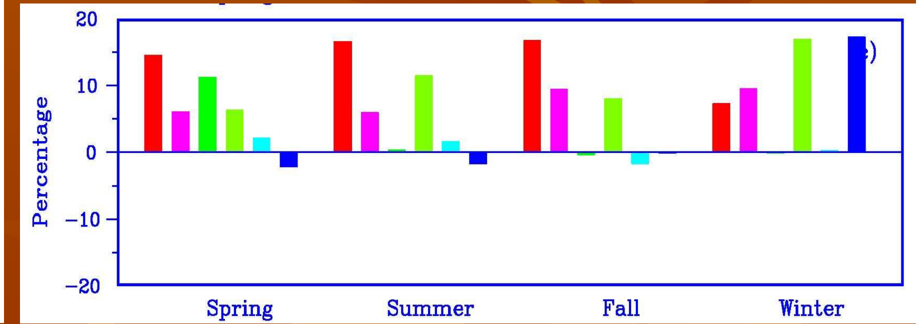
Circulation



Westerly wind change



Precipitation change



Westerly (dry) winds prevail. GGW reduces (increases) transport of dry (wet) air and therefore increases precipitation.

Major changes produced by RegCM

- Overall summer precipitation in eastern U.S. decreases, opposite to the change due to afforestation in mid-latitudes
- Precipitation changes in the South are different between summer and winter, and between Atlantic and Gulf coast.
- Soil moisture and air humidity increases and decreases, respectively
- Most significant change in evapotranspiration occurs outside the afforestation region
- The hydrological changes are related to the modification in wind field, which in turn modifies atmospheric transport of moisture and heat

Conclusions

- Afforestation in the South may reduce warm season water resources in some areas due to precipitation reduction
- Simulations with real time period, long-term, improved domain, and spin period are needed to reduce uncertainty
- Comparisons with measurements are needed

Thanks!