A Framework for Understanding Climate Regions

Report prepared for
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1.0 Introduction

The condition of park unit natural resources are linked, directly and indirectly, to the climate of a region. The status and dynamics of plant associations, migratory or resident mammal and bird populations, insect outbreaks, and hydrological resources are tied to climate. This tie may be as a function of long-term climatic conditions or subject to the frequency of extreme events. Knowledge of such climatic relationships are integral to research efforts and management decisions. This perspective is of increasing importance in light of current and potential rapid climate change.

This report presents a framework for understanding regional climates. The primary goal is to help network ecologists become familiar with regional climate dynamics which influence local ecological dynamics. Secondly, this report serves as a guide for creating a series of regional climate overview reports.[3] These reports are to provide a global-to-landscape perspective on regional climates of the United States and territories. For this framework, I first lay out a conceptual basis for talking about regional climates and propose climate regions for use by the I&M network (§2.0). The framework follows, as a guide to considering the spatial and temporal characteristics of a region (§3.0-4.0). The concluding section (§5.0) summarizes key points.

2.0 Background – Regional Climates

2.1 Climate Regime Concept

A key concept in physical geography is that climate is organized spatially into regimes, each with characteristic conditions. A consistent set of processes operating across a region underlies this similarity. We recognize the Mediterranean-type climate regime of California, for example, as being characterized by (a) mild, wet winters influenced by Pacific maritime air and mid-latitude cyclonic storms, (b) very dry summers dominated by subsiding air from the North Pacific subtropical high pressure system, and (c) interannual variability strongly connected to El Niño-Southern Oscillation (ENSO; see §4.2). Climate regimes, and the climate regions defined by them, are useful constructs which allow us to understand the suite of planetary, continental, and regional processes that create a local climate. At the same time we recognize these as generalizations, that any region consists of a diversity of local climates.

2.2 Regime Properties

Regimes are characterized by:

> *General uniformity of climatic properties and processes over a region.* This similarity extends across a range of timescales (e.g., hourly to interannual), such that daily event structure and teleconnections characterize a regime as much as its long-term means.

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[3] This follows from a plan for I&M overview reports to be developed for each U.S. climate region. Potentially these would be by NPS scientists and other experts in a region's climate and ecology. Guidelines for report preparers are:

- Writing should keep in mind the goal – to present a comprehensible, cohesive picture of climate across scales that is accessible to park ecologists and managers.
- Report length must balance such depth and breadth with brevity, as utility can be facilitated by modest length (e.g., 10 published pages, plus figures and references). Recognizing the difficulty in reaching this balance, discussion should be kept pertinent, interesting, and tight to keep length down.
- To achieve these points, reports would benefit from editorial review as part of or in addition to a scientific review.

Tied to broad-scale atmospheric and adjacent ocean circulation dynamics. The context for a regime is set by:

- Global circulation dynamics that prevail for latitudinal zone and season – in the atmosphere (e.g., tropical moisture convergence, cold-air outflow from the polar vortex) and of an adjacent ocean (e.g., coastal warm current). (See §3.1)
- Continental physiography – e.g., mountain systems, coastline geography. (§3.2)

As a result of these dynamics, seasonal air masses of continental or maritime and high or low latitude origins tend to prevail over and so distinguish regimes (Figure 1a,b; Bryson 1966, Mitchell 1976).[4] Strahler (1969) presents a climate classification based on these underlying dynamics (Table 2).

Relatively rapid spatial shifts at regime boundaries. Transitions are on the order of 100km wide and represent rapid shifts in dynamics and characters between distinct regimes (Figure 1).

Long-timescale shifts. While we generally talk about climate regimes in terms of a given geography, boundaries shift significantly at multidecadal (Neilson and Wullstein 1983), centennial to millennial (Woodhouse and Overpeck 1998), and longer timescales.

Significant within-regime spatial heterogeneity. This is especially evident in surface climate variables. Within the context of overall regime features, this heterogeneity arises from:

- Broad latitudinal/longitudinal gradients due to shifting intensity of prevailing atmosphere circulation dynamics.
- Finer-scale change in temperature, precipitation, and other surface variables reflecting heterogeneity in, for example, topography and landcover (§3.3).

Close correspondence to biotic regions. This correspondence is reflected in many climate classification systems delineated by (or at least guided by) biomes or smaller biogeographic divisions (e.g., Köppen 1931,[5] Thornthwaite 1948, Rumney 1968). Conversely, many ecological regionalization schemes are defined by a consistency in climate regime (Walter 1994, Neilson 1987, Bailey 1996).

2.3 Recommendation for NPS I&M Climate Regions – NEON Domains

Designation of climate regions for the I&M network can follow one of two strategies: (1) a biogeographical approach, where ecological biome shifts define climatic regions (e.g., following classification schemes noted in the last section), or (2) a strictly climate approach that seeks internal consistency in key climate variables. Following the latter strategy, the National Ecological Observatory Network (NEON)[6] used multivariate clustering analysis of surface climate (Table 1) in combination with air mass boundaries (Figure 1) to delineate a set of 20 operational domains for the United States (Figure 2). To complement this classification, Hargrove and Hoffman (2006) also evaluated within-region heterogeneity for the domains.

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[4] Similarly-based regimes for maritime domains are explored by Low and Hudak (1997) and Bailey (1996).
[5] For descriptions of the Köppen system, see: http://www.blueplanetbiomes.org/climate.htm and http://en.wikipedia.org/wiki/K%C3%B6ppen_climate_classification. Polygon coverages for the U.S. and selected states can be downloaded from: http://snow.ag.uidaho.edu/Clim_Map/koppen_usa_map.htm.
[6] http://www.neoninc.org/

The NEON domains are well suited to serve as I&M climate regions. They offer advantages of:

(1) Being climate based – rather than biogeographical or political.
(2) Capturing significant spatial differences in climate across the U.S. – without splitting the country into an unmanageable number of regions.
(3) Permitting NPS climate research and datasets organized by these regions to benefit from and contribute to NEON syntheses.

2.4 Describing Regional Climates

2.4.1 A Framework for Climate Region Reports

Climate operates through a cascade of interrelated spatial and temporal scales (Figure 3). I've discussed how climate regimes, while regional by definition, reflect and affect climate processes across a wide range of space and time scales (§2.2). This provides a framework for expressing the geography (§3.0) and dynamics (§4.0) of regions.

These sections are designed as a report-writing guide for placing a region in a spatial context (with respect to both broad and finer scale processes) and for considering its short and long-term behavior. Each report's goals are to sufficiently cover a wide enough range of climate topics and describe within-region diversity of climates, giving adequate context to park science and management.

The guide's structure is designed to be adaptable for a given region. The sections offer up factors, some key to a region and others not so relevant in a given case. At the same time, this is not a complete list – as a report is developed, I expect other factors offering insights into that region's climatology will become clear and added in. In the guide, I provide references to further support report development, with information on the world's and U.S. regional climates and the processes that create them.

2.4.2 Regional Analyses – General References and Sources of Regional Information

General climatological surveys take different approaches to presenting regional climates. Rumney (1968) examines climates of the world's biomes, with specific coverage of North America. Walter (1994) presents a climate diagram scheme as a key for discerning ecologically critical aspects of climate. Barry and Chorley (2003, p. 225ff) and Trewartha (1981) provide a dynamical overview of North American climates. Bailey (1995) gives brief summaries of the climates of U.S. ecoregions; his books (Bailey 1996, 1998) provide broader context.

Example regional analyses are Sheppard et al. (2002) for the American Southwest and Kittel et al. (2002) for the Rocky Mountains. Their discussion ranges from global circulation through intraregional aspects of these climates.

State narratives give a regional perspective to their climates (e.g., NOAA 1985). These are often online through individual state climatologist offices and the NOAA regional climate centers (Table 3).[7] U.S. and individual state climatological maps useful for regional description are also available from the Western Regional Climate Center (WRCC)[8] and Oregon Climate Service.[9]

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[7] For example, western state climate narratives are at: http://www.wrcc.dri.edu/CLIMATEDATA.html (listed on page's lower right).
[8] NOAA Climate Atlas - http://www.wrcc.dri.edu/climmaps/ and PRISM precipitation maps (Daly et al. 2002)- http://www.wrcc.dri.edu/precip.html http://www.prism.oregonstate.edu/
[9] Oregon Climate Service, PRISM Group - http://www.prism.oregonstate.edu/

Selected data sources for regional analyses are presented in Table 3. Spatiotemporal techniques appropriate for analysis of regional climates are surveyed by Kittel (2008).

3.0 Geography of Regional Climates

A natural spatial progression is to start with the global and hemispheric context of a region and then superimpose continental and landscape factors that modify the coarser-scaled controls. This paints a picture of a region that shows both its cohesive features and its climatic texture – together, a mosaic of climatic landscapes in a single frame.

3.1 Global Atmospheric Circulation as Prime Determinant – Creation of a Regional Climate, Part I

3.1.1 The Basics

In §2.2, I said that climate regimes are tied to broad-scale atmospheric and adjacent ocean circulation dynamics. The origin of these circulations lies, in the broadest sense, by the equator-pole imbalance in radiative inputs vs. outputs (net gain in low latitudes, net loss in high latitudes). Atmosphere, ocean, land, and cryosphere processes function to equilibrate this imbalance by transporting low-latitude heat poleward. These earth climate system components accomplish this transport via interconnected, complex dynamics in ways that determine regional climates. I cover oceanic circulation relevant to terrestrial climates in §3.2.3.

For its part, atmospheric global circulation can be put in terms of four linked components. From equator to poles, these are:

- Intertropical Convergence Zone (ITCZ) – at the equatorial convergence of the Trades.
- Subtropical High Pressure Centers (STH) – with subsiding, divergent flow in the subtropics.
- Mid-latitude Baroclinic Zone[10] and its Westerly Jet Stream – at the meeting of tropical and polar air (Figure 1).
- Polar Vortices – the source of cold polar air.

The next section (§3.1.2) very briefly notes dynamics of these circulation elements as they set features of regional climate. More extensive overviews of the climate system are given by most introductory physical geography and meteorology textbooks (e.g., Strahler and Strahler 2006); Barry and Chorley (2003) give an advanced, but accessible (i.e., limited use of numerics) presentation (see also Peixoto and Oort 1992).[11] As noted earlier (§2.4.2), Barry and Chorley (2003, §10.B, p. 225ff) and Trewartha (1981) take a dynamical view of the climates of North America.

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[10] A baroclinic region is formally where a temperature gradient exists on a constant pressure surface.

[11] An earlier (1992) edition of Barry & Chorley is available in part on "google books:" http://books.google.com/books?id=bIw9AAAAIAAJ. Peixoto and Oort (1992) is also available in part: http://books.google.com/books?id=3tjKa0YzFRMC.

3.1.2 Global Atmospheric Circulation Patterns and Surface Climate Regime

Defining dynamics, characteristic thermal and moisture regimes, biomes, and corresponding Strahler climate types and, as appropriate, NEON domains for these elements are:

Intertropical Convergence Zone – Equatorial and Tropical Wet Climates

- Defined by convergence of warm moist air in the tropics – this convergence is generally of Northern and Southern Hemisphere Trade Winds. Lifting at the convergence[12] generates a high precipitation band about the equator.
- Moisture seasonality – set by a muted to intense summer wet-winter dry annual cycle. The wet-dry seasonal contrast at a given location is determined by the latitudinal breadth and annual north-south swing of the ITCZ.
- Thermal seasonality minor – if anything, it's cooler during the summer wet season due to prevalence of mid-day cloud cover. Lack of freezing temperatures.
- Biomes: tropical rain (evergreen) forest to tropical dry (deciduous) forest.
- Strahler climate types 1, 5 (Table 2).

Subtropical High Pressure Centers – Subtropical Dry Climates

- Atmospheric circulation dominated by warm, dry air subsiding out of the Subtropical Highs.[12] Flow is divergent at the surface: equatorward return flow to the ITCZ (the Trades) and poleward flow, the source of tropical air for the mid-latitudes.
- Arid moisture regime – potential evapotranspiration far exceeds precipitation. Very low annual precipitation, low seasonality, with high interannual variability.
- High temperatures, moderate seasonality, with no or infrequent winter frost ($\leq$ once every 3 yrs)
- Subtropical deserts.
- Strahler climate types 3, 4 (Table 2), NEON domain 14 (Figure 2).

Mid-latitude Baroclinic Zone and Westerlies – Temperate to Boreal Wet and Dry Climates

- A strong latitudinal gradient in tropospheric temperature (a "baroclinic zone"[10]) develops at the meeting of tropical and polar air in the mid-latitudes. This gradient sets the location of the Mid-latitude Westerly Jet Stream. Mid-latitude cyclonic storms embedded in the jet organize and intensify the regional temperature gradient into warm and cold fronts and produce precipitation.
- Seasonality – dominated by the north-south swing of the Mid-latitude Jet and seasonal incursions of polar and tropical air masses (referred to as the Polar Front).
- Temperature regime dominated by passage of warm and cold fronts in winter in temperate regions and year-round in the boreal zone. Latitude and continental physiography further determine warm to cold regional character (§3.2).
- Given sufficient moisture, cyclonic storms bring precipitation in the form of rain or snow. Within this circulation domain, continental physiography largely determines humid to arid regimes (§3.2).
- Biomes range from warm to cold temperate forests, grasslands, and deserts and boreal forests
- Strahler climate types 6-7, 9-12 (Table 2), NEON domains 1-3, 5-13, 15-16, 19 (Figure 2).

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[12] The ITCZ and the STH's are the upward and downward limbs, respectively, of the Hadley Circulation. The Hadley Circulation is a thermally-driven meridional atmospheric circulation, with (1) equatorward surface flow (the Trades) from subtropics to the ITCZ, (2) lifting in the ITCZ, (3) poleward upper air flow to the subtropics, and (4) subsiding air in the STH's.

Polar Vortex – Polar Cold Climates

- High terrestrial (infrared) radiation loss relative to low solar radiation drives the creation of extreme cold air especially in winter. The core of this cold is encircled by strong upper air westerlies, referred to as the Polar Vortex.[13] Extreme cold air exiting polar regions creates an Arctic/Antarctic Front in transition to the subarctic and subantarctic.[14] Further equatorward flow supplies (not-as-extreme) cold polar air to the mid-latitudes. Subarctic/Subantarctic reaches can be influenced by cyclonic storms from late spring through early fall.
- Seasonality – the Polar Vortex is pronounced in winter, reduced or not present in summer.
- Thermal regime – predominance of cold air, with strong poleward decrease and strong seasonality following net radiation balance.
- Moisture regime – a strong poleward decrease and strong seasonality in moisture follows temperature patterns. This is a result of the low moisture capacity of very cold air.
- Biomes: Boreal woodland[14] to Arctic wet tundra, to polar desert.
- Strahler climate types 13-14 (Table 2), NEON domain 18: Tundra (Figure 2).

Transitions between these circulation systems can have distinct regional climates, usually a season-dependent blend of characteristics of both systems. For example:

Tropical Dry Climates – Transitional between ITCZ and STH-dominated climates

- Tropical dry, highly seasonal precipitation climates – at the poleward summer limits of ITCZ influence and strongly dominated by Subtropical Highs in winter. In some locations, the short rainy season is from summer monsoonal or trade-wind flow (§3.2) rather than from the ITCZ.
- Moisture regime – very short rain season, intense intervening dry season.
- Vegetation predominately *savana* and thorn forest.
- Dry end of Strahler climate type 5 (Table 2).

Mediterranean Climates – Transitional between STH and Mid-latitude Westerlies-dominated climates

- Strongly dominated by a STH in summer and mid-latitude cyclonic storms in winter. California's Mediterranean-type climate is the North American example.
- Winter wet-summer dry moisture regime arises from the seasonal switching of these circulation systems.
- Subtropical (years with frost infrequent) to warm temperate (frosts annually) thermal regime.
- Mediterranean vegetation – mosaic of summer drought-tolerant chaparral, woodlands, and grasslands.
- Strahler climate type 8 (Table 2), NEON domain 17: Pacific Southwest (Figure 2).

3.2 Continental Physiography as Modifier – Creation of a Regional Climate, Part II

A continent's location on the globe and its physiography modify the way global circulation patterns play out across the continent. Four key continental determinants are:

- Latitudinal span (§3.2.1)
- Size and shape (§3.2.2)

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[13] See http://nsidc.org/arcticmet/patterns/polar_vortex.html

[14] In the Northern Hemisphere, the Arctic Front roughly corresponds to the Arctic tundra-boreal woodland treeline.

- Continent-ocean basin geometry (§3.2.3)
- Major topographic features – Cordillera and highlands (§3.2.4)
- Up-scale effects on global atmospheric circulation (§3.2.5)

3.2.1 Latitudinal Span Relative to Global Atmospheric Circulation Patterns

North America spans nearly the full latitudinal extent of the Northern Hemisphere (7 to 83ºN). This span intersects the major atmospheric global circulation elements from tropical to polar (§3.1). As a result, different regional climates are established by markedly different broad-scale atmospheric dynamics.

3.2.2 Continental Size and Shape

Continent size and shape dictate the degree of influence of oceanic vs. continental air masses on regional climates.

Maritime Climates. We generally recognize that oceanic islands and continental regions adjacent to oceans have "maritime climates." Relative to more removed, isolated "continental" climates, maritime regional climates have:

- Reduced seasonal temperature cycle due to the ameliorating effect of a nearby water body – Arises from the greater heat capacity[15] of water vs. land.
- Higher humidity – Due to proximity of moisture sources.

The maritime influence is just that, a modifier of broader controls. Maritime moisture regimes vary based on prevailing global atmosphere circulation patterns:

- Under the influence of Subtropical Highs, coastal climates tend to be foggy with low precipitation (§3.2.3).
- Those in line with the Trades and the Mid-latitude Westerlies receive high rainfall (§3.2.4).

Features of coastal climates also depend on adjacent ocean dynamics (see §3.2.3).

Continental Climates. Continental climates tend to have large seasonal temperature swings, loosing heat rapidly in winter, gaining it rapidly in summer. Continental climates are:

- Regions of winter cold air generation in high latitudes – e.g., Siberia, subarctic Canada. In mid-latitudes, centers of strong summer heating (for the latitude), especially if also arid[16] – e.g., Northern Great Plains (Mitchell's Region III, Figure 1b; see caption).
- Isolated from moisture sources –
  - In low and mid-latitudes, these climates are arid or semi-arid (e.g., Gobi Desert).
  - In higher latitudes, continental areas are generally sub-humid (rather than arid because low temperatures result in low potential evapotranspiration), but drier than more maritime counterparts (e.g., central vs. eastern boreal Canada).

The longitudinal breadth of North America in mid- and high latitudes lends its central regions to strongly continental climates.[17] Such isolation is also facilitated by mountain ranges blocking flow from moisture sources (§3.2.4.1, §3.2.4.2). (Strahler climate types 9-11, Table 2).

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[15] A material with high heat capacity (e.g., water) requires a greater input of heat energy to raise the material's temperature a set amount than does a material with low heat capacity (e.g., land). This means that water temperatures rise and decrease seasonally more slowly than land temperature with the same heat input/loss.

[16] Arid regions have higher heating rates because heat energy is not going into evaporating water.

[17] The effect of continentality on thermal regime is often assessed with the "continentality index:" http://amsglossary.allenpress.com/glossary/search?id=continentality1

Monsoon Climates – Continents generate their own circulation. All continents have sufficiently large land masses and adjacent tropical/subtropical oceans to setup strong thermally-driven circulations – the monsoons. In summer, continental heating contrasts with cooler (though warm) subtropical/tropical oceans. The resulting thermal circulation, the summer monsoon,[18] draws moist-laden air from the warm ocean supporting what can be intense summer convective rainfall (thunderstorm).

The North American Monsoon pulls moisture from the Gulfs of Mexico and California into the American Southwest, Colorado Plateau, and Southern to Central Great Plains (Adams and Comrie 1997, Sheppard et al. 2002). These areas correspond to Mitchell's Region VI (Figure 1b, see caption; NEON domains 10-11 and 13-14, Figure 2). The monsoonal front progresses inland north- and northeastward, arriving in the American Southwest and Colorado Front Range by early July and early August, respectively.

3.2.3 Continent-Ocean Basin Geometry – Role of Adjacent Global Ocean Dynamics

As noted, the character of maritime climates depends on both global atmosphere and oceanic dynamics (§3.2.2). The relationship with an adjacent ocean relies on how the continent is oriented with and influences the ocean. Two such continent-ocean basin interactions are:

- Winter sea ice-bound coastlines (§3.2.3.1)
- Ocean gyre boundary currents (§3.2.3.2)

3.2.3.1 Arctic/Antarctic Coasts

Extensive high-latitude coastlines are sea-ice bound (historically) for much of the winter –seasonally eliminating the ameliorating effect of open water. Primary examples are the east-west running Eurasian and North American coastlines with the Arctic Ocean. Here, winter sea ice formation is supported by continent-ocean basin geometry – the near-continuous ring of these continents at high latitude blocks warmer warm flows into the Arctic.

3.2.3.2 Subtropical Ocean Gyres and Their Boundary Currents

From the tropics to high mid-latitudes, west- and east-coast climates differ. This arises from basin-wide ocean gyre circulations centered over the subtropics[19]. Arms of the gyres are wind-driven to the west in the tropics, to the east in mid-latitudes. However, bounded by north-south running continents, the gyres run poleward and equatorward. Warm westward equatorial waters are deflected poleward up east coasts (e.g., the Gulf Stream). Eastward mid-latitude currents are forced both equatorward down west coasts bringing colder water to the subtropics (e.g., the California Current) and poleward bringing relatively warm water into the subarctic[20] (e.g., the North Atlantic and Norwegian extensions of the Gulf Stream).

Warm Current, Humid Climates – East coasts and subarctic west coasts

- East coasts – Western boundary ocean currents, as the Gulf Stream, are a source of warm, moist air year-round to the subtropical to mid-latitude east coasts of continents (Strahler climate type 6; Table 2).
- In North America, the exceptionally low, open topography of the central U.S. permits Gulf Stream waters in the Gulf of Mexico to supply warm, moist air well into the interior of the

[18] Summer monsoon is also referred to as the "wet monsoon," in contrast to the reverse-flowing winter or "dry monsoon." The most commonly cited example of this seasonal switch is over the Indian Subcontinent.
[19] Ocean gyres definition and descriptions: http://amsglossary.allenpress.com/glossary/search?id=gyres1
[20] Without significant continental mass in the Southern Hemisphere high mid-latitudes (50-60ºS), there is no equivalent deflection in the subantarctic

continent as well as the Eastern Seaboard (Figure 1). Here, marine tropical air meets similarly unimpeded continental polar air (see §3.2.4.2). These fronts generate precipitation for much of central and eastern North America and, in spring and early summer, spawn tornados. (Strahler climate type 10, Table 2).

- Hurricanes – Warm waters of western boundary currents support the development of tropical cyclones[21] – a significant element of these climates.
- Vegetation ranges from warm to cold temperate mesic mixed forests[22] to tallgrass prairie.
- Subarctic west coasts – Extensions of these currents to the opposite side of their ocean basins supply ameliorating air to subarctic maritime regions of Alaska and northern Europe. These climates are less frigid and with reduced thermal seasonality than other maritime climates for the latitude (Strahler climate type 12, Table 2)

Cold Current, West Coast Dry Climates –

- West coasts in the subtropics – Eastern boundary ocean currents, such as the California and Humboldt Currents, circulate cold water past arid and semiarid coasts. This moisture paradox – deserts adjacent to a moisture source – occurs because these currents underlie a Subtropical High. Subsidence out of the High caps vertical motion and suppresses precipitation generation (§3.1.2); the current's cooling of overriding air also curbs convection.
- The currents do nonetheless supply moisture to adjacent coasts but primarily in the form of extensive and persistent fog.
- Predominant vegetation: Fog deserts.[23]
- Strahler climate type 4: West coast desert climate (Table 2).
- Subtropical cold currents are supported by equatorward winds out of the STH and are dynamically linked to deep ocean water upwelling, further enhancing cold sea surface temperatures. Off the Peruvian coast, these interactions establish the El Niño action center (§4.2).

3.2.4 Continent's Major Topography – Cordillera and Highlands

Each continent has its own arrangement of cordillera and extensive highlands, complicating the arrangement of regional climates. North America is largely characterized by major north-south ranges: the Appalachians, Rocky Mountains, Sierras Madre, and the Sierra Nevada/Cascades.

Aside from topographic effects of elevation, slope, and aspect on *local* climates, major mountain ranges and continental highlands create regional climates through three key processes:

- Orographic interception of global atmospheric circulation (§3.2.4.1)
- Orographic blocking and redirection of air masses (§3.2.4.2)
- Orography crossing altitudinal atmospheric discontinuities (§3.2.4.3)

3.2.4.1 Topographic Interception of Hemispheric Atmospheric Circulation

The topographic interception of moist air masses off oceans creates enhanced precipitation on the windward side and diminished on the lee (rain shadow). This air mass modification intensifies the continentality of interior climates (§3.2.2, re: 'Continental Climates'). Prevailing atmospheric circulation, character of transported air masses, and rain shadow magnitude determine a continent's

[21] Tropical cyclones are known as hurricanes in the Americas, typhoons in East and Southeast Asia.
[22] Mixed forests with mixtures, depending on regional climate, of broadleaf deciduous, broadleaf evergreen, and needleleaf evergreen tress.
[23] A classic example is the Namib Desert in southwest Africa

particular geography of mesic vs. arid climates (Figure 1a). Two key examples, one for the tropics and one the mid-latitudes, are:

Trade Wind Climates – The Trades and a Mountain Front

- Interception of warm moist Trade Winds by continental-coastal or island topography – resulting uplift creates a high precipitation climate.
- These tropical and subtropical wet climates are often disjunct from ITCZ wet climates, separated by inland dry climates.
- Moisture seasonality tied to seasonal shifts in trade wind direction and intensity.
- Tropical to subtropical thermal regimes – with subtropical regions subject to stronger thermal seasonality, with wintertime cold and mid-latitude cyclonic storms.
- Vegetation: Tropical and subtropical seasonal-wet to dry forest.
- Strahler climate type 2: Trade wind littoral (Table 2), NEON neotropical domains: 4, 20 (Figure 2).

Temperate West Coast Wet Climates – Mid-latitude Westerlies and a Mountain Front

- Extensive mountain ranges facing the Mid-latitude Westerlies receive enhanced precipitation, with markedly arid climates in their lee. This is most intense where westerlies are strongest and persist year-round (e.g., British Columbia and the Pacific Northwest).
- Moisture seasonality tied to seasonal shifts in the Westerlies.
- Thermal regime – cool temperate, maritime.
- Vegetation: Temperate rain forests.
- Strahler climate type 7: Marine west coast climate (Table 2), NEON domain 16: Pacific Northwest (Figure 2).

Orographic enhancement may not be restricted to one side of a mountain system – different air masses may characteristically arrive from different directions. The Southern Rockies can, for example, receive moisture from the Pacific, the Gulfs of Mexico and California, or from the Canadian Arctic – each generating a precipitation enhancement and shadow pattern particular to the air mass (Figure 1c).

3.2.4.2 Topographic Barriers and Redirection

While orographic interception significantly alters deep air masses as they pass over (§3.2.4.1), mountain ranges block and steer shallower air masses, such as maritime air or polar/Arctic air capped by strong inversions. For example, shallow (1000 ft or so) Canadian Arctic air masses are blocked or at least impeded by the Rockies' Front Range from Alberta to Colorado, protecting the Pacific Northwest, California Mediterranean, and much of the interior West from the brunt of "Arctic Blasts." In the process, the Rockies keep these fronts in line to meet warm moist Gulf air (§3.2.3.2, re: 'Warm Current, Humid Climates').

3.2.4.3 Atmospheric Vertical Discontinuities – One Mountain, Two Climate Regimes

High elevations often reflect the mechanisms and character of lowland climates, following a topographic gradient of decreasing temperatures and increasing precipitation. The highest elevations in major mountain systems and highlands can, however, reach beyond the level of influence of mechanisms dominating lower climates, resulting in a markedly different regime.

As an example, precipitation ends abruptly on mountains at elevations exceeding the top of a deep, but capped moist layer in the lower troposphere. This is common in tropical coastal and island mountains with tops above the altitude of the marine layer (e.g., 10,000-12,500 ft). Here, extremely dry alpine stands above wet climates – e.g., on Mona Loa, Hawai'i; or for a case more regional in extent, Ecuador and Columbia's Andean páramo.[24]

3.2.5 Up-scale Effects on Global Atmospheric Circulation – Ridging and Lee Cyclogenesis

In addition to their global-to-regional downscale influence on surface climates, continental geometry and orography also have an up-scale effect on atmospheric circulation. In the vicinity of and downstream from a continent, its presence and features modify the intensity and position of the ITCZ, Subtropical Highs, Mid-latitude Jet, and the Polar Vortex (e.g., Ruddiman and Kutzbach 1991, for the Tibetan Plateau). These in turn affect the extent and character of regional climates.

In the conterminous U.S., dynamic interaction of the Jet Stream with the Rocky Mountain massif favors (1) development of a high pressure ridge over the Intermountain West and (2) downstream generation of mid-latitude cyclonic storms (lee cyclogenesis). These effects, respectively, enhance aridity of the West and storm intensity in the central and eastern U.S.

3.3 Landscapes Under a Region's Climate – The Character of Regional Heterogeneity

The concept of regional climate helps us segregate the broader-scale elements of climate from landscape or microhabitat aspects. Because an important feature of regional climates is their within-domain spatial heterogeneity (§2.2), our understanding of regions benefits from a framework for identifying landscape and site factors and how they modify broader controls. Along these lines, Jenne (1941) and Major (1951) presented a factorial approach to understanding soil genesis and vegetation ecology, respectively. They saw regional climate as exerting an overarching control over local dynamics, followed by effects of topography, soil parent material, and biota. It's the interactions of these factors in space and time that create a pattern of microclimates across a landscape, a pattern that tends to be characteristic for a region. Bailey (1996) lays out a similar approach to understanding climatic heterogeneity in ecoregions.

4.0 Temporal Dynamics of Regional Climates

4.1 Characteristic Time Scales

In the discussion of regional climate types and mechanisms (§3.0), emphasis was on mean and seasonal features. However, much of the character of regional climates are at other temporal scales – from hourly to centennial – introduced in the overview of regime properties §2.2. These other time scale-dependent features are also closely tied to global atmospheric regime and continental controls. These features arise because the different processes that define a regime each operate at a characteristic time scale (Figure 3) and have distinguishing longer-term behavior (e.g., multidecadal drought).

Of temporal dynamics that describe a regional climate, I focus here on teleconnections – regional interannual-multidecadal variability linked to hemispheric climate dynamics (§4.2-§4.3). This emphasis is driven by the importance for understanding region-global links in the context of a changing climate.

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[24] For a brief description: http://www.worldwildlife.org/wildworld/profiles/terrestrial/nt/nt1006_full.html

Other key temporal scales for depicting regional climates are:

- Hourly and daily event structure – tied to atmospheric regime, for example:
    - In summer, sporadic localized convective rainfall vs. drizzle of coastal fog (Strahler climates 9 vs. 4, Table 2)
    - Rapid spring thaws and winter blizzards (such as for Strahler climate type 10, Table 2).
- Seasonality – variance in annual cycle, for example, by:
    - Subregions (e.g., Greater Yellowstone Science Learning Center 2008)
    - Decade (e.g., Kittel et al. 2008)
- Historic climate trends – across multiple variables, seasons, subregions
- Multidecadal to millennial regime shifts – e.g., Neilson and Wullstein 1983, Woodhouse & Overpeck 1998 (cf. §2.2)

4.2 Interannual Variability Patterns – Hemispheric Teleconnections[25]

Teleconnections are dynamic ties between local climate variability and remote hemisphere-scale atmospheric and ocean processes. Such linkages are fundamental to our understanding the roots of regional interannual climate variability and to exploring the mechanisms by which hemispheric processes scale down to the ecology of species and landscapes (Stenseth and Mysterud 2005).

Predominate teleconnections for North America have their source in four major interannual to multidecadal oscillations of the climate system. Two oscillations are in the Pacific, two in the Atlantic – within these, one is multiyear, the other multidecadal:

El Niño-Southern Oscillation (ENSO) – A roughly 3-7 year oscillation in sea surface temperatures (SST) and sea level pressure (SLP) in the tropical Pacific (Trenberth 1997; Table 4). Components are:

- El Niño refers to a period of anomalously warm SST off Peru and Ecuador, extending west across the equatorial Pacific – the cold phase is referred to as La Niña.
- Linked to sea surface change is a swing in SLP, the Southern Oscillation, between western and eastern tropical Southern Pacific – representing a cross-basin exchange of air mass. As part of this oscillation, decreasing pressures in the South Pacific Subtropical High reduces the strength of the corresponding Trades, the ITCZ, and upwelling associated with the Humboldt Current (resulting in warm El Niño conditions).
- El Niño teleconnections are global. For North America, El Niño conditions are tied to higher winter precipitation in the American Southwest and warmer Pacific Northwest winters.
- North American teleconnections are dependent on Pacific Decadal Oscillation phase.

Pacific Decadal Oscillation (PDO) – Multidecadal oscillation in North Pacific SST north of 20ºN (Mantua et al. 1997;[26] Table 4). Features:

- 'Warm phase' has warm SST in the northeast Pacific, but cold in central and western North Pacific – the cold phase has the opposite pattern. Warm and cold phases generally persist for 20-30 years (50-70 yr oscillation).[27] Since mid-1990's, in a warm phase.
- The PDO reflects major North Pacific climate regime shifts – in the past century these were in 1924 (to warm phase), 1946 (to cold), and 1976 (to warm). Over the last couple of

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[25] Material in §4.2 and 4.3 adapted from Kittel (2008).

[26] See: http://www.atmos.washington.edu/~mantua/REPORTS/PDO/PDO_cs.htm

[27] There's an additional power spectra peak at 15-25 yr. (Minobe, S. 1997: A 50-70 year climatic oscillation over the North Pacific and North America. *Geophys. Res. Letters* 24: 683-686; Minobe, S. 1999: Resonance in bidecadal and pentadecadal climate oscillations over the North Pacific: Role in climatic regime shifts. *Geophys. Res. Letters* 26: 855-858.)

decades, the PDO index has switched back and forth in sign – consequently, it's not clear if the PDO is in the process shifting to a cold phase, or in a lull within the warm phase.

- The PDO is inversely coordinated with the *North Pacific Index oscillation (NPI),* sea level pressure changes in the Aleutian Low Pressure Center (Trenberth and Hurrell 1994). During the warm PDO phase (warm SST in the northeast Pacific), cold SST's in the central North Pacific deepen the Aleutian Low (negative NPI). Stronger south winds around the east side of the Low supports the incursion of warm waters off the Pacific Northwest coast and into the Gulf of Alaska.
- North American teleconnections: Warm phase PDO gives warmer winter temperatures from Alaska, the Pacific Northwest, through central western Canada, and colder in the Southeast. During the warm phase, the deeper (and more eastward) Aleutian Low sends the winter Mid-Latitude Jet to the south – so that the American Southwest and northern Mexico are wetter and southern Canada and northern tier U.S. drier.

North Atlantic Oscillation (NAO) – A 6-10 year oscillation[28] in SLP in the North Atlantic between the Icelandic Low and Azores Subtropical High (Hurrell et al. 2003; Table 4).

- In positive NAO years, the gradient between the Icelandic Low and Azores High is strong, intensifying the strength of the Mid-Latitude Jet over the North Atlantic. The strength of these pressure centers and the Jet are reduced in negative NAO years.
- The NAO dynamics are considered part of the *Northern Annular Mode (NAM)* oscillation, also referred to as the Arctic Oscillation (AO; Thompson and Wallace 2000).
- Strongest teleconnections are downstream in Europe, yet North America still experiences significant effects. In positive NAO years, strengthened wintertime circulation around the west side of the Azores High brings wet mild conditions from the tropics to the eastern U.S., that around the Icelandic Low draws cold dry Arctic air into northeastern Canada.

Atlantic Multidecadal Oscillation (AMO) – Multidecadal oscillation in North Atlantic SST (Schlesinger and Ramankutty1994; Table 4). Features:

- Equatorial to subarctic North Atlantic SST oscillates in unison in this long-period dynamic. Cold and warm phases generally persist for 20-40 years (65-70 yr oscillation). Since mid-1990's, in a warm phase.
- U.S. teleconnections include: Warm phase AMO tends to bring drought to the Midwest and Southwest, wetter conditions to Florida and Pacific Northwest, and greater frequency of severe Atlantic hurricanes. However, these AMO teleconnections depend on PDO phase (McCabe et al. 2004).[29]

These climate system oscillations have characteristic centers of action, as just described, typically in places where there is strong coupling between the ocean and atmosphere. These centers are quasistationary, constrained by ocean basin geometry and basin-wide ocean circulation. The centers have characteristic quasiperiodic, multiyear modes of behavior in ocean and atmospheric measures (e.g., SST, SLP). The oscillations are controlled by long-acting, geographically-broad interactions between atmospheric and ocean circulations and run deep in both systems. For overviews of these oscillation systems, their centers of action, temporal dynamics, and teleconnections, see Stenseth et al. (2003), Steward (2005),[29] and online resources (Table 4).

Teleconnections operate as downstream consequences of center-of-action changes in the location and strength of warm and cool pools of ocean water, and of semipermanent high and low pressure systems in

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[28] J.W. Hurrell and H. van Loon. 1997. Decadal variations in climate associated with the North Atlantic Oscillation. *Climatic Change*, 36:301-326, 1997.

[29] See Steward (2005): http://oceanworld.tamu.edu/resources/oceanography-book/oceananddrought.html

the lower troposphere. The consequences are shifts in the position and intensity of the Intertropical Convergence Zone, Mid-latitude Jets, and Subtropical and Polar Vortex – and so of tropical and mid-latitude storm tracks, summer monsoons, winter advection of warm or cold, moist or dry air masses, and of the stability of the marine layer – all factors that define our climate regimes (e.g., Dai et al. 1998, Castro et al. 2001, McCabe et al. 2004).

4.3 Properties of Circulation Oscillations and Their Teleconnections

Circulation indices offer us the opportunity to understand linkages from global to local dynamics. Exploring this scale translation and seeking mechanisms in interpretation requires insights into the nature of circulation oscillations.

Certain features of oscillations help us understand how their teleconnections work:

Dynamics at centers of action fluctuate seasonally. In the extratropics, the strongest signal-to-noise ratio is commonly in winter, giving the strongest teleconnections.[30] However, this depends on local dynamics – e.g., teleconnections are strongest in summer for the North American summer monsoon (Castro et al. 2001).

Teleconnections are strongest during the strongest periods of opposite oscillation phases. The teleconnection signal during weaker states is usually swamped by other climate system signals and too diminished by distance.

Circulation oscillations over different ocean basins interact in the generation of teleconnections. This leads to conditional teleconnections, where the phase of one oscillation influences the downstream expression of another (e.g., McCabe et al. 2004, as noted earlier[29]).

Oscillation indices track climate dynamics of broad regions of the globe, with strong spatiotemporal coherence across many variables. Stenseth and Mysterud (2005) layout a conceptual framework for how these hemispheric, seasonal, multivariate indices present an integrated view of climate that setups local conditions for a season or longer in ways that can have as much power in explaining ecological dynamics as do analyses of local weather (Forchhammer and Post 2004).

Additional considerations in scale linkages to landscapes and species are:

Local conditionality – How the same teleconnection forcing gets played out across landscapes and regions can be conditional on geographic features such as aspect, altitude, and latitude. This is especially the case if teleconnections affect where a weather threshold, such as a storm's snowline, crosses your domain (Stenseth and Mysterud 2005).

Ecological indirect effects – In evaluating linkages to ecological dynamics (skipping over local climate), keep in mind that some consequences of circulation teleconnections may be indirect or with strong lags, arising from population and ecosystem (trophic) dynamics and from geographic linkages (e.g., for regional or hemispheric migrants) (Forchhammer and Post 2004).

Important caveats and common pitfalls in teleconnection analyses include:

Responses nonlinear. Within a given oscillation's phase, teleconnections are not expressed the same way in each occurrence at a location. Teleconnections may in fact change sign at lower forcings than at higher one within the same oscillation phase. This is because oscillation dynamics often shift

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[30] For an example from the Pacific Northwest, see http://www.cses.washington.edu/cig/pnwc/clvariability.shtml, Figures 1 and 3.

the latitudinal position of, for example, storm tracks more into a region and with more intense teleconnection shifting systems more the same direction but now out of the region.

Responses nonstationary. Teleconnections also appear to change with time. As noted, some of such nonstationarity can be attributed to behavior conditional on the phase of other oscillation systems. Aside from such conditionality, teleconnections may not have held throughout the historical record nor persist in the future.

Prediction. Much attention has been given to the prospect of predicting local climate and ecological dynamics based on teleconnections. While teleconnections may be found with local dynamics may be statistically significant, the percent variance explained may put into question the utility of the relationship for prediction.[31] Low variance explained comes from two sources: (1) nonlinearity, non-stationarity, and indirect effects that reduce detection, and (2) that circulation dynamics is only part of the story. We recognize the problems of proxies: (1) centers of action for oscillations are much removed and the signal is altered in transit by downstream climate processes and (2) other, independent, local factors also control local climate and ecological behavior.

5.0 Summary

This report provides a framework for understanding broad-scale controls over and dynamics of a region's climate. The basis for this lies in:

(1) Regional climates can be described in terms of spatially and physically coherent regimes – a set of features and generating processes that distinguish its climate (§2.0, §3.0; Table 2).

(2) These regimes also have characteristic temporal dynamics across a wide range of meteorological and climatic time scales (§4.0; Figure 3 and caption).

(3) Such regimes have their foundation in global and continental processes (§3.1, §3.2; Figure 1).

(4) Regional influence on local climates is modified by a landscape's topography, soil origins, and biota with time (§3.3). Broad-scale controls are nonetheless strong, and the pattern of microclimates across a landscape tends to be characteristic for a region.

(5) Among a region's temporal dynamics, teleconnections are key – expressing region-specific linkages to global processes (§4.2-4.3).

For these reasons, climate regions provide a useful construct for organizing and interpreting climate data across the NPS I&M Network. This report recommends the NEON domains (Figure 2) as well suited to serve the Network (§2.3). Finally, the report's framework provides a guide for generating overviews surveying U.S. regional climates to support this Network activity.

[31] It is not unusual for teleconnections to have highly significant regressions, say $p<0.01$, but with low R^2's (fraction variance explained), such as <0.30.

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Tables and Figures

Table 1. Climate and related variables used in the development of the NEON Domains (see text §2.3 and Figure 2). While soil water holding capacity is not a climate measure *per se*, it influences how drought prone a site is. (Adapted from Hargrove, W.W., 2006: http://www.geobabble.org/~hnw/neon/withindomainrep/table.html).

Factor Type	Variable	Seasonal Qualifier
Thermal	Number of days above 90°F (82ºC)	During the local growing season
	Number of days below 32°F (0ºC)	During the local non-growing season
Precipitation	Precipitation sum	During the local growing season
	"	During the local non-growing season
	Number of days with measurable precipitation	During the local growing season
	"	During the local non-growing season
Soil moisture capacity	Soil plant-available water holding capacity to 1.5 m	N/A
Insolation	Total solar insolation – accounting for clouds, aerosols, slope, and aspect physiography	During the local growing season
	"	During the local non-growing season

N/A = not applicable

Table 2. Strahler's (1969) climate classification system based on global circulation mechanisms (see text §2.2). Highest level of organization is by low, mid-, and high latitude zones for low and mid-elevation climates. Regions are then discriminated by relative dominance of the Intertropical Convergence Zone (ITCZ), subtropical high pressure centers, mid-latitude cyclonic storms, high latitude frontal zones, and polar and Arctic air mass sources (§3.1). Highland climates are treated as a separate group (§3.2.4). (Table derived from text in Barry and Chorley 2003).

Identifier	Climate Type	Latitudinal Band	Fundamental Mechanisms and Characteristics*†
(A) Low-latitude climates controlled by equatorial and tropical air masses			
1	Wet equatorial climate	10°N to 10°S Asia 20°N to 10°S	Converging equatorial and mT* air masses produce heavy convectional rains; uniform temperature.
2	Trade wind littoral climate	10º to 25°N and S	High-sun† trade winds alternate seasonally with subtropical high pressure; strong seasonality of rainfall, high temperatures.
3	Tropical desert and steppe	15° to 35°N and S	Dominance of subtropical high pressure gives low rainfall and high maximum temperatures with moderate annual range.
4	West coast desert climate	15° to 30°N and S	Dominance of subtropical high pressure. Cool seas maintain low rainfall with fog and small annual temperature range.
5	Tropical wet-dry climate	5° to 15°N and S	High-sun wet season, low-sun† dry season; small annual temperature range.
(B) Mid-latitude climates controlled by both tropical and polar air masses			
6	Humid subtropical climate	20° to 25°N and S	High-sun moist mT air and low-sun cyclones give well-distributed annual rainfall with moderate temperature regime.
7	Marine west coast climate	40° to 60°N and S	Windward coasts with cyclones all year. Cloudy; well-distributed rainfall with low-sun maximum.
8	Mediterranean climate	30° to 45°N and S	Hot, dry summers associated with the subtropical highs alternate with winter cyclones bringing ample rain.
9	Mid-latitude continental desert and steppe	35° to 50°N and S	Summer cT air alternates with winter cP air.* Hot summers and cold winters give a large annual temperature range.
10	Humid continental climate	35° to 60°N	Central and eastern continental locations. Frontal cyclones. Cold winters, warm to hot summers, large annual temperature range. Well distributed precipitation.
(C) High-latitude climates controlled by polar and Arctic air masses			
11	Continental sub-Arctic climates	50° to 70°N	Source region for cP air. Very cold winters, short, cool summers, extreme annual temperature range. Year-round cyclonic precipitation.
12	Marine sub-Arctic climate	50° to 60°N and 45° to 60°S	Dominated by the winter Arctic frontal zone. Cold, moist winters, cool summers; small annual temperature range.
13	Polar tundra climates	N of 55°-60°N S of 60°S	Arctic coastal margins dominated by cyclonic storms. Humid and cold, moderated somewhat by maritime influences in winter.
14	Ice sheet climates	Greenland and Antarctica	Source regions of Arctic and Antarctic air. Perpetual frost, low snowfall except near coasts.
(D) Highland climates – localized and varied in character.			

* Air mass abbreviations: mT = maritime tropical, cT = continental tropical, cP = continental polar.
† High-sun and low-sun seasons generally correspond to higher-latitude summer and winter, but are used here because of the ambiguity of these terms in the low latitudes. Cyclones refer to mid-latitude cyclonic storms associated with frontal systems (vs. tropical cyclones, such as hurricanes)

Table 3. Online resources for near-real time regional context: monitoring and outlooks products. (See text §2.4.2). (Modified from Kittel 2008)

Source	Web Entry Point*
NOAA Regional Climate Centers	http://www.wrcc.dri.edu/rcc.html ▪ e.g., for Western U.S. – http://www.wrcc.dri.edu/CLIMATEDATA.html
NOAA Climate Prediction Center	http://www.cpc.ncep.noaa.gov/ – Climate monitoring U.S., Pacific Islands, Global: ▪ http://www.cpc.ncep.noaa.gov/products/monitoring_and_data/ ▪ http://www.cpc.ncep.noaa.gov/products/precip/CWlink/
NOAA National Climate Data Center	http://www.ncdc.noaa.gov/ ▪ http://www.ncdc.noaa.gov/oa/climate/research/monitoring.html ▪ http://lwf.ncdc.noaa.gov/oa/climate/research/cag3/cag3.html
National Integrated Drought Information System	http://www.drought.gov/ ▪ National Drought Mitigation Center – http://drought.unl.edu/
Natural Resource Conservation Service	Snow course maps – http://www.wcc.nrcs.usda.gov/snowcourse/
Western Water Assessment	http://wwa.colorado.edu/ ▪ http://wwa.colorado.edu/forecasts_and_outlooks/forecasts.html
State Climatologists	http://www.stateclimate.org/ ▪ e.g., for Wyoming http://www.wrds.uwyo.edu/sco/climate_office.html ▪ e.g., state climate narrative for Illinois - http://www.isws.illinois.edu/atmos/statecli/General/Illinois-climate-narrative.pdf .
Other regional sources	Northern Great Plains and Rocky Mountains – http://www.umac.org/environment/climate/ihe ndex.html

* For additional listings, see: http://wwa.colorado.edu/forecasts_and_outlooks/ics_srcs.html

Table 4. Major teleconnection patterns for United States and territories and online entry-point resources with descriptions and maps. Oscillation abbreviations are given in the text §4.2. (From Kittel 2008)

Teleconnection Pattern*†	Web Resources
ENSO teleconnections	▪ http://www.cru.uea.ac.uk/cru/info/enso/ ▪ http://www.cdc.noaa.gov/ENSO/ – o http://www.cdc.noaa.gov/ENSO/enso.climate.html o http://www.cpc.ncep.noaa.gov/products/precip/CWlink/ENSO/composites/ US by climate region and state – o http://www.cpc.ncep.noaa.gov/products/monitoring_and_data/ENSO_connections.shtml US: for climate extremes – o http://www.cdc.noaa.gov/Climaterisks/ o http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/lanina/us_impacts/ustp_impacts.shtml ▪ http://www.cses.washington.edu/cig/pnwc/aboutenso.shtml o See *PDO teleconnections* for combined PDO & ENSO effects ▪ http://jisao.washington.edu/analyses0500/#enso
PDO & NPI teleconnections	▪ http://www.atmos.washington.edu/~mantua/REPORTS/PDO/PDO_cs.htm; also Mantua et al. (1997) ▪ http://www.cses.washington.edu/cig/pnwc/aboutpdo.shtml o Combined PDO & ENSO effects – ▪ http://www.cses.washington.edu/cig/pnwc/clvariability.shtml ▪ http://www.cses.washington.edu/cig/pnwc/compensopdo.shtml ▪ http://jisao.washington.edu/analyses0500/#pdo ▪ http://www.beringclimate.noaa.gov/data/BCinclude.php?filename=in_PDO ▪ See *AMO teleconnections* for combined AMO & PDO effects ▪ NPI: see Trenberth & Hurrell 1994, Hurrell 1996
NAM/AO & NAO teleconnections	▪ http://jisao.washington.edu/analyses0500/#ao ▪ http://www.cpc.ncep.noaa.gov/data/teledoc/nao.shtml ▪ http://nsidc.org/arcticmet/patterns/arctic_oscillation.html ▪ http://www.ldeo.columbia.edu/res/pi/NAO/ ▪ http://www.cru.uea.ac.uk/cru/info/nao/
AMO teleconnections	▪ http://oceanworld.tamu.edu/resources/oceanography-book/oceananddrought.html o Includes combined AMO & PDO effects; also McCabe et al. (2004) ▪ http://www.aoml.noaa.gov/phod/amo_faq.php
Other Major Teleconnection Patterns –	▪ http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml
East Atlantic (EA)	
West Pacific (WP)	
East Pacific-North Pacific (EP-NP)	▪ http://jisao.washington.edu/analyses0500/#pna
Pacific/North American (PNA)	▪ http://jisao.washington.edu/data_sets/pna/
Tropical/Northern Hemisphere (TNH)	
Pacific Transition (PT)	

* For creating custom teleconnection correlation maps, see: http://www.cdc.noaa.gov/Correlation/.
† For a glossary of terms related to circulation oscillations and teleconnections, see http://www.ucar.edu/news/backgrounders/patterns.shtml

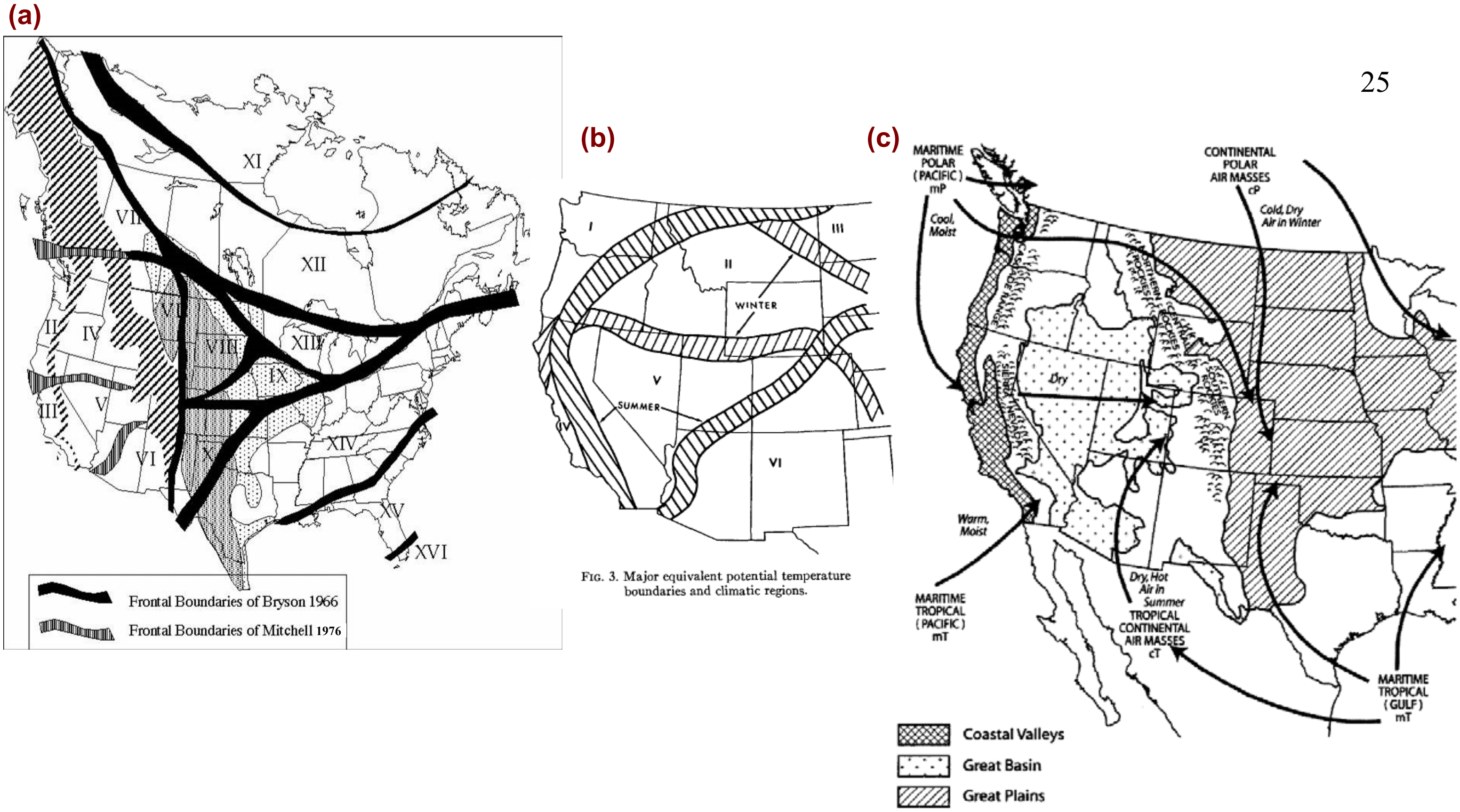

Figure 1. (a) Characteristic air mass boundaries across the conterminous U.S. and Canada, as described by Bryson (1966) and Mitchell (1976).[33] Heavy diagonal hatching indicates major mountain systems, dense and open stippled areas are short and tall grasslands in the Central U.S. (b) Mitchell's (1976) original layout, showing that some regimes boundaries are set by winter frontal positions and other by summer fronts. (c) Air masses source areas and flow patterns influencing climates of the western U.S. (Kittel et al. 2002).[34] Roman numerals in (a, b) indicate climate regimes delineated by these boundaries (numbering differs for the two figures). Those for (b) follows; compare this description to (c), showing air mass source areas and flow patterns:

> "Region I is characterized by the frequent intrusion of air masses from the Pacific during winter and during much of the summer. Region II also is affected by the frequent intrusion of Pacific air masses during the winter, but is under the influence of what might be called interior air during the summer. Region III is dominated by interior air in the summer but a frequent exchange of air masses from the Pacific and the Arctic occurs during winter.
>
> "Regions IV, V and VI have winters characterized by infrequent intrusion of Pacific air during the winter, but each has its own characteristic summer control. Region IV is under the influence of Pacific air during the summer as well as during the winter, whereas Region V is under the influence of interior air during the summer. Region VI has a summer rainy season brought by the influx of monsoon air from the Gulf of Mexico and the Gulf of California." (Mitchell 1976)

(Link to initial text reference: §2.2)

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[33] Image from Hayden, B (2005) "NEON – Past, Present and Future" PowerPoint presentation. ESA Annual meeting, Montreal, Canada. (http://www.neoninc.org/documents/ESA05/ESA05-02Hayden.ppt).

[34] Original graphic from A. Benedict and B. Bash, 1991, *A Sierra Club Naturalist's Guide to The Southern Rockies* Sierra Club Books, San Francisco, 578 p.)

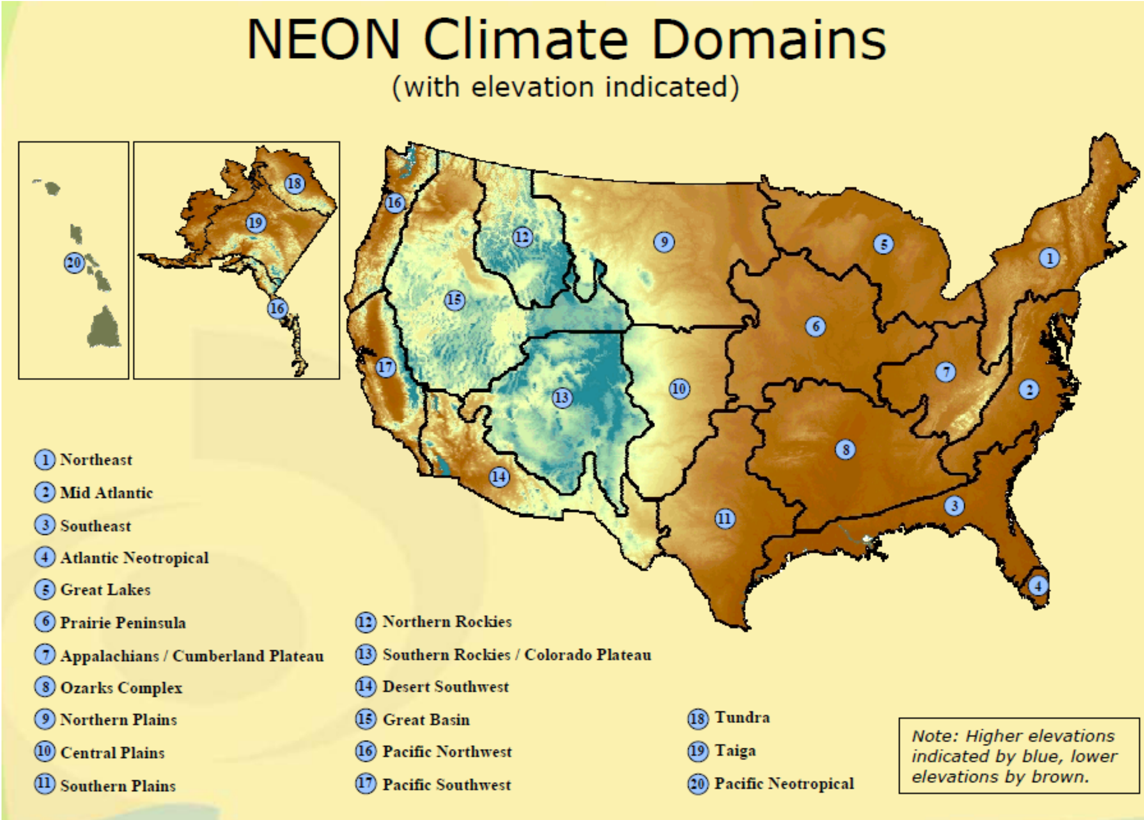

Figure 2. NEON[35] domains based on multivariate analysis of 9 climate and related environmental variables (Table 1), air mass boundaries (Figure 1), and expertise (Hargrove and Hoffman 2004, 2006).[36,37] These domains are recommended to serve as I&M climate regions (see text §2.3).

[35] NEON = National Ecological Observatory Network
[36] Image source: http://www.neoninc.org/documents/neon_map/NEONDomainsSlide_v1.3.pdf
[37] For analysis methodology, see also http://www.geobabble.org/~hnw/borders/

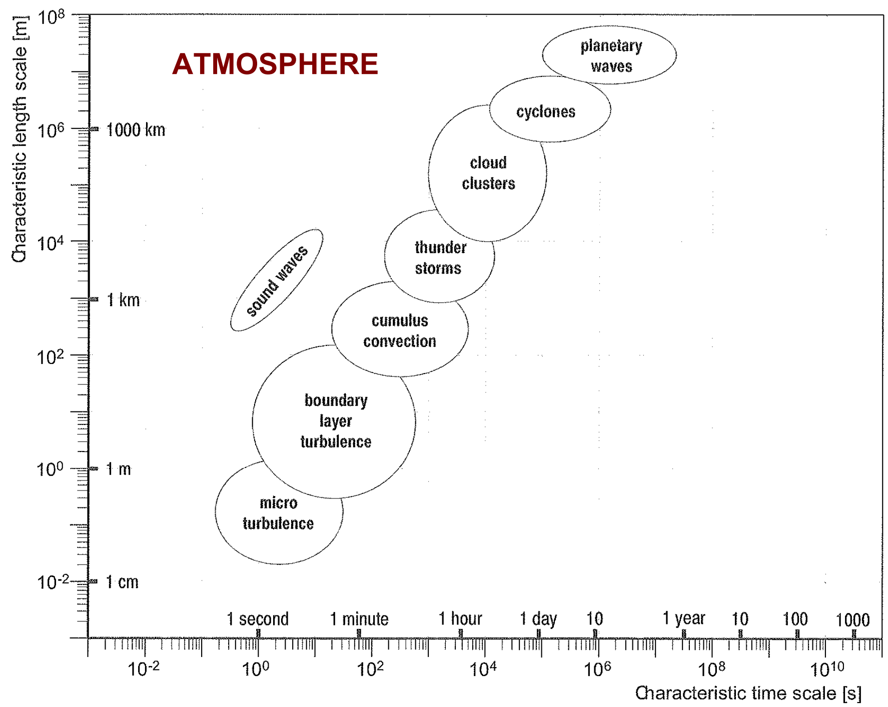

Figure 3. The relationship between characteristic temporal and spatial scales for weather-related processes (time scales ≤1 year; von Storch and Zwiers 2002). Climate processes arise from interactions among earth system components and forcings, resulting in behavior over longer periods and broader domains – including interannual-site, decadal-regional, and centennial-continental dynamics. (Links to text §2.4.1, §4.0)