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A Discriminant Analysis Model of Alaskan Biomes Based on Spatial Climatic and Environmental Data

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ABSTRACT. Classification of high-latitude landscapes into their appropriate biomes is important for many climate and global change-related issues. Unfortunately, large-scale, high-spatial-resolution observations of plant assemblages associated with these regions are generally unavailable, so accurate modeling of plant assemblages and biome boundaries is often needed. We built different discriminant analysis models and used them to "convert" various combinations of spatial climatic data (surface temperature and precipitation) and spatial environmental data (topography, soil, permafrost) into a biome-level map of Alaska. Five biomes (alpine tundra and ice fields, Arctic tundra, shrublands, boreal forest, and coastal rainforest) and one biome transition zone are modeled. Mean annual values of climatic variables were less useful than their annual extrema in this context. A quadratic discriminant analysis, combined with climate, topography, permafrost, and soil information, produced the most accurate Alaskan biome classification (skill = 74% when compared to independent data). The multivariate alteration detection transformation was used to identify Climatic Transition Zones (CTZs) with large interannual variability, and hence, less climatic consistency than other parts of Alaska. Biome classification was the least accurate in the CTZs, leading to the conclusion that large interannual climatic variability does not favor a unique biome. We interpret the CTZs as "transition biome areas" or ecotones between the five "core biomes" cited above. Both disturbance events (e.g., fires and subsequent plant succession sequences) and the partial intersection of the environmental variables used to characterize Alaskan biomes further complicate biome classification. Alaskan results obtained from the data-driven quadratic discriminant model compare favorably (based on Kappa statistics) with those produced by an equilibrium-based biome model for regions of Canada ecologically similar to the biomes we studied in Alaska. Climatic statistics are provided for each biome studied.

Key words: Arctic, Alaska, biome, vegetation, climate, climatic transition zones, classification, discriminant analysis, fires, climographs, boreal forest, coastal rain forest, alpine tundra, shrublands, Arctic tundra, ecotone

RÉSUMÉ. Le classement des paysages de hautes latitudes dans les biomes adéquats revêt de l'importance dans le cadre de nombreux enjeux relatifs aux changements climatiques et à d'autres changements d'envergure mondiale. Malheureusement et en règle générale, il n'existe pas d'observations spatiales de haute résolution et à grande échelle pour ce qui est des assemblages de végétaux pour ces régions. C'est pourquoi il faut souvent procéder à la modélisation des assemblages de végétaux et des limites des biomes. Nous avons élaboré différents modèles d'analyses discriminantes dont nous nous sommes servis pour « transformer » divers ensembles de données climatiques spatiales (température de la surface et précipitation) et diverses données sur l'environnement spatial (topographie, sol, pergélisol) en carte des biomes de l'Alaska. La modélisation porte sur cinq biomes (toundra alpine et champs de glace, toundra arctique, arbustaie, forêt boréale et forêt pluviale côtière) et sur une zone de transition de biome. Les valeurs moyennes annuelles des variables climatiques ont été moins utiles que leurs extremas annuels dans ce contexte. Une analyse discriminante quadratique, combinée aux données relatives au climat, à la topographie, au pergélisol et au sol, a permis d'aboutir au classement de biomes alaskiens le plus précis (habileté = 74 % lorsque comparé aux données indépendantes). Nous avons recouru à la transformation de la détection de l'altération à variables multiples (*multivariate alteration detection transformation*) pour identifier les zones de transition climatique (ZTC) ayant une importante variabilité interannuelle et, par conséquent, une moins grande uniformité climatique que d'autres parties de l'Alaska. Le classement des biomes était moins précis dans les ZTC, ce qui nous a amenés à conclure que l'importante variabilité climatique interannuelle ne favorise pas un biome unique. Nous interprétons les ZTC comme des « régions de biomes de transition » ou des écotones entre les cinq « biomes principaux » dont il est question ci-dessus. Les deux perturbations (c'est-à-dire les incendies et les séquences subséquentes des végétaux) et l'intersection partielle des variables environnementales utilisées pour caractériser les biomes alaskiens compliquent davantage le classement des biomes. Les résultats alaskiens obtenus à partir du modèle discriminant quadratique dérivant des données se comparent favorablement (en fonction des statistiques kappa) à ceux obtenus par un modèle de biome en équilibre pour des régions du Canada similaires du point de vue écologique aux biomes que nous avons étudiés en Alaska. Des statistiques climatiques sont fournies pour chaque biome étudié.

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Mots clés : Arctique, Alaska, biome, végétation, climat, zones de transition climatique, classement, analyse discriminante, incendies, climogrammes, forêt boréale, forêt pluviale côtière, toundra alpine, arbustaie, toundra arctique, écotone

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INTRODUCTION

A biome can be defined as a major regional or global biotic community, such as a grassland or desert, characterized chiefly by the dominant forms of plant life and the prevailing climate. Here, we discuss Alaskan biomes in the context of their response to both global and regional climate change processes. To clearly identify bioclimate subzones within the Arctic bioclimate zone, we use the nomenclature of the Circumpolar Arctic Vegetation Map project (Walker et al., 2005). Some of the Alaskan biomes discussed occur within the Arctic bioclimate zone.

High-Latitude Global and Regional Climate-Change Processes

High-latitude biomes, partially characterized by frozen or seasonally frozen ground, large carbon stores, and extensive areas of poorly aerated soils (Hobbie and Trumbore, 2000; Walker, 2000), are coupled to regional climate through albedo and water/energy fluxes and to global climate through the fluxes of the greenhouse gases, CO_2 and CH_4 (Chapin et al., 2000). The biogeochemical processes that control the Arctic carbon budget, however, are very sensitive to changes in soil temperature and moisture (Oechel et al., 1993). These important soil parameters can be significantly altered by either regional climate change (Chapman and Walsh, 1993; Kaplan et al., 2003) or vegetation redistribution (Smith and Shugart, 1993), or both.

The effects of climate change in the Arctic include higher air temperatures (Chapman and Walsh, 1993), increased precipitation (Kattenburg et al., 1996), and degradation of permafrost (Jorgenson et al., 2001). These changes have direct effects on Arctic biomes, such as enhanced photosynthesis by Arctic plants (Oechel and Billings, 1992), and colonization by tall woody plants (shrub-tundra, forest-tundra) into areas of warmer, better drained soils resulting from degrading permafrost (Rovansek et al., 1996; Lloyd et al., 2003a, b). But they also have indirect effects, such as increased nutrient mineralization rates (Nadelhoffer et al., 1992; Epstein et al., 2000). Climate warming-induced changes in vegetation, permafrost, and soils can also significantly affect regional landscape processes such as fire spread, seed dispersal, and feedback to climate (Chapin et al., 2000; Rupp et al., 2000a, b, 2001). Clearly, there is a dynamic interplay between climate, vegetation, topography, permafrost, and soils (Hare and Richie, 1972; Laberge and Payette, 1995; Pielke and Vidale, 1995; Lynch et al., 1999; Suarez et al., 1999).

High-Latitude Biomes

Alaska can be divided into three major bioclimate zones: 1) the Arctic Bioclimate Zone; 2) the Subarctic Bioclimate Zone; and 3) the Coastal Rainforest Bioclimate Zone. The Circumpolar Arctic Vegetation Map (CAVM) project (Walker et al., 2005), following the approach of the Pan Arctic Flora initiative (Elvebakk, 1999), defined the Arctic to be equivalent to the Arctic Bioclimate Zone, a region with tundra vegetation, an arctic climate (cold winters, cool summers, precipitation in most areas is low [< 50 cm] and mostly comes in the form of snow) and arctic flora (low growing plants such as dwarf shrubs, sedges, graminoids, herbs, lichens, and mosses, scattered grasses and forbs that form arctic tundra) and with the treeline taken as its southern limit. In this context, CAVM (Walker et al., 2005:268) adopted a definition of tundra from Gabriel and Talbot (1984): "Low growing vegetation beyond the cold limit of tree growth both at high elevation (alpine tundra) and at high latitude (arctic tundra)." Thus, tundra regions with no arctic flora (e.g., the Aleutian Islands, which have boreal flora) are excluded. The climate of the Aleutian Islands is oceanic, with relatively moderate and fairly uniform temperatures and heavy rainfall. Likewise, alpine tundra regions south of the latitudinal treeline are excluded.

CAVM divides the Arctic Bioclimate Zone into five bioclimate subzones (A–E) based on a combination of summer temperature and vegetation (Walker et al., 2005). Subzone A is the northernmost, coldest, smallest (only 2% of the non-glaciated Arctic) and the most barren subzone. Subzone E is the southernmost, warmest, largest (36%) and the most vegetated. Historically, in North America, the Arctic has been divided into two parts (e.g., Bliss, 1997): the High Arctic (corresponds to CAVM subzones A, B, and C); and the Low Arctic (subzones D and E). Fewer barrens and glaciers, more lakes and wetlands and more diverse vegetation occur moving south from subzone A to subzone E. Taller shrubs and more dense moss mats also occur in the south, notably in subzones D and E. Subzones A (< 5% cover of vascular plants, up to 40% cover by mosses and lichens), B (5–25% cover of vascular plants, up to 60% cover of cryptogams) and C (5–50% cover of vascular plants) are characterized by more open and very low-stature vegetation found mostly on mineral soils. Subzone D (50–80% cover of vascular plants) is characterized as interrupted closed vegetation, while subzone E (80–100% cover of vascular plants) is referred to as closed canopy. Subzones D and E occur mostly on peat-rich soils. See Walker et al. (2005) for more detailed characterizations.

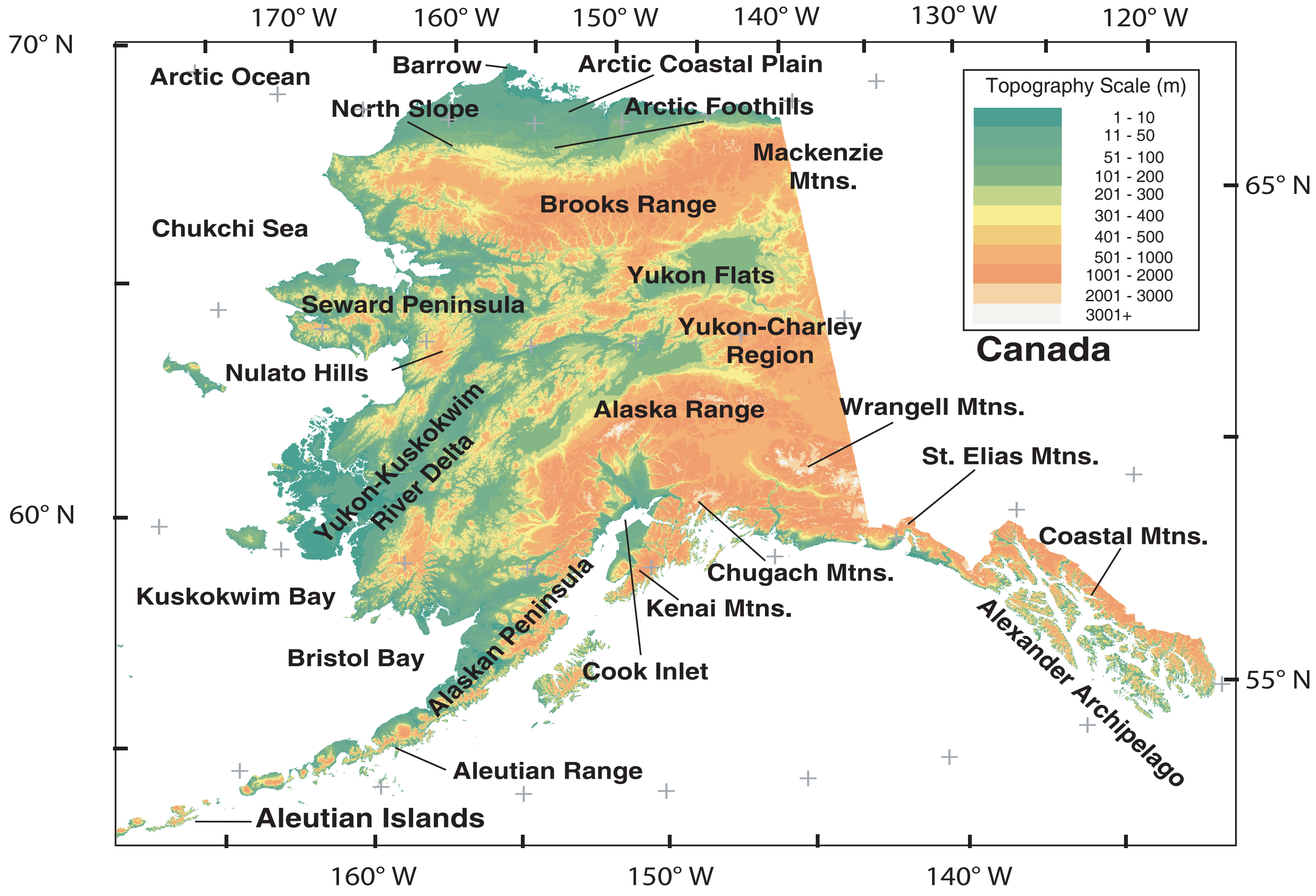


FIG. 1. Topographic map of Alaska, showing location of mountain ranges and place-names cited in the text.

Subzones A and B do not occur in Alaska. Subzones D and E comprise most of Arctic Alaska, except for a narrow strip along its northern coast, where subzone C is found (see Walker et al., 2003: Plate 1 insert). The southern boundaries of these subzones correspond approximately to the isotherms for mean July surface temperatures of 7˚C (Subzone C), 9˚C (Subzone D), and 12˚C (Subzone E) (Raynolds et al., 2005; Walker et al., 2005). Walker et al. (2005) give a concise summary of Alaskan Arctic vegetation. The most abundant vegetation types occur in the wetlands (sedge grass, moss wetlands; sedge, moss dwarf-shrub wetlands; moss low-shrub wetlands), which are concentrated near the Yukon-Kuskokwim River delta and the Arctic Coastal Plain (Fig. 1). Tussock-sedge, dwarf-shrub, and moss tundra occur in the Arctic Foothills of the Brooks Range and the central portion of the Seward Peninsula. Both non-carbonate and carbonate mountain complexes occur within the Brooks Range. A more detailed plant community–level mapping of Arctic Alaska, compatible with the larger-scale CAVM map, is given by Raynolds et al. (2005).

The Subarctic (also referred to as Boreal) Bioclimate Zone has a continental climate characterized by long, very cold winters; brief, warm summers; and relatively low precipitation (e.g., Hare and Richie, 1972; Bonan et al., 1995). Cold acidic soils limit nutrient availability for vegetation growth, and permafrost occurs under large areas of the active layer. The most dominant tree species are conifers. White spruce and balsam poplar develop riparian forest along rivers and large streams. Black spruce, tamarack, and shrub/moss wetlands grow on cold lowlands; birch and spruce are found on north-facing slopes; and aspen and birch form deciduous stands on well-drained southern exposures. Fire is a major disturbance factor in the boreal biome (e.g., Gardner et al., 1996, 1999; Rupp et al., 2002). For a more detailed discussion of the Alaskan boreal forest biome, see Bonan et al. (1995), Chapin et al. (2000), and Baldocchi et al. (2000).

The Alaskan Coastal Rainforest Bioclimate is largely determined by proximity to the ocean (Fleming, 1997). Precipitation is very high and temperatures are relatively warm, and the annual temperature range is small compared to its boreal counterpart (see Simpson et al., 2002: Fig. 12). Here, fires occur infrequently. In Alaska, the coastal temperate rainforest grows on the south flanks of the Coastal Alaska Range, the Chugach Mountains, and the islands of the Alexander Archipelago (Figs. 1 and 2).

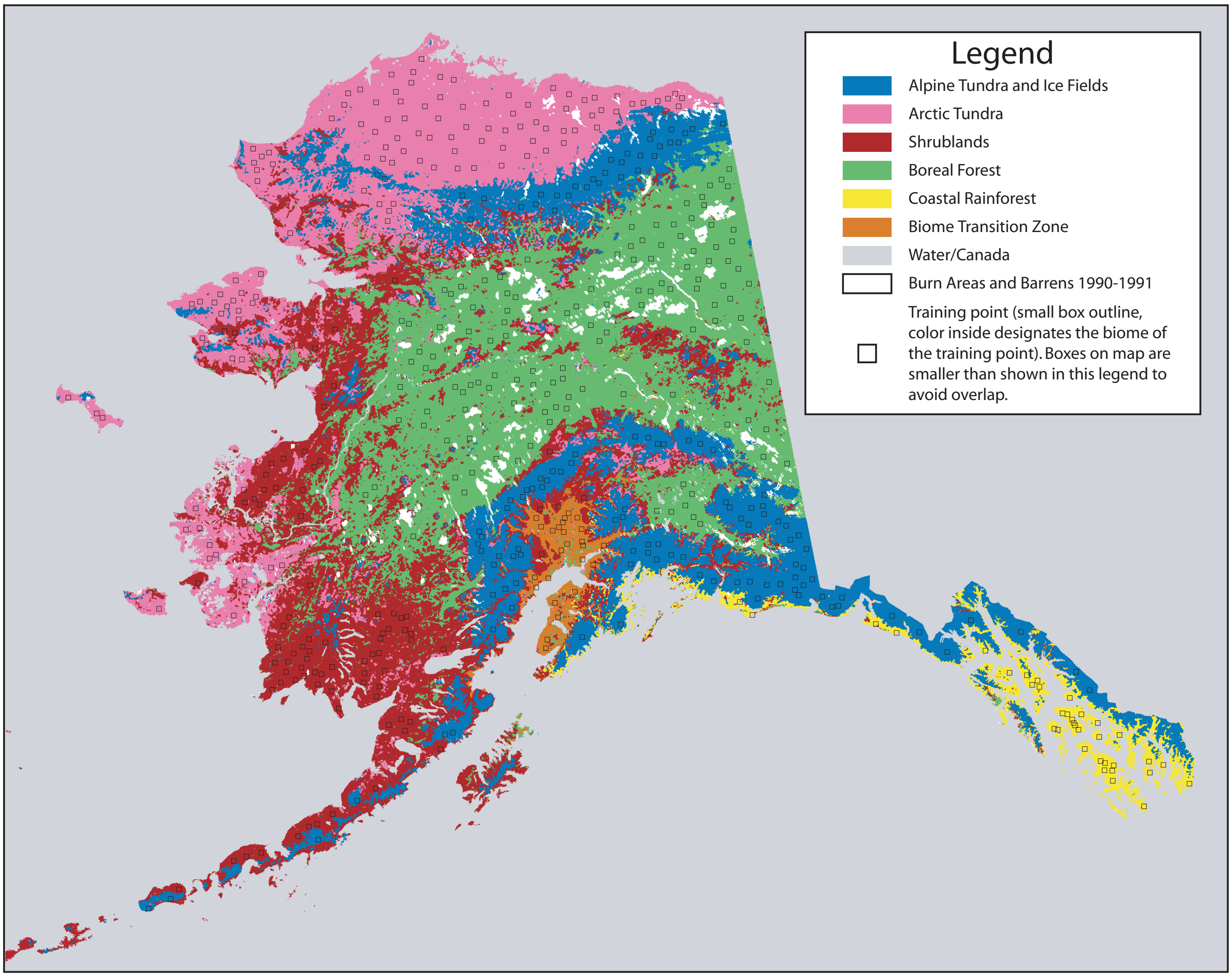


FIG. 2. Vegetation biome map of Alaska used in this study, with white overlay showing fire scars and barrens for 1990–91 (data from Fleming, 1997). Small squares show locations of training set points used in the discriminant analysis. Model/training set development was based on less than 1% of available data; more than 99% of data were used to validate model results.

Permafrost and the Active Layer

The active layer, typically under 1 m in thickness, is the biologically active region of ground. It freezes every winter, thaws every summer, and covers the permafrost (perennially frozen subsoil). Permafrost, both continuous and discontinuous, covers vast areas of the Arctic. It can be a primary environmental control on vegetation through its effects on drainage (McGuire et al., 2003). For example, long-term vegetation succession and changes in active layer thickness in the Low Arctic (bioclimate subzones D and E) are thought to be strongly influenced by waterlogging or paludification (Walker and Walker, 1996; Walker et al., 2003) in locations where permafrost limits the depth of water drainage. Permafrost also strongly influences soil development and geomorphology in the Arctic because it often leads to impeded drainage, chemical reduction, salinity, and the efflorescence of salts on soil surfaces (Fitzpatrick, 1997).

The interactions between climate change, zonal vegetation, and permafrost are very complex. In the Alaskan High Arctic (bioclimate subzone C) near Barrow, Alaska, well-drained mineral soils prevail. Here, climate warming might produce conditions more similar to those of the Low Arctic (subzones D and E). Such conditions would lead to more extensive moss layers and thicker soil organic horizons, while paludification would increase soil moisture and decrease active layer thickness (Walker et al., 2003). At the southern extreme of the Alaskan bioclimate gradient (Subzone E), especially near the treeline, climate warming would cause permafrost to become more discontinuous, the active layer might thicken, and areas of shrub-tundra or forest or both might develop in areas without permafrost.

Significant increases in ground temperature have accelerated permafrost degradation in many parts of Alaska (Osterkamp and Romanovsky, 1999; Jorgenson et al., 2001) and this degradation, through associated expansion of thermokarst-related landforms, has the potential to change the distribution and extent of plant communities in the Arctic and Subarctic (Lloyd et al., 2003a). Establishment of trees and tall shrubs (willow, shrub birch) at the Arctic treeline, for example, appears to be restricted by the availability of well-drained microsites. Thus, this expected response of the species to regional climate change will depend on further degradation of permafrost (Hobbie and Chapin, 1998; Lloyd et al., 2003a, b).

Topography

Topography is an extremely important factor in Alaskan climate-biome interactions because Alaska has a large number of east-west oriented mountain ranges (Fig. 1). Topography affects regional climate (Van Cleve et al., 1991, 1996) and seed dispersal (Malanson and Cairns, 1997) and limits tree colonization and survival (Körner, 1998). Recent simulations of the influence of topographic barriers on treeline advance at the forest-tundra ecotone in northeastern Alaska, for example, indicate that the Brooks Range is a major constraint on regional forest expansion onto the currently treeless North Slope (Rupp et al., 2001).

Vegetation and Soils

Accumulation of litter, nitrogen cycling, and biochemical weathering are the primary plant processes related to soil formation. Tundra soils often contain several centimeters of free organic matter at the surface because the rate of decomposition is low. The organic matter is usually acidic, which fosters mineral weathering, partially compensating for the low Arctic temperatures that impede weathering and soil formation. In Alaska, biomass tends to increase southward along a transect from subzone C to the southern boreal forest (Giblin et al., 1991). Along this same transect, dead organic matter has a secondary peak in the tussock vegetation of the tundra zone and a much larger primary peak in the northern boreal forest. Available data show varied relationships in the Arctic among organic matter accumulation, decomposition rate, temperature, water in the soil, and plant growth (Fitzpatrick, 1997).

Process-Driven and Data-Driven Models of Vegetation Distribution

Models used in the earth and environmental sciences broadly separate into two classes: 1) process models, so-called because they are based on detailed descriptions of the physics-chemistry-biology of the system being modeled; and 2) data-driven models that use methods of machine learning (e.g., neural network, discriminant analysis) to model the system under study. Process-based models can be further classified into two basic categories (Prentice and Solomon, 1991): dynamic models, which predict the transient response of vegetation to changes in climate over time (e.g., Daly et al., 2000; Kittel et al., 2000; Stitch et al., 2003), or equilibrium-based models, which assume that vegetation is in equilibrium with climate (e.g., Prentice et al., 1992; Neilson, 1995). In recent years, all these types of models, with variations and in combination, have been used to model large- and regional-scale patterns of vegetation. Each approach has a unique set of costs and benefits. Dynamic vegetation models, for example, are limited by scale (i.e., their usefulness for global applications is questionable because of computational and data limitations), but they have the potential to predict transient vegetation responses at local to regional scales (Prentice and Solomon, 1991). Equilibrium-based models (e.g., Prentice et al., 1992; Lenihan and Neilson, 1993; Neilson, 1995), however, can accurately provide insights useful for linking changes in vegetation distributions to different climate-change scenarios at either regional or global scales.

Fires, Secondary Succession, and Model Biome Classification

Fire is a primary stochastic physical process that influences high-latitude vegetation (Timoney and Wein, 1991). Its frequency and the extent of burn areas are highly variable and strongly influenced by meteorological conditions. Under conditions favorable to fire (e.g., low humidity, high temperature, high winds), the nature and extent of the available biomass and the topographic variability within an area determine the ultimate extent of the burn area (Wein, 1976). For example, fires in the tundra are usually small (Timoney and Wein, 1991) and occur at low intensities, and recovery takes place within a few years of the burn (Wein and Bliss, 1973), while fires in forested areas are more frequent, burn more intensely, produce larger burn areas, and have much longer recovery times (Rowe et al., 1975). The severity of the burn also affects recovery time (Racine, 1981).

Recent frame-based, spatially explicit simulations of Subarctic vegetation response to climate change (Rupp et al., 2000a) are generally consistent with the observations cited above. In a frame-based model, the temporal changes in vegetation are partitioned into a set of states, called frames (Noble and Slatyer, 1980); each frame simulates those processes important to that frame; and each frame runs as an independent submodel that can result in a switch to a different frame (Starfield et al., 1993). The different frames represent alternative states of upland vegetation (upland tundra, white spruce forest, broad-leaved deciduous forest, dry grassland) found in Subarctic Alaska. Within each frame, the biotic and abiotic factors used to determine a switch from one frame to another are modeled. Rupp's simulations show that upland tundra and broad-leaved deciduous forest (with relatively low flammability) generally support only small fires, but that the white spruce forest (with relatively high flammability) produces not only many small fires, but also large fires that can account for as much as 60% of the total area burned. Two other important generalizations were derived from the simulated results: 1) topographic barriers had little impact on fire size in low-flammability vegetation, but reduced average fire size and increased the number of fires in high-flammability vegetation; and 2) large fires were more common in landscapes with large, continuous patches of two vegetation types, whereas the frequency of fire increased for low-flammability vegetation as the heterogeneity of the vegetation increased.

Lightning is the primary causal agent for fires in the remote and largely unpopulated areas of Alaska and adjacent areas of Canada (Hess et al., 2001), although man-made fires have increased in frequency (Wein, 1976; Hufford et al., 1998). Interannual climatic variability, largely associated with El Niño Southern Oscillation (ENSO) events, also has a significant impact on fire conditions, lightning-related fire frequency, and the extent of burns in Alaska (Hess et al., 2001). ENSO-related changes in the mid-latitude Northern Hemisphere atmosphere (e.g., Wallace and Gutzler, 1981), for example, produce a ridge of high pressure (the North American High) that extends along the entire west coast of North America and a simultaneous expansion and intensification of the Aleutian Low. These changes are associated with anomalous winter weather conditions, slightly warmer and much wetter along the Gulf of Alaska and slightly warmer and much drier in the Alaskan interior (Hess et al., 2001; Simpson et al., 2002). These interior conditions result in a shorter vegetation green-up in early spring followed by an extended vegetation dry-out in summer. Moreover, in summers following El Niño winters, dry thunderstorm activity increases in interior Alaska (see Hess et al., 2001: Table 4). Statistics on the areas burned since 1940 show that 15 out of the 17 biggest forest-fire years in Alaska occurred during moderate to strong ENSO periods, and that those 15 years account for nearly 63% of the total area burned during the last 58 years.

The occurrence of wildfires is expected to increase with global warming (Overpeck et al., 1991), especially in the boreal forest (Flannigan and Van Wagner, 1991). Data from the boreal forest of western Canada showing that the average area burnt has doubled in the past 20 years (Kasischke et al., 1999) are consistent with this expectation. Increases in fire frequency and extent are also predicted to produce a shift in vegetation from a conifer-dominated to a deciduous-dominated forest (Rupp et al., 2000b, 2001, 2002), which, in turn, could provide biotic feedback to regional warming (Chapin et al., 2000).

Secondary succession following fire is one of the primary processes controlling variation in forest structure and composition in interior Alaskan forests (Fastie and Lloyd, 2003). Fire recovery times vary greatly, however, with vegetation assemblage. After a fire in low Subarctic open forests, tree stands may remain shrub-dominated for 25–50 years, produce high canopy cover in about 50 years, and approach a climax forest in about 150–200 years (e.g., Black and Bliss, 1978). High Subarctic forest-tundra, however, may remain shrub-dominated indefinitely (i.e., fire-induced "tundra"; Timoney and Wein, 1991; Lutz, 1955): recovery times may exceed 50 years, and climax conditions are approximated only after 200–500 years. Specific species also possess traits that render them more or less resilient to fire compared to other species (Rowe, 1970; Payette et al., 1982; Fastie and Lloyd, 2003).

The complex process of secondary succession in response to fire and other disturbance events and the highly variable time scale over which burnt areas reach climax vegetation assemblage complicate any model of Alaskan biome classification. Therefore, burn areas are excluded from further consideration in this analysis. Most burn areas in Alaska occur within the boreal forest biome (Fig. 2, white overlay), while comparatively few burn areas appear in the Arctic tundra biome. This distribution is consistent with previously cited studies. Fire-scar areas throughout Alaska over the 50-year period 1950–99 (see DISCUSSION) generally occur in the boreal forest biome, and this pattern is consistent with the 1990–91 pattern (Fig. 2). But over the longer 50-year period, several burns of significant size also occurred in the shrublands and Arctic tundra biomes.

OVERVIEW OF THIS STUDY

Classification of high latitude landscapes into their appropriate biomes is important for many regional and global issues related to climate change. Unfortunately, large-scale, high–spatial resolution observations of plant assemblages associated with these regions are generally unavailable. Therefore, accurate modeling of plant assemblages and biome boundaries is often needed. The present study uses various combinations of the available spatial climatic (surface temperature, precipitation) data and spatial environmental (topography, soil, permafrost) data to evaluate their effectiveness in characterizing different Alaskan biomes (alpine tundra, Arctic tundra, shrublands, boreal forest, coastal rainforest) and a biome transition zone. Then, discriminant analysis is used to build a statistical model that "converts" the spatial climate and spatial environmental data into a biome-level map of Alaska with a spatial resolution of 1 km × 1 km. The accuracy of the modeled biome map is statistically compared both with independent ground truth data and with results obtained with other models, using the Kappa statistic, for equivalent biomes. The Multivariate Alteration Detection (MAD) transformation is used to detect Climatic Transition Zones (CTZs) in Alaska. Such regions are important for understanding biome distributions because vegetation communities are largely distributed along environment gradients (Kaplan et al., 2003). The space-time gradient information provided by the MAD analysis is used: 1) to distinguish "core biome areas" from "transition biome areas" or ecotones that occur within the Alaskan vegetation landscape, and 2) to modify Fleming's (1997) original Alaskan vegetation biome map by inclusion of the ecotones. In this context, an ecotone

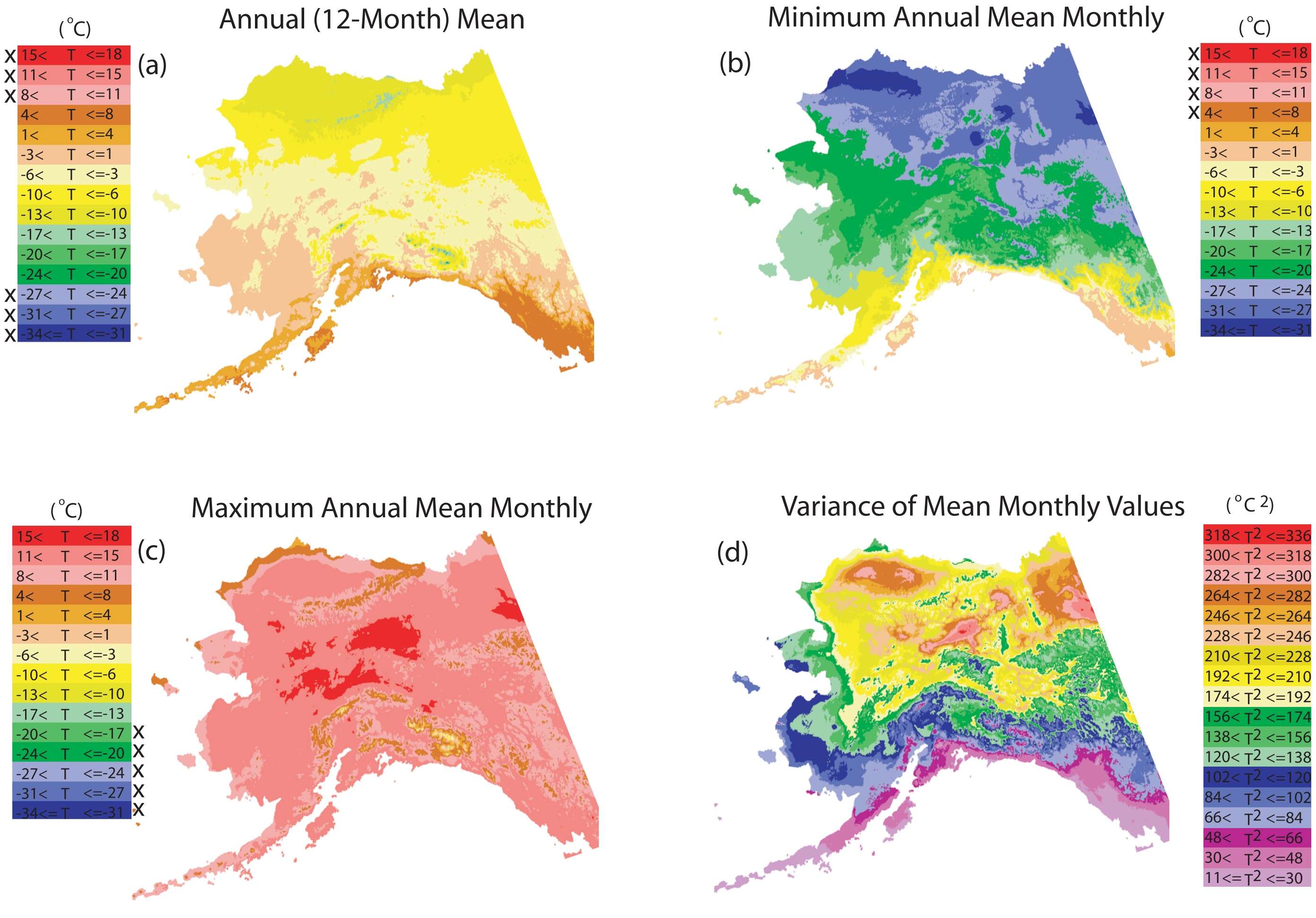


FIG. 3. SCAS temperatures. a) annual (12-month) mean, b) minimum annual mean monthly, c) maximum annual mean monthly and d) variance of monthly values. The color key for panels a, b, and c covers the full range of values for the three maps, with "X" indicating value ranges that do not occur in the data for each specific panel. This figure was constructed from various panels originally shown in Simpson et al. (2005).

is defined as a transitional area between two core biomes, for example, the boreal forest-shrubland ecotone. It has its own characteristics and also shares certain characteristics of the two core biomes.

DATA SETS

Surface Temperature and Precipitation

Alaskan climate data used in this study came from maps that included mean monthly surface temperature and precipitation produced by Oregon State University's Spatial Climate Analysis Service (SCAS, now called the PRISM Group) using the Parameter-elevation Regression and Independent Slopes Model (PRISM, see Daly et al., 1994, 2000, 2001, 2002). For details of the PRISM model process used to produce the maps, inputs to the PRISM model for the Alaskan case, and map validation with independent in situ data, see Simpson et al. (2005: Figs. 16, 17).

Figure 3 shows annual (12-month) surface temperatures (mean, mean annual minimum, mean annual maximum, and variance) computed for 1960–90. Analogous data for precipitation are given in Figure 4. Note that the data in Figure 4a are not mean annual total precipitation values, but rather the mean monthly values averaged over the 12 months of the year. An approximate mean annual total precipitation at a given location can be obtained by multiplying these values by 12. Annual maximum and minimum surface temperature (or precipitation) at a given location were defined as the maximum and minimum values, respectively, in the 12 mean monthly time series of surface temperature (or precipitation) at that location. Variance was computed locally from the 12 mean monthly values.

Maximum seasonal differences (mean July–mean January [Fig. 5a, b]) in surface temperature occur in central Alaska and adjacent areas of Canada, while minimum seasonal differences occur in southeast Alaska, throughout the Aleutian Islands, and in a narrow coastal region around much of Alaska (Fig. 5c). Maximum monthly precipitation occurs at different locations in Alaska during different months. Interior Alaska and adjacent areas of Canada, for example, have maximum precipitation in summer (Fig. 5d), while southeastern Alaska has maximum precipitation in

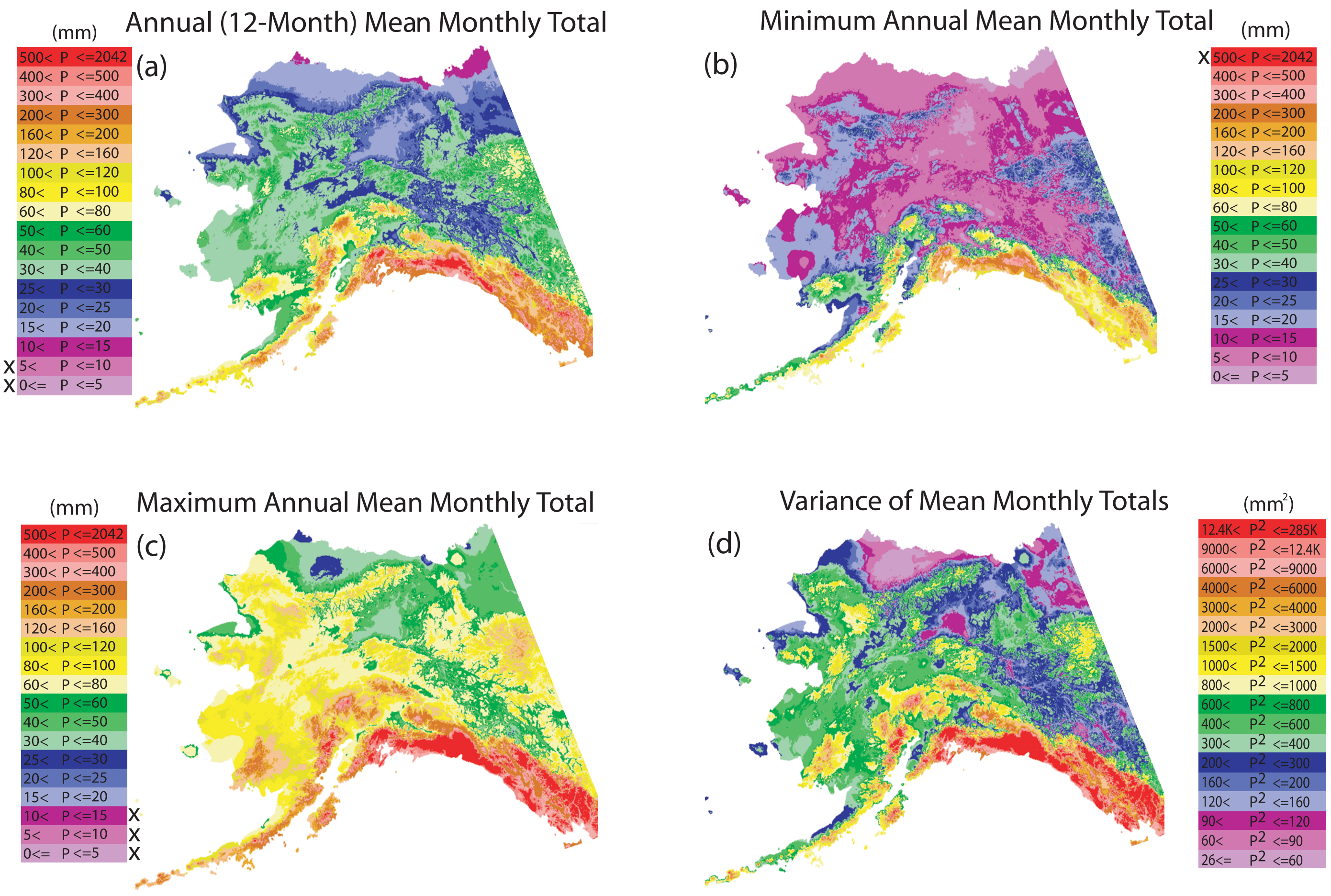


FIG. 4. SCAS annual (12-month) precipitation, with details as in Figure 3.

winter (Fig. 5e). The range in seasonal variation can be quite large and is location-specific (Fig. 5f). See Simpson et al. (2002, 2005) for details.

Alaskan Biomes

An Alaskan vegetation biome map (Fig. 2), based on the phenological classification of Fleming (1997), provides unique land cover characteristics for Alaska at high spatial resolution. It was developed using procedures for the lower 48 states (Loveland et al., 1991). The general procedure involves three steps: 1) a stratification of vegetated and barren land; 2) an unsupervised classification of multitemporal Advanced Very High Resolution Radiometer (AVHRR) data (cloud-free and snow-minimized false thermal color infrared maps and maps of maximum Normalized Difference Vegetation Index (NDVI) 10-day composites that occurred over Alaska's growing season in 1990–91); and 3) post-classification stratification of the classes into homogeneous land cover regions using ancillary data (e.g., elevation, climate, ecoregions, land resource areas, land use and land cover data, political boundaries, water bodies, state and local land use, land cover maps) and expert knowledge.

Topography

The U.S. Geological Survey's Earth Resource Observation Systems (EROS) Data Center Global 30-second elevation grid (GTOPO30) for Alaska (Fig. 1) was used as input to the PRISM model (to produce the SCAS Alaskan data) and to other specific analyses described here.

Permafrost

The U.S. Geological Survey's EROS Alaska Field Office produced a geo-referenced digital map and associated attribute data for the distribution of Alaskan permafrost at the scale of 1:2 500000 based on the source map (polyconic projection) of Ferrians (1965). The digital data were projected into the standard Alaskan Albers Equal Area projection (Fig. 6).

Soil

The Alaskan soil data set consists of a georeferenced digital map and attribute data based on an exploratory soil survey of Alaska (U.S. Department of Agriculture [USDA], 1979). This survey is a broad-based inventory

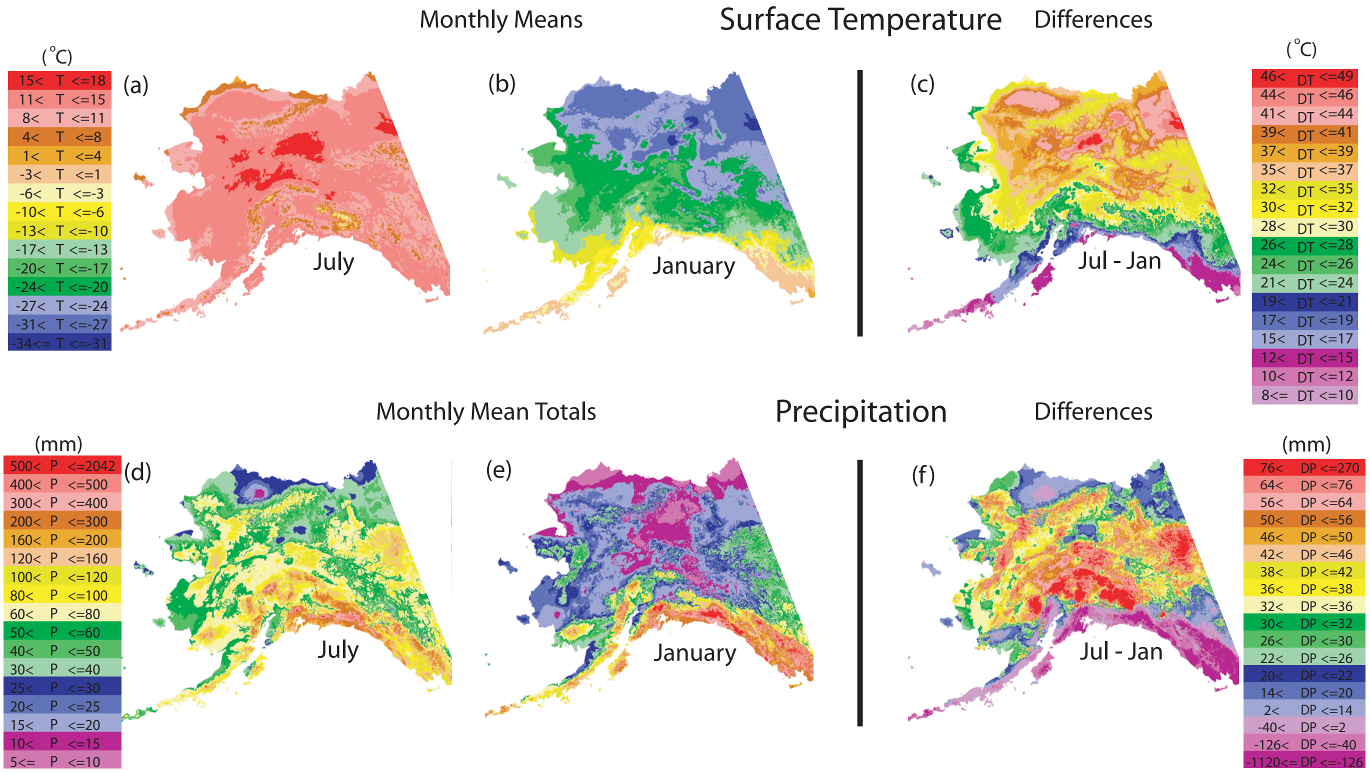


FIG. 5. Mean monthly surface temperature and precipitation for July (a, d) and January (b, e), and July-January seasonal differences (c, f). The color scales on the left apply to July and January, and those on the right to the differences.

of soil and nonsoil areas that occur in repeated landscape patterns. Unlike most other State Soil Geographic Data Base (STATSGO) products (1:250000 scale) produced by the USDA's Natural Resources Conservation Service, the Alaskan soil map is provided at the coarser 1:1 000 000 quadrangle unit. Each STATSGO map is linked to the USDA's Soil Interpretations Record (SIR) attribute database, which gives the proportionate extent of the component soils and their properties for each map unit. The SIR database includes over 25 physical and chemical soil properties, interpretations, and productivity (e.g., available water capacity, soil reaction, salinity, agricultural classification, interpretation for engineering use, vegetative land cover). For Alaska, each map unit consists of one to three components; the components are soil subgroup phases, and their percent composition represents the estimated areal proportion of each within a given map unit. Random transects and remote sensing of landforms and vegetation patterns were used to validate the composition and interpretations of map unit delineations. Actual classification of soil and the design/name of map units are based on the soil taxonomy used by the USDA (1975 and updates).

The database for Alaska has 268 soil units, each consisting of up to three unique soil types that taken together render the map unit unique. There can be up to 21 different soil types in a unit, but only those three that best characterize the unit are listed in the STATSGO User Guide. We have aggregated the 268 soil units into their appropriate taxonomic orders (from Great Groups to Suborders to Orders) to produce the soil classification shown in Figure 7, which is consistent with its intended use in this study and with past ecological studies (e.g., Fitzpatrick, 1997).

Conversion of ArcGIS Map Representation to Digital Format

The permafrost and soil maps of Alaska were received as ArcGIS polygon representations and converted to standard Linux floating point representations. A Portable Network Graphics format (PNG) image file was created from an exported version of the ArcGIS data file and imported into Matlab, where a two-dimensional matrix of floating point values was constructed. Values in this matrix correspond to coded values in either the original soil database or the permafrost database, but they can now be algebraically manipulated. In the case of permafrost, no reclassification was required. For soil, we regrouped values from Great Group to Order, following the same USDA soil taxonomy used to produce the original soil classification.

Other Data Considerations

Various data sources treat Alaskan coastlines somewhat differently. SCAS, for example, typically extends surface temperature and precipitation beyond the coastline to include nearshore areas (e.g., the Alexander Archipelago). The vegetation biome data set, however, largely restricts data to land areas. This variation in data treatment near Alaskan

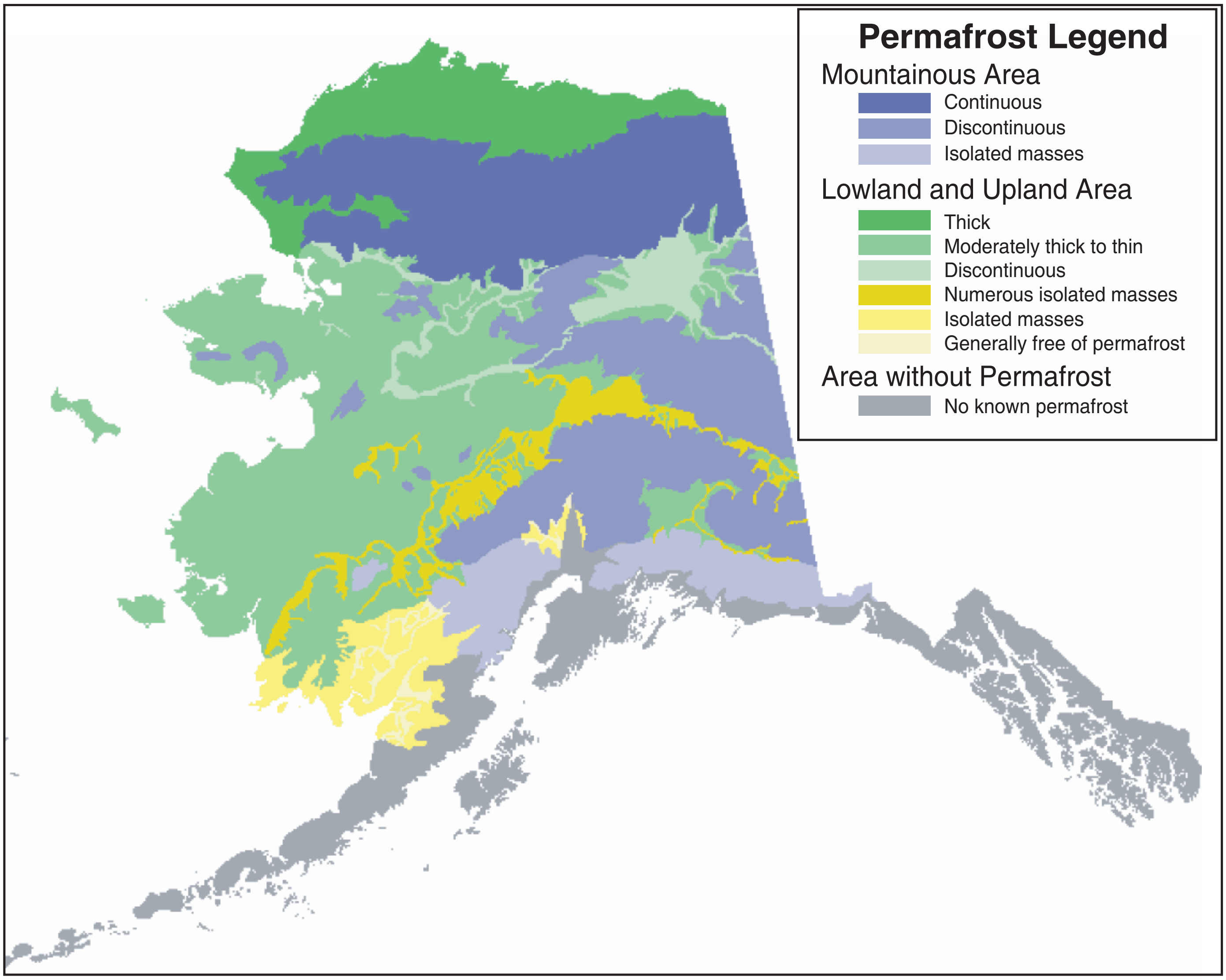


FIG. 6. Permafrost distribution in Alaska, based on the earlier mapping of Ferrians (1965). Data from the Alaska Field Office, Earth Resource Observation Systems (EROS), U.S. Geological Survey.

coastlines has no significant effect on results. When data from a single data set are used, then that data set's full grid is shown. When multiple data sets are involved, then only pixels common to all data sets are used.

METHODS

Discriminant Analysis

A discriminant analysis (DA) model was developed to classify multivariate data (pixels) at the 1 km × 1 km spatial resolution into either one of Fleming's (1997) five Alaskan biomes or his transition zone (6 classes). Seven assumptions should be satisfied for accurate DA. Five of these assumptions are relatively straightforward to satisfy rigorously and are not discussed further. Failure to satisfy the requirement that the covariance matrices for each modeled class be approximately equal can prevent maximum class separation. Quadratic DA mitigates this problem (Cooley and Lohnes, 1971; Krzanowski, 1988). Each class should also have a multivariate normal (MVN) density function. If this condition is not satisfied, then the classification may not be optimal in the sense of minimizing errors. DA, however, is robust and can tolerate some deviation from these assumptions (Lachenbruch et al., 1973; Lachenbruch, 1975). Three forms of DA are used: 1) linear DA, which fits a MVN density function to each class using a pooled estimate of covariance computed across all classes; 2) quadratic DA, which fits MVN densities with covariance estimates stratified by class; and 3) generalized distance metric (Mahalanobis) DA, which uses Mahalanobis distances to stratify the covariance estimates.

DA, as used in this study, needs a training set containing sufficient accurate information so that the distinct classes in the multivariate data set can be properly characterized.

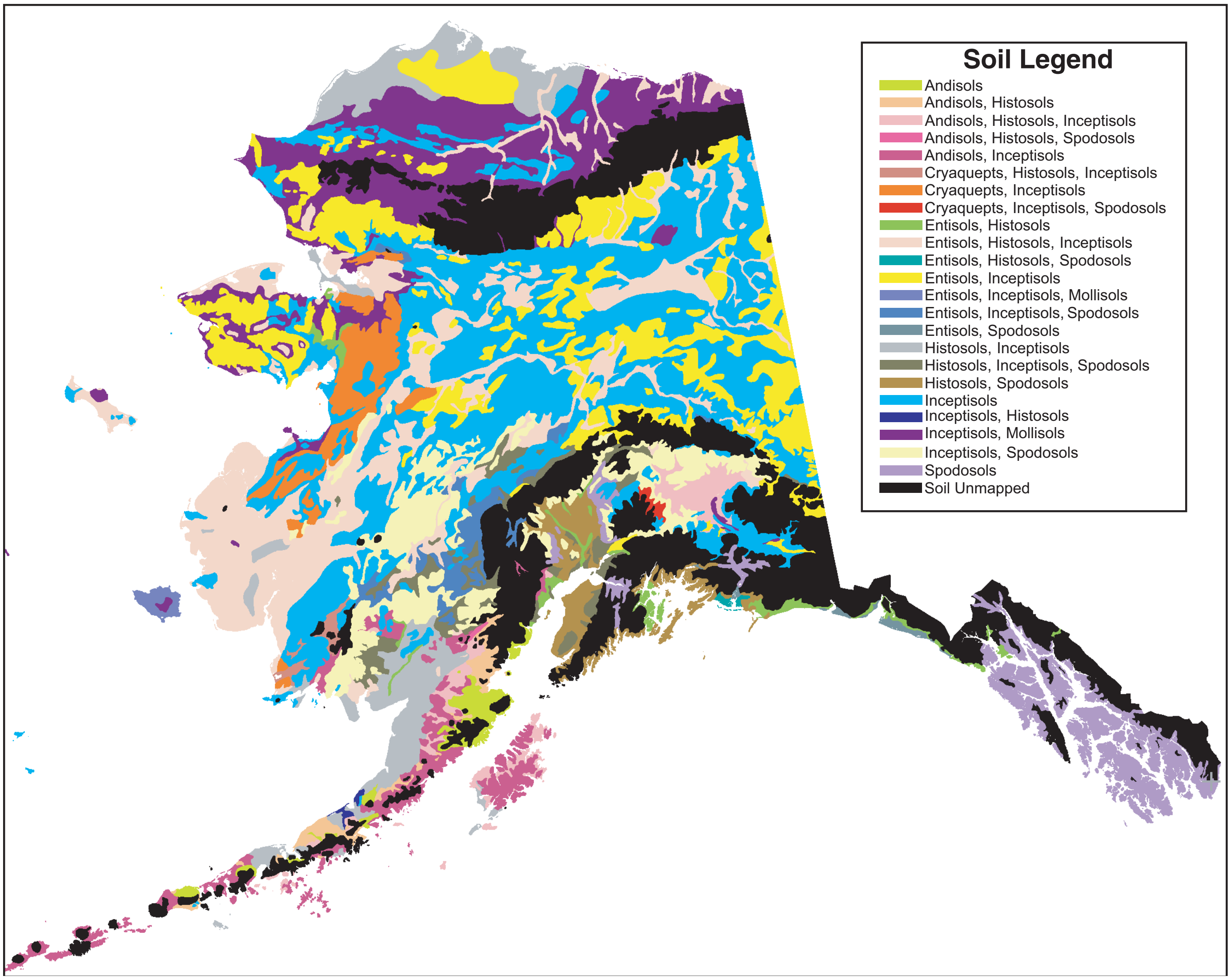


FIG. 7. Soil distribution in Alaska, based on U.S. Department of Agriculture soil survey, but shown at the taxonomic order level. Data from the Alaska Field Office, Earth Resource Observation Systems (EROS), U.S. Geological Survey.

The training set must be large enough so that all classes are statistically well sampled but also be small enough so that the statistical degrees of freedom are not so large as to render the model ineffective in classifying novel data, i.e., data in the parent multivariate data that are not included in either model and/or the training set development (here, novel data > 99%). Candidate training points were selected to ensure pure groups. Thus, pixels within 8 km of the biome boundaries in the ground truth map (Fig. 2) were excluded. Unmapped or invalid data (e.g., rivers, lakes, burn areas, barrens) were likewise excluded. No training point occurs within a 10 km × 10 km neighborhood surrounding any other training point to help achieve statistical independence of training points.

The Alaskan vegetation biome map (Fig. 2) was assumed true. Candidate training set data points were randomly selected for the five biomes and the transition zone, subject to the above constraints. Statistical culling was also performed on each candidate point to: 1) eliminate any redundancy in the data; 2) ensure all exclude criteria were properly satisfied; and 3) minimize any hand–eye–computer mouse coordination issues associated with the manual selection of candidate training set data points. The locations of the training points (squares on Fig. 2) are geographically well distributed, and each Alaskan biome and transition zone is represented. Less than 1% of the total available input data (Figs. 1, 3, 4, 6, and 7) and of the ground truth data (Fig. 2) were used for model or training set development (Table 1). This small-sized but statistically representative training set helps to ensure that the model will successfully generalize beyond its training, consistent with the requirements of modern classification theory (Devijver and Kittler, 1982; Cheevasuvit et al., 1986; Rumelhart et al., 1986; Haralick and Shapiro, 1993; Ripley, 1996).

TABLE 1. Number of points in the two training sets used to represent a given Alaskan biome, with soil excluded from the input information vector used by the models (top row) and with soil included (bottom row). More than 99% of the available input data and validation data were treated as novel data and were not used in either model or training set development.

	Alpine Tundra and Ice Fields	Arctic Tundra	Shrublands	Boreal Forest	Coastal Rainforest	Biome Transition Zone	Total Number of Training Points	Percent of Total Available Data Used in Training Set/Model Development
Without Soil	123	118	83	121	35	25	505	0.04%
With Soil	38	249	198	241	59	42	827	0.07%

Multivariate Alteration Detection (MAD) Transformation

The Multivariate Alteration Detection (MAD) transformation was used to detect the locations of CTZs. The MAD transformation (Nielsen et al., 1998) is based on standard canonical correlation analysis (see texts by Cooley and Lohnes (1971) and Anderson (1984) for a detailed discussion of canonical correlation analysis). MADs find spatial regions of maximum, simultaneous temporal change in multivariate data. Thus, MADs differ considerably from empirical orthogonal functions (EOFs) because EOFs treat each variable separately and do not measure change. MADs use two data sets (X, Y) of multivariate observations, taken at different times but mapped to the same spatial grid, and transform them into a difference between linear combinations of the original variables simultaneously. In the present context, X is the Alaskan surface temperature (T) and precipitation (P) maps for January and Y is the corresponding maps for July. MADs sequentially extract uncorrelated difference patterns where each new pattern shows maximum difference (change) under the constraint of being uncorrelated with previous patterns (i.e., the MAD 1 and MAD 2 patterns shown for the multivariate T and P data discussed later in the text). See Nielsen et al. (1998) for computational details.

Most MAD analyses have used temporally unaveraged data. For such analyses, high MAD values indicate regions of large temporal change. Because of the long-term (30-year) mean monthly T and P data used in this MAD analysis, regions of Alaska with inconsistent (unstable in time) climatic characteristics (alternating between periods of cold/warm temperatures and low/high precipitation) have low MAD values. Therefore, a narrow window of low MAD values about zero, ± 0.5, is used in this study to detect these regions of climatic instability. Conversely, those regions with consistent (stable) but different climatic characteristics over time (e.g., relatively warm and wet for many portions of coastal Alaska; relatively cold and dry for interior Alaska) have high MAD values but of opposite sign.

The Kappa Statistic

The Kappa (κ) or KHAT statistic (Cohen, 1960) provides a quantitative measure of agreement or disagreement between the modeled Alaskan biomes and ground truth. Unlike other frequently used statistical measures of agreement, the Kappa statistic also incorporates a correction for the overall proportion of chance-expected agreement. See Cohen (1960), Fleiss (1981) and Monserud and Leemans (1992) for computational details. Values for κ fall within the unit interval [0,1], where 1 indicates perfect agreement between the two sets of observations and values close to zero indicate that the agreement is no better than chance. Landis and Koch (1977) provide the degree of agreement rating for the Kappa values.

RESULTS

The sensitivity of biome classification to input information vector content was evaluated using 14 different input information vectors and linear discriminant analysis, chosen because it is very common in the literature and often provides a baseline for comparison with other types of discriminant analysis. The best input information vector (i.e., the one that produced the highest classification skill measured against independent ground truth) was then used with quadratic and Mahalanobis discriminant analyses, and these results were compared with those obtained from the linear analysis.

Sensitivity to Input Information Vector

The 14 input information vectors (Table 2) generally show a pattern of increasing climatic and environmental comprehensiveness (and complexity) and produce increased classification skill (relative to the truth map) from left to right across the table. There is, however, a notable exception. While the inclusion of either maxima/minima or variance information for an environmental variable (e.g., surface temperature, precipitation) increases classification skill relative to the inclusion of mean values only in the analyses, the simultaneous use of both is less effective than the use of extrema information alone (Table 2, entries D1–D4). Means and extrema are typically better than means and variances as indicators of the biogeographical distribution of Alaskan biomes.

The above result is consistent with empirical probability density functions for both near-surface temperature and precipitation at other locations (Von Storch and Zwiers, 1999). The statistical distribution for the amount of precipitation at West Glacier, Montana (USA), for example,

TABLE 2. Discriminant variables used with the 14 input information vectors evaluated. Model skill is defined as percent agreement between the Alaskan biome truth map (Fig. 2) and the corresponding map produced by a given (D1–D14) input information vector used with linear discriminant analysis. Data sources and definitions of discriminant variables are given in the text.

	Input Information Vector Designator (D1–D14)													
Discriminant Variable	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14
Annual Mean (12 Month) Temperature	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Variance of Mean Monthly Temperatures			X	X			X	X	X	X			X	X
Maximum Annual Mean Monthly Temperature		X		X		X		X	X	X			X	X
Minimum Annual Mean Monthly Temperature		X		X		X		X	X	X			X	X
Annual Mean (12 Month) Total Precipitation	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Variance of Mean Monthly Values			X	X			X	X	X	X			X	X
Maximum Annual Mean Monthly Total Precipitation		X		X		X		X	X	X			X	X
Minimum Annual Mean Monthly Total Precipitation		X		X		X		X	X	X			X	X
Permafrost	X	X	X	X	X	X	X	X			X	X	X	X
Topography											X	X	X	X
Soil					X	X	X	X		X		X		X
Model Skill (%)	51.7	66.6	63.5	64.0	56.5	70.8	68.0	70.6	63.3	69.8	55.9	59.9	69.4	72.4

depends on the accumulation time (Lettemaier, 1995). For short time scales (daily, weekly, monthly), precipitation accumulation is not normally distributed. Only for much longer accumulation time scales (e.g., annually) does precipitation have an approximately normal distribution. This time-scale distribution dependence occurs because precipitation is produced by two different atmospheric dynamical processes: atmospheric convection and large-scale uplift of air. The convection process depends largely on local thermodynamics and produces more intense convective rain, but for short durations, while the uplift process, which is linked to large-scale tropospheric circulation, produces less intense rain, but over longer periods of time. Thus, several authors (e.g., Sansom and Thomson, 1992; Bell and Subastini, 1994) have suggested using a sum of two statistical distributions to model precipitation.

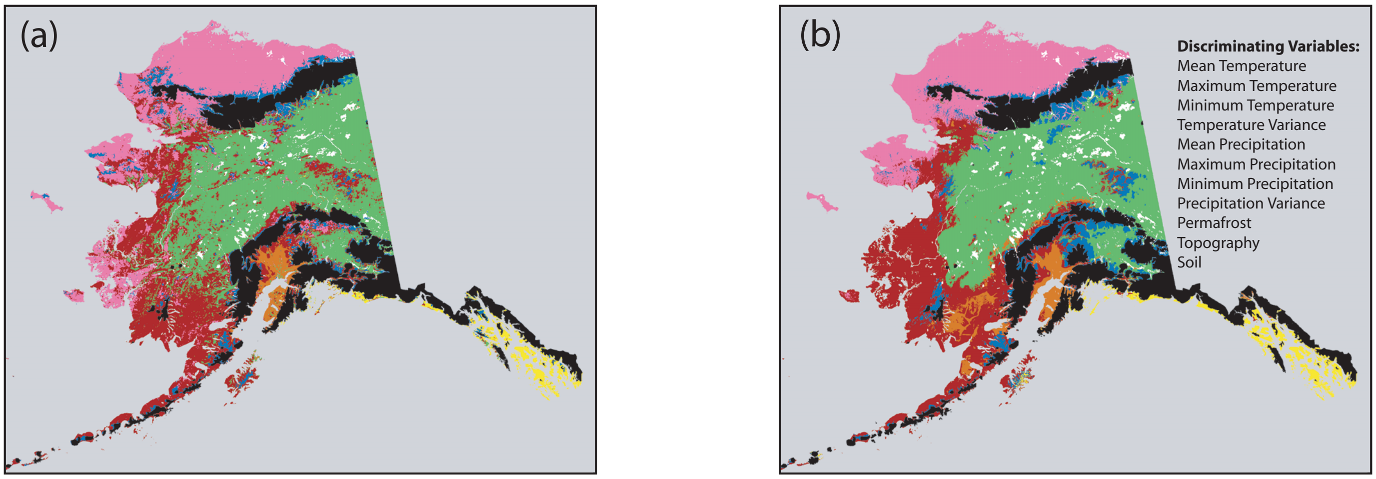
Temperature also departs from a normal distribution. Cold temperature extremes (1900–86) at Napoleon, North Dakota (USA), for example, occur over a relatively broad range, producing a long negative tail in the empirical probability density function, whereas the warmer extremes are more tightly clustered (Nese, 1994). Likewise, long-term (1901–80) mean monthly winter temperatures (January, February) in Hamburg, Germany, show a step-like empirical distribution function that is not well approximated by a normal distribution (Von Storch and Zwiers, 1999). As the empirical probability density functions depart from the normal distribution, they can become wider or narrower, or have tails with different characteristics, or both. Higher-order statistical moments (e.g., skewness, a measure of the tail properties of a distribution) and extrema then become more and more important.

The addition of soil as a discriminating variable to these same analyses (Table 2, entries D5–D8) significantly improves skill. Elimination of permafrost as a discriminating variable in the analyses (Table 2, D9) has a decided negative impact on the classification, but it is largely compensated for by the inclusion of soil in the analysis (Table 2, D10). Results obtained by including topography, permafrost, and soil in the analysis (Table 2, D12) are also better than those obtained when soil is excluded (Table 2, D11). Again, using only means of environmental variables in these two analyses decreases discriminant model skill relative to similar analyses that include some measure of variability. Best results, however, are obtained when the full range of parameters describing surface temperature and precipitation is combined with permafrost, soil, and topography (Table 2, D14). For this case, the classification skill is 72.4%.

Quadratic, Linear, and Mahalanobis Analyses

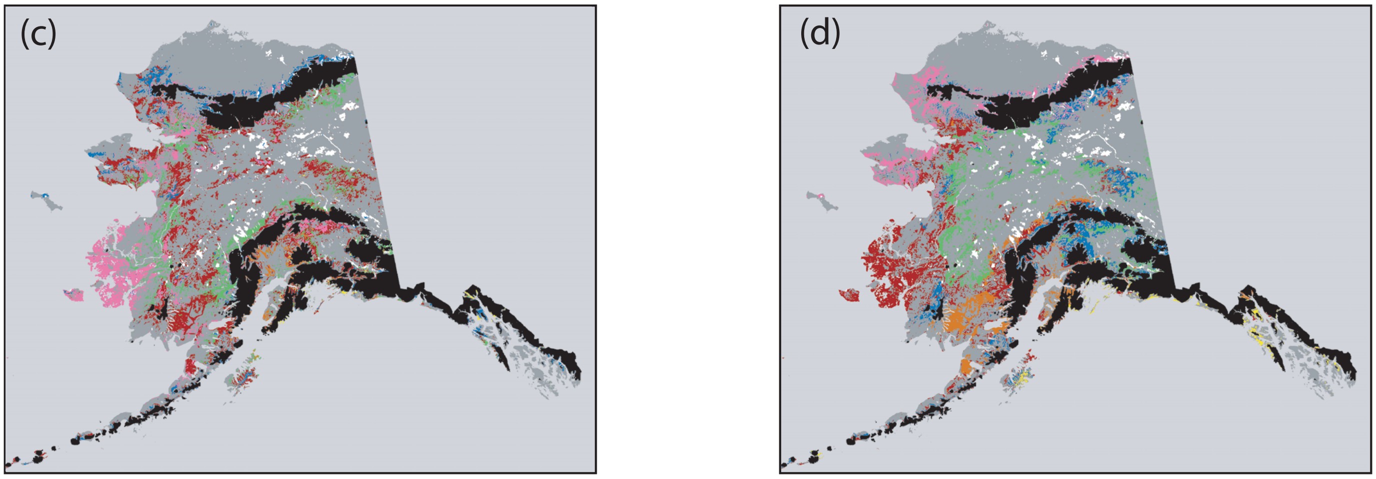
Quadratic or Mahalanobis discriminant analysis can sometimes yield better results than the linear analysis. Table 3 summarizes classification skill obtained from models with these three discriminant analyses using the seven input information vectors that contain soil. The general pattern of increasing skill with more comprehensive input information vectors, discussed earlier only for the linear model, also holds for the quadratic and Mahalanobis models. Overall, the quadratic model consistently has the best skill regardless of input information vector used. With the best available input information vector (D14), the quadratic model has the highest skill (74.0%), the Mahalanobis model has the lowest skill (68.3%), and the linear model skill (72.4%) falls in between them. These additional analyses also support the earlier conclusion that the extrema of surface temperature and precipitation are better indicators of Alaskan biome type than are their variances.

The spatial distributions of the various classification results provide additional insights into the usefulness of a given discriminant analysis for modeling the Alaskan biomes. Comparison between the biome truth map (Fig. 8a) and the best biome classification map produced by the linear discriminant analysis (Fig. 8b), with all discriminant variables included in the analyses (Table 2, D14), indicates that both maps agree reasonably well on the large scale. The black overlay in Figure 8 shows regions excluded from the analysis because soil information is not available; in general,



Biome Truth Map

D14 Linear



D14 Linear Underdetect

D14 Linear Overdetect

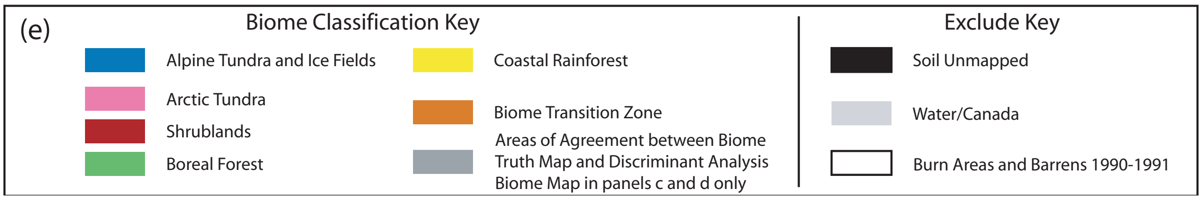


FIG. 8. Biome-level maps: a) truth map used for validation based on Figure 2, with black overlay showing unmapped soil areas. (This map is reproduced in Figs. 9a and 10a for easier comparison with the modeled maps in those figures); b) map produced by the linear discriminant analysis model (Table 3, D14). c) Biomes underdetected by the linear discriminant analysis and their locations. Dark grey in panels c and d indicates locations where the modeled and ground truth biome-level maps agree. d) Same data as in panel c but showing the biomes that were incorrectly modeled and their locations. Also shown are areas excluded from the analysis: water/Canada (light grey), burn areas and barrens (white), and unmapped soil areas (black).

these are mountainous regions (e.g., Alaska Range, Brooks Range, and Wrangell-St. Elias Mountains). Areas of light grey (ocean, inland water, and Canada) and white (burnt areas) in Figure 8 are also excluded.

Areas of disagreement between the map modeled by linear discriminant analysis and the biome truth map are indicated in Figure 8c and d. Dark grey indicates where the two maps agree. Figure 8c shows where the linear analysis model underdetected a given Alaskan biome class, while in Figure 8d, the same data are colored to show the incorrect biome produced by the same model at each colored location. For example, a significant region of the Yukon-Kuskokwim River Delta that should have been classified as Arctic tundra biome was assigned to the scrubland biome, and a region of the alpine tundra and ice fields biome on the northern side of the Brooks Range in northwestern Alaska was also incorrectly assigned to the Arctic tundra biome. There was also significant overdetection of the biome transition zone in southwestern Alaska.

The quadratic model (Fig. 9b) significantly improved the accurate identification of the Arctic tundra biome compared to the linear analysis (Fig. 8b), but underdetected

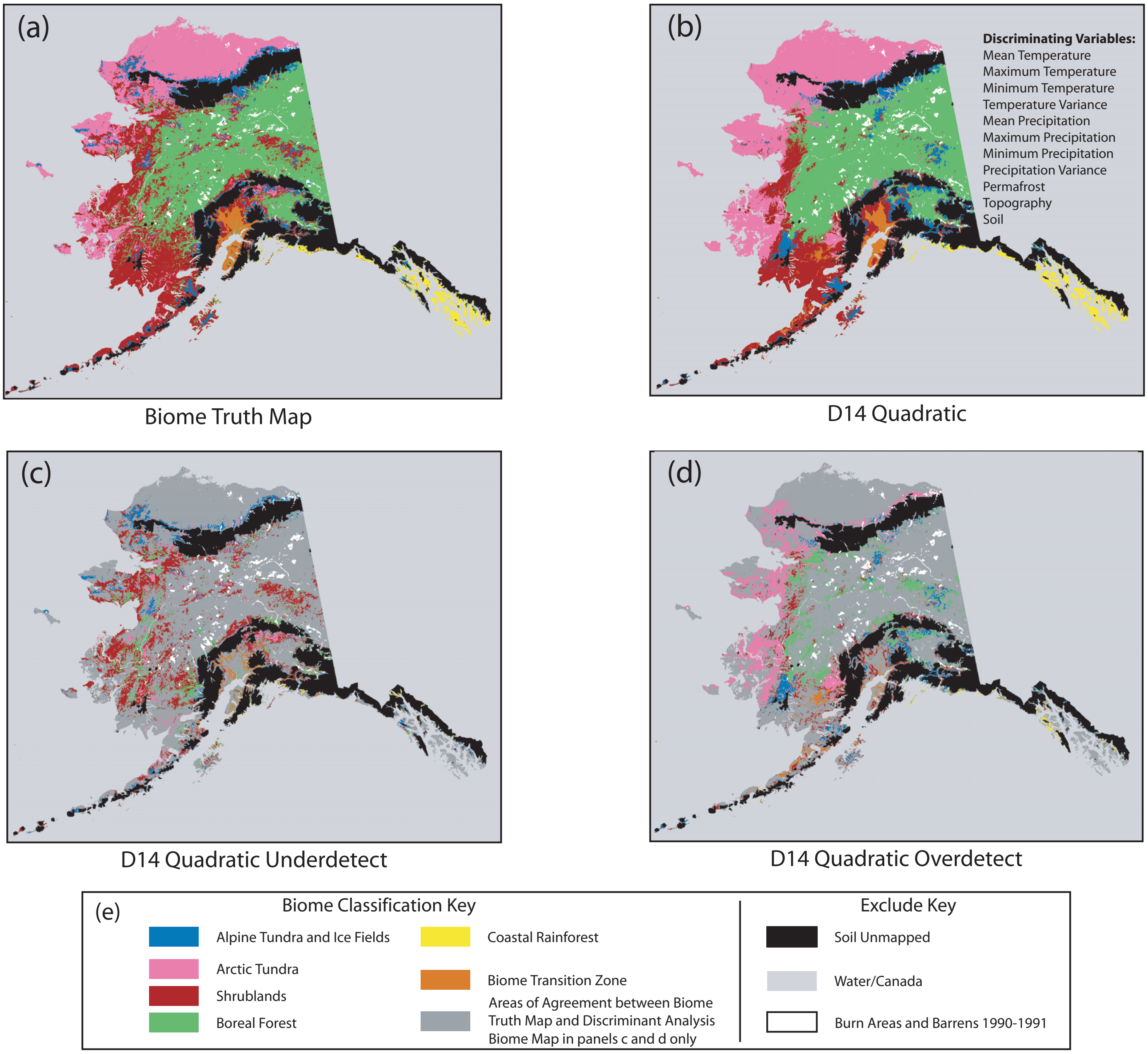


FIG. 9. Analogous to Figure 8, but showing results obtained with the quadratic discriminant analysis model.

the shrubland biome in several locations, including the Yukon-Kuskokwim River Delta. This area has relatively low spatial climate gradients (Figs. 3 and 4) that might make it sensitive to small changes in model predictions. In this area, small changes in the model can translate into different large-scale biome predications. However, the quadratic model (Fig. 9b, c, and d) reduced overdetection of both the biome transition zone and the alpine tundra and ice fields biome found in the linear analyses (Fig. 8b, d). Thus, not only is the biome map produced by the quadratic model superior overall to that obtained with the linear model (Table 3), but it also more accurately identifies most regional biome extents and their boundaries.

Results for the Mahalanobis model (Fig. 10) are decidedly inferior to those produced by either the quadratic or the linear model. This classification, for example, greatly extended the range of the alpine tundra and ice fields biome relative to the truth map and the maps from other models. The Mahalanobis model uses a generalized distance metric computed over a local neighborhood to stratify the covariance estimates used in the analysis. Results shown here suggest that the spatial variation of vegetation in Alaska is highly non-linear (biome dependant) and that a local distance metric is inappropriate, especially in regions of high environmental gradient.

An overall comparison of the biome maps produced by the three discriminant analysis models (Figs. 8, 9, and 10)

TABLE 3. Comparison of results obtained with the linear, quadratic, and Mahalanobis discriminant analysis models for those input information vectors (Table 2) that contain soil as a component. Model skill is defined as percent agreement between the specific modeled biome map (Figs. 8b, 9b, 10b) and the corresponding Alaskan biome truth map (Fig. 9a), with unmapped soil areas excluded.

	Input Information Vector Designator						
Discriminant Analyses Model Skill (%)	D5	D6	D7	D8	D10	D12	D14
Linear Model	56.5	70.8	68.0	70.6	69.8	59.9	72.4
Quadratic Model	59.6	73.0	69.6	72.9	72.2	60.7	74.0
Mahalanobis Model	52.8	66.0	66.5	67.3	65.5	54.9	68.3

leads to the following conclusions. The quadratic model 1) defines the ecotransition zone found in the truth map much more accurately; 2) identifies the Arctic tundra biome more accurately, especially along the western coastal region of Alaska; 3) reduces errors in accurate identification of the boreal forest biome; and 4) reduces overdetection of the alpine tundra and ice field biome (although none of the models deal well with this class). Of all the models, the Mahalanobis discriminant model produces the least satisfactory results.

DISCUSSION

Alaskan Biome Classification

Discriminant analysis models (linear, quadratic, Mahalanobis) were used to classify Alaska into either one of five biomes or the biome transition zone originally proposed by Fleming (1997), using 14 different input information vectors. Less than 1% of either the available model input data (Figs. 1, 3, 4, 6, and 7) or the available ground truth data (Fig. 2) was used for either model or training set development. The remaining novel input data (> 99%) were used by the models to produce 1 km × 1 km spatial resolution Alaskan biome level maps. The remaining novel ground truth data (> 99%) were used to validate these maps. The inclusion of topography, permafrost, and soil type as inputs to the analyses consistently improved classification skill compared to skill values obtained when only surface temperature and precipitation were used.

A comparison of the biome classifications produced by the three discriminant analysis models (Figs. 8, 9, and 10; Tables 2 and 3) shows that the quadratic discriminant analysis most accurately modeled the five Alaskan biomes and the biome transition zone. Although none of the models dealt well with the alpine tundra and ice fields biome, the use of the quadratic model did reduce the overdetection of this class.

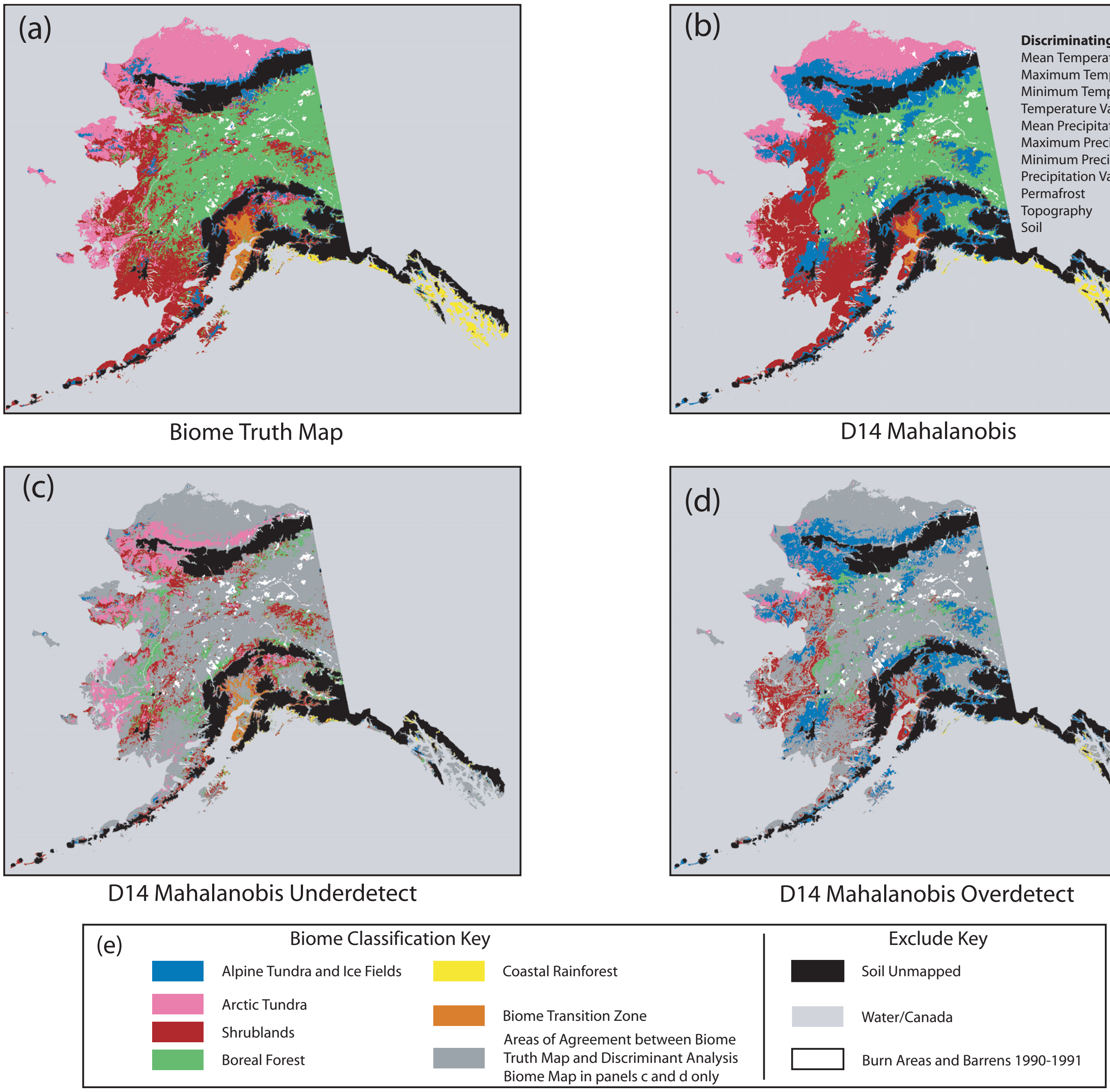
Data-driven models (e.g., neural networks, supervised clustering algorithms, discriminant analyses) are usually good interpolators, but they may be poor extrapolators if the problem is highly non-linear, or if the training set is not sufficiently representative of the novel data to be classified, or both. The successful generalization of the quadratic discriminant analysis model in this application is indicated by the model skill obtained (74%), especially when the size of the model development/training set is very small (less than 1% of the novel data being classified; Table 1). This success shows that the input information vector (D14) was properly chosen to represent the various Alaskan biomes, that the training set was well constructed, and that it is representative of the biomes being modeled. Moreover, the small amount of data needed for model development and training set construction makes this approach attractive for other polar regions for which few data are available.

Factors Complicating Alaskan Biome Classification

Several factors can compromise the ability of any classification scheme to assign a correct biome accurately to a given location in Alaska. These include inadequate sampling, co-registration errors, errors in the vegetation biome truth map, the natural complexity of biomes, and an incomplete ensemble of environmental variables, as well as fire (discussed earlier), Climatic Transition Zones, and the partial overlap of some Alaskan environmental variables.

Inadequate Sampling: Alaska is about 20% the size of the contiguous United States but the environmental network that monitors its climate is sparse. Moreover, most of the monitoring stations are located in either populated or low-elevation areas. High-elevation regions of Alaska (e.g., Coastal Mountains, St. Elias Mountains, Wrangell Mountains, Brooks Range, Alaska Range, Nulato Hills, see Fig. 1) are undersampled.

The SCAS data mitigate some of these sampling issues. First, the input data used by SCAS to model mean monthly surface temperature and precipitation were both varied in kind and spatially extensive (see Simpson et al., 2005: Fig. 3, Table 2). Second, SCAS used the European Centre for Medium-range Weather Forecasts (ECMWF) reanalysis of temperatures at the 500 millibar height, in conjunction with the two-layer PRISM model, to account for the effects of Alaskan wintertime atmospheric temperature inversions. Third, almost all precipitation gauges in the American observing system measure total liquid precipitation (rain plus melted frozen precipitation), and the majority of precipitation gauges in Alaska are unshielded. Wind-induced undercatch of up to 100% or more can occur during winter, especially for snowfall at high wind speeds, when unshielded gauges are used to make the observations (e.g., Goodison et al., 1981; Zhang et al., 1996; Yang et al., 2000). To minimize undercatch, the SCAS analysis



Biome Truth Map

D14 Mahalanobis

D14 Mahalanobis Underdetect

D14 Mahalanobis Overdetect

FIG. 10. Analogous to Figure 8, but showing results obtained with the Mahalanobis discriminant analysis model.

preferentially used shielded SNOTEL gauge data (where available) over National Weather Service unshielded gauge data (see Simpson et al., 2005 for details). A more detailed description of wind-induced undercatch of precipitation is given by Adam and Lettemaier (2003). Fourth, an in situ validation of the SCAS data set for a particularly remote and undersampled region of Alaska (north-south transects from the Arctic Coast to the southern foothills of the Brooks Range; these transects also sample the Arctic Coastal Plain, the Arctic Foothill, and the Brooks Range [Fig. 1]) shows that the SCAS data set, in terms of both shape function and absolute value, is consistent with the independent station data (Simpson et al., 2005: Figs. 16, 17, Table 3).

Co-registration Errors: Data were remapped (where necessary) to a standard Alaskan Albers Equal Area Projection at 1 km spatial resolution with an accuracy of about ± 2 km. This unavoidable error, given the origins of the various components incorporated into the total data set (see DATA SETS), is unlikely to have any significant effect on the biome classifications, except perhaps at biome boundaries, and in areas such as mountainous regions where environmental gradients are steep.

Inconsistent native spatial resolutions among the various data sets also contribute to uncertainty in biome classification, whether observed (Fig. 2) or modeled (Fig. 9). Surface temperature and precipitation, for example, were originally developed at 2.5 arc-minute resolution and then resampled to a 1 km × 1 km grid. Other data sets (permafrost, soil) were originally developed as polygon coverages of uncertain spatial resolutions. Moreover, the ancillary information used by Fleming (1997, 2000) to develop the vegetation biome truth map (Fig. 2) was available at a variety of spatial resolutions. These inconsistencies in native spatial resolutions could have significant effects on biome classification.

Errors in Vegetation Biome Truth Map: The biome truth map (Fig. 2) was assumed true, but it is based on AVHRR-derived Normalized Difference Vegetation Index (NDVI) data. However, noise effects limit the NDVI data (Lagouarde et al., 1986; Bégué et al., 1998). These effects include spatial and temporal variation in atmospheric aerosols, total precipitable water vapor, and surface conditions (e.g., phenology of vegetation); surface reflectance changes associated with time-varying AVHRR viewing and illumination geometry, which are also orbit-dependent; and undetected clouds (Ba et al., 1995). A maximum temporal compositing technique is generally used to minimize these effects, but it is only partially successful (e.g., Cihlar, 2000). Additional errors in the truth map could also have been introduced by errors in the ancillary data used in its construction, or the unsupervised classification process (clustering and maximum likelihood) used by Fleming (1997) to assign phenological classes to the NDVI data, or both.

Natural Complexity of Biomes: Biomes are not closed and static, but open and dynamic: they coexist and interact with the environment and with each other. Moreover, many of the biological and physical processes that characterize biomes, such as those processes we studied, are unique to the high latitudes, and their sensitivities to climate change are poorly understood. Scale-dependent processes on the order of 1 m to 1 km are also known to affect Arctic vegetation (e.g., Schaefer and Messier, 1995) but cannot be resolved in this study.

Incomplete Ensemble of Environmental Variables: Climate gradients, especially gradients of growing-season warmth, soil moisture, and snow cover, determine large variations in the structure, composition, and function of Arctic biomes (Kaplan et al., 2003). Snow cover, for example, is especially important in the Arctic tundra, where snow-shrub interactions have climatic implications (Sturm et al., 2001). However, these variables are strongly influenced by cloud cover and insolation at the ground level, for which annual and seasonal maps are not readily available. Thus, the set of environmental and climatic variables used in this and most other studies of Arctic processes must be considered incomplete.

MAD-Defined Climatic Transition Zones (CTZs) and Alaskan Biomes

Vegetation communities are generally distributed along environmental gradients, with "core biome areas" often having more landscape homogeneity than "transition biome areas," which are more heterogeneous. A well-documented example is the steppe-tundra ecotone found in interior Alaska around Kathul Mountain (Lloyd et al., 1994). This ecotone consists of a broad region of intermingling between steppe taxa and more drought-resistant alpine tundra taxa, with an abrupt shift from the mixed steppe–tundra to woodland, shrub-dominated alpine tundra at the ridge line of Kathul Mountain. Path analysis for the ecotone showed that 1) the transition from low steppe to alpine tundra vegetation is primarily associated with a gradient of decreasing soil temperature; 2) the more abrupt transition is mostly associated with sharper gradients in soil moisture and depth; and 3) within-steppe variation in vegetation is associated with gradients in soil phosphorus and moisture.

Long-term climate change processes can also alter the spatial distribution of vegetation. The Multivariate Alteration Detection (MAD) transformation (see METHODS) was used to differentiate temporally consistent (small interannual variability) from temporally inconsistent (large interannual variability) spatial regions of climatic variables that influence the biogeographical distribution of vegetation.

The MAD analysis used 30-year mean monthly surface temperature and precipitation maps of Alaska for January and July (Fig. 5) as input. Thus, regions of temporally inconsistent climatic characteristics will have near-zero MAD values (Fig. 11a, b, regions of dark grey overlay). See METHODS for further interpretation. Such regions serve as CTZs between climatic regions, each region characterized by a more consistent pattern of climatic variability (see Simpson et al., 2002). Most of the CTZs separate the climatic region of coastal Alaska (relatively warm temperatures and high precipitation) from that of interior Alaska (relatively cold temperatures and generally much less precipitation). This characterization of the coastal regime is especially true for the coastal regions of southeast, south-central, and southwestern Alaska and the Aleutian Islands, where sea ice is not an important consideration. Note, however, that even a narrow coastal strip adjacent to the Arctic Ocean near Barrow, Alaska, is warmer in winter than the Arctic Inland (Coastal Plain) because of a persistent wintertime atmospheric temperature inversion, while the same region is cooler than the Coastal Plain in summer (see Simpson et al., 2005: Fig. 13 and the relevant text, which also discusses the larger area of the Brooks Range in this context). MAD 2 (Fig. 11b) is consistent with MAD 1 (Fig. 11a), but MAD 2 is more strongly influenced by precipitation whereas MAD 1 is more influenced by surface temperature.

An edge-detecting LOG operator (see Simpson, 1992 for details) extracted the spatial boundaries (Fig. 11c, d respectively) of the CTZs defined by MAD 1 and MAD 2. The relation between errors in the quadratic discriminant classification (Fig. 9c, d) and the location and spatial extent of the CTZs as delineated by those boundaries are shown in Figure 11e and f. Misclassified pixels within the CTZs, for example, account for a significant portion of the discrepancy between the model classification and

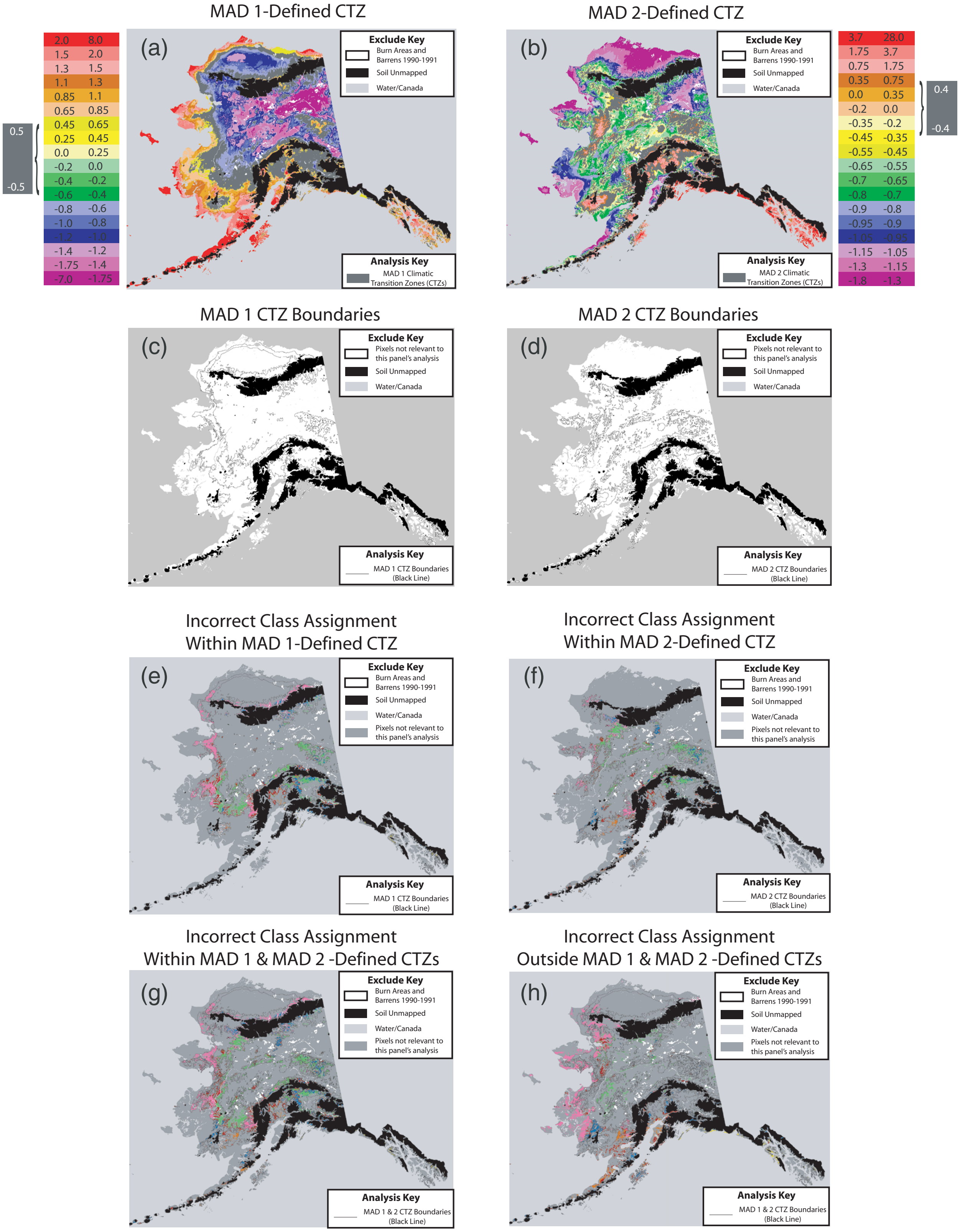


FIG. 11. Climatic Transition Zones (CTZs) as defined by the Multivariate Alteration Detection transformation (MAD) (from Simpson et al., 2002). a): MAD 1. Dark grey indicates CTZs with inconsistent climatic conditions (i.e., MAD 1 values between ± 0.5 and MAD 2 values between ± 0.4), which generally lie between the more climatically consistent (but very different) coastal and interior climatic regions. b): MAD 2. details analogous to panel a). c) and d): Thin black lines indicate boundaries of the CTZs determined from an edge detection of the CTZs shown in a) and b); white denotes pixels not relevant to the present analysis and provides a good contrast background for the black edges. e), f), and g) show disagreement between the quadratic discriminant classification (Fig. 9b) and the ground truth (Fig. 9a) within the CTZs of MAD 1 (e), MAD 2 (f) and MAD 1 and MAD 2 (g). h) is analogous to panel g, except outside the CTZs. Colors in e) to h) represent modeled biomes and follow the same color scheme as Fig. 9d. Dark grey overlays in panels e) to h) indicate pixels not relevant to the present analysis, not areas of agreement with the truth map as in Figures 8, 9, and 10.

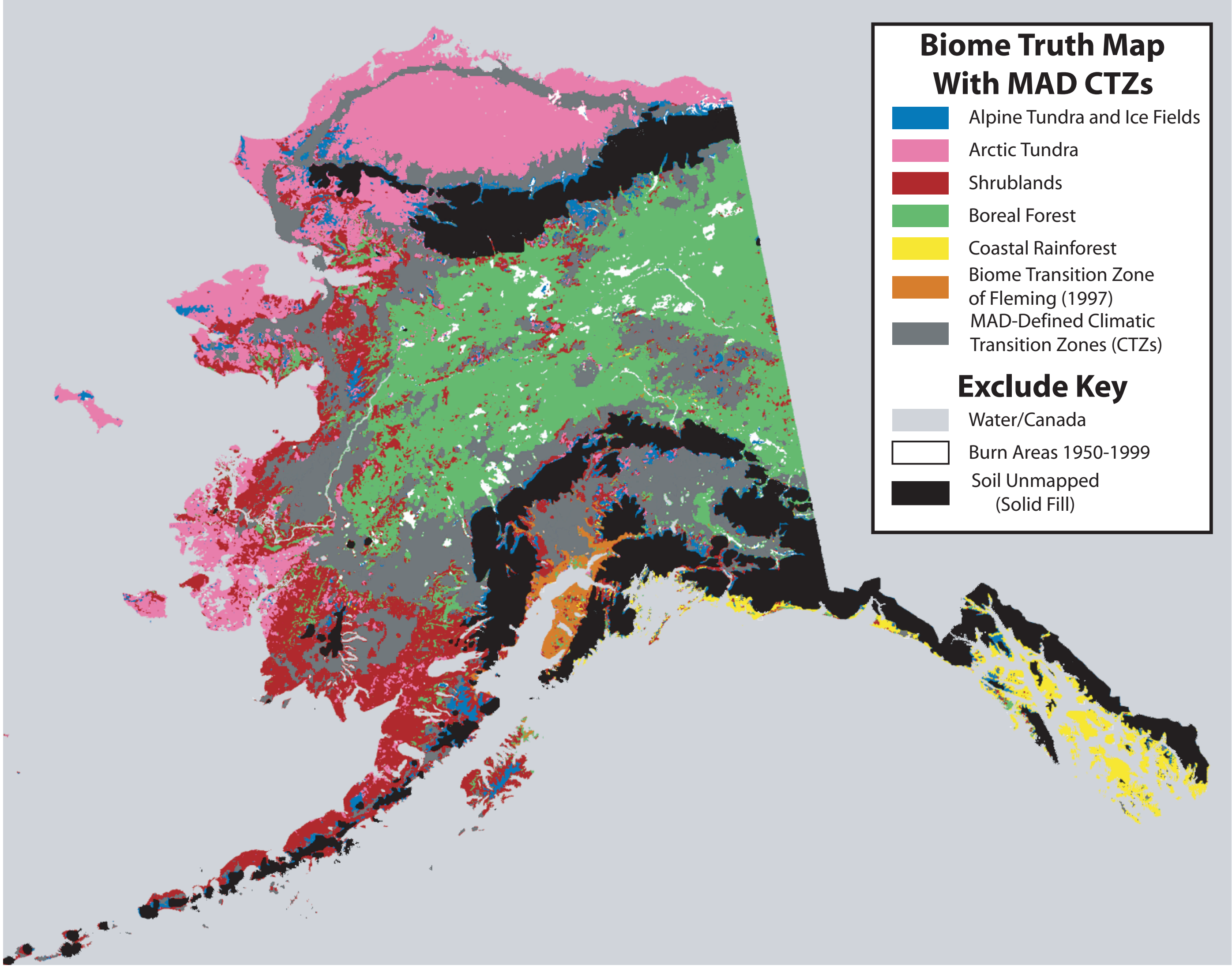


FIG. 12. Biome truth map with overlay of the MAD-defined climatic transition zones shown in Figure 11a and b. We interpret these CTZs as "transition biome areas" (or ecotones) that occur at various boundaries between the five "core biome areas" defined in the original map of Fleming (1997).

the ground truth for the boreal forest, Arctic tundra, and shrublands biomes. To a lesser degree, pixels in these CTZs also account for misclassifications in the coastal rainforest and alpine tundra biomes and in the biome transition zone defined by Fleming (1997). All pixels misclassified by the discriminant analysis that occur within the MAD-defined CTZs (Fig. 11g) account for 55.09% of the total pixels misclassified; those outside those CTZs (Fig. 11h) account for 44.91%. Misclassified pixels in the CTZs associated only with MAD 1 represent about 45.8% of the 55.09%, those associated only with the MAD 2-defined CTZs represent 32.5%, and those common to the MAD 1 and MAD 2 CTZs represent 21.7%. Errors in classification outside the CTZs (Fig. 11h) indicate that other factors (e.g., fire, data sampling, and co-registration errors) also affect the classification skill.

The large interannual variability of the CTZs results in an environment that might not uniquely favor one biome over another. The CTZs are more consistent with a mosaic-type variation in vegetation, in which microclimatic details determine which characteristic assemblage of plants (e.g., boreal forest vs. shrublands) performs best in specific locations. We offer in Figure 12 a revised biome map for Alaska, in which the MAD-derived CTZs are explicitly incorporated. We interpret these areas of the map as "transition biome areas," or ecotones, that occur between various boundaries of the five "core biome areas" defined in the original map of Fleming (1997). The MAD-defined CTZs occur in three primary regions of Alaska: 1) in the interior Yukon-Charley region; 2) near the boundary of the boreal forest/shrubland biomes; and 3) within the Cook Inlet area, site of the original biome transition zone defined in Fleming's map; however, the MAD-defined zone in Figure 12 is larger than Fleming's zone.

Mountains form many of the boundaries between Alaskan biomes. For example, the Brooks Range separates the Arctic tundra from the interior boreal forest, while the Alaska Range and Chugach Mountains isolate the interior

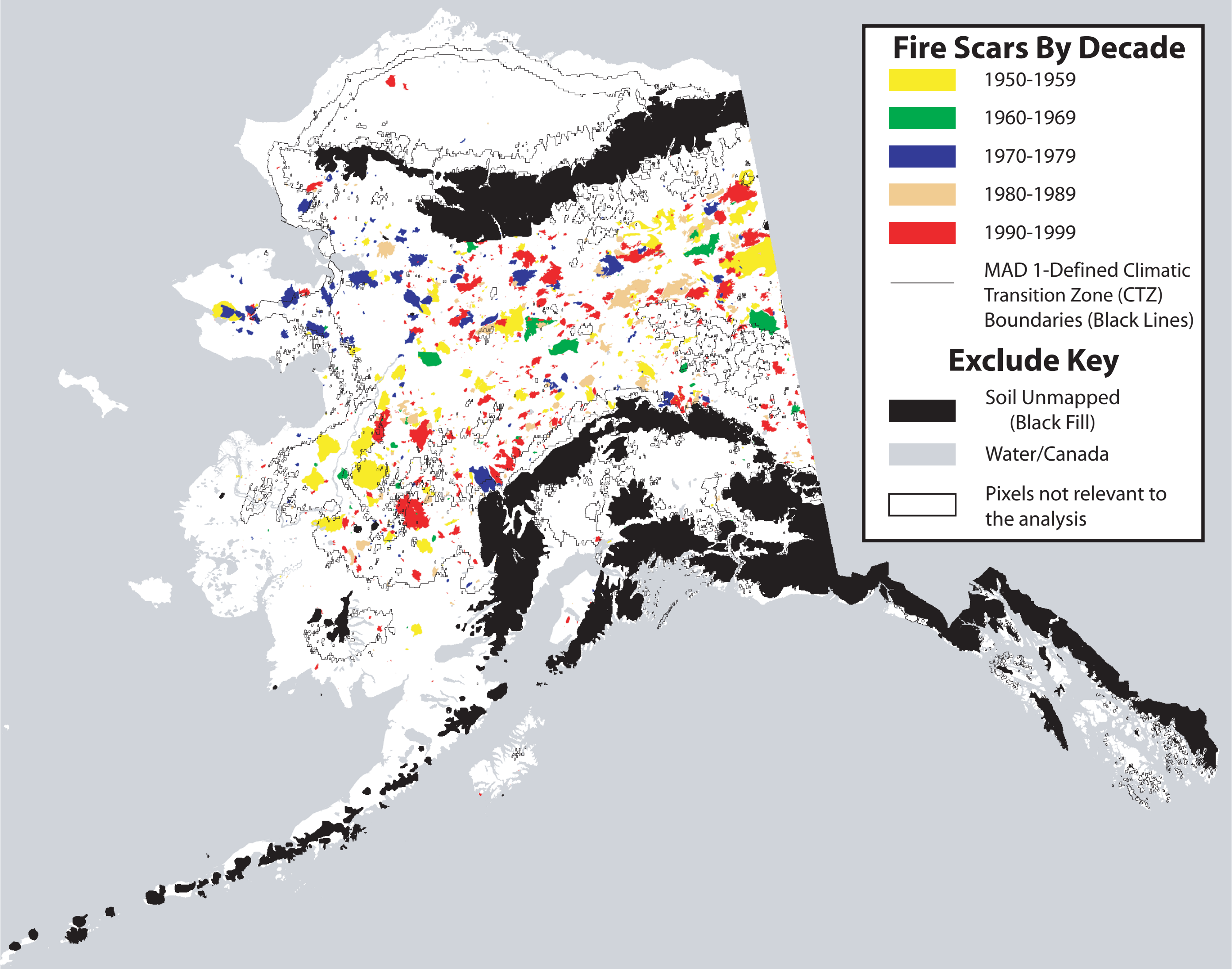


FIG. 13. Fire scars in Alaska (by decade, from 1950 to 1999) shown as overlay on the MAD 1-defined CTZ boundaries (thin black lines) from Fig. 11c. White shows pixels not relevant to the analysis, which also excluded water/parts of Canada (grey) and regions of unmapped soil (black). Data from Alaska Fire Service, Bureau of Land Management, Ft. Wainwright, Alaska. Available at http://agdc.usgs.gov/data/projects/fhm/.

boreal forest from the coastal rainforest. Mountains can block, especially in a north-south direction, the horizontal movement of air masses (temperature and precipitation), but they can also funnel summer storms from offshore into interior Alaska. The Bering Sea coastal shrub tundra and the interior boreal forest, unlike most other Alaskan biomes, have no distinct mountain barrier between them. Simpson et al. (2002) hypothesized that the western coastal marine boundary layer (enhanced cloud cover, reduced insolation, cooler soil and surface temperatures) effectively acts like an orographic boundary, limiting the westward expansion of the boreal forest toward the Bering Sea coast. The location of the north-south-oriented MAD-defined CTZ in western Alaska (Fig. 12) is consistent with this hypothesis because the inland extent of the western coastal marine boundary layer can vary considerably from year to year because of large-scale and regional variations in atmospheric circulation and sea-ice distribution associated with ENSO-type events and other global change processes occurring in the Arctic.

The Yukon-Charley region in interior Alaska is flanked on the southwest by the Alaska Range and on the north by the Brooks Range. The variable topography in the region (200 m to 1800+ m) produces large variations in weather and climate over relatively short horizontal space scales. The vegetation in this region is not well known, but satellite data indicate that significant changes in vegetation also occur over small space scales. The MAD-defined CTZ (Fig. 12) indicates that the climatic/environmental conditions of the Yukon-Charley area are highly sensitive to relatively small space scales, implying the presence of many small ecotones in the region.

Figure 13 shows the MAD 1-defined CTZs overlain on the decadal (1950–99) distribution of Alaskan forest fires. A comparison of these data and the quadratic biome classification (Fig. 9b) shows that many of the regions of

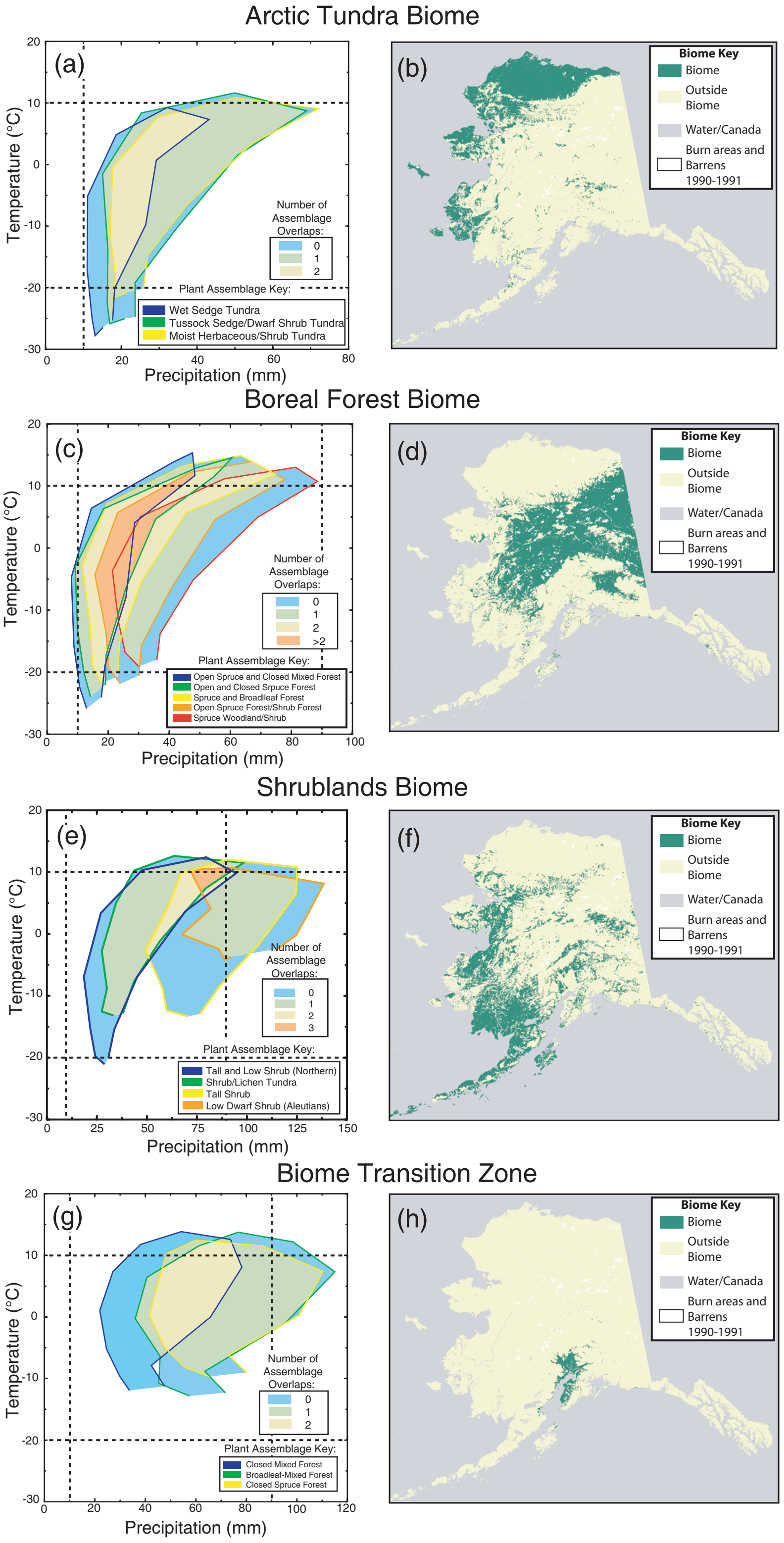


FIG. 14. a) Climographs (darker colored line segments) for the three plant assemblages that characterize the Arctic tundra biome. The darker colored outlines represent particular plant assemblages. The lighter colored overlays show the overlap in the mean monthly surface temperature and precipitation (T, P) space of these plant assemblages. b) Alaskan distribution of these three plant assemblages. The remaining panels show analogous data for the boreal forest biome (panels c, d), the shrublands biome (panels e, f), and the biome transition zone (panels g, h) defined by Fleming (1997). The dashed black box in panels a, c, e, and g defines the region of (T, P) space common to all four biomes. Climographs plotted to a common (T, P) scale can be found in Simpson et al. (2002: Fig. 12).

incorrect classification (Fig. 9c and d) relative to the available ground truth (Fig. 9a) occur in regions of Alaska subject to both large interannual climatic variability and fire-related disturbances. Both processes affect plant succession, which, in turn, further complicates either process-driven or data-driven biome modeling of Alaskan vegetation distributions.

The Partial Overlap of Environmental Variables for Different Biomes

Mean monthly values of surface temperature (T) and precipitation (P) were less useful than other discriminant variables for differentiating Alaskan biomes (Tables 2 and 3). Climographs, plots of mean monthly T versus P for a specific vegetation class, partially explain this result. The 19 Alaskan vegetation classes (Table 4) used to produce the climographs shown in Figures 14 and 15 are based on the phenological classification of Fleming (1997, 2000). Fleming used these vegetation classes to characterize the five Alaskan biomes and the biome transition zone shown in his original map (Fig. 2).

The dynamic range of (T, P) space across all the Alaskan biomes is very large. Therefore, the climograph of a given biome is plotted on a unique scale to emphasize the particular attributes of that biome and to provide adequate (T, P) spatial separation for plant assemblage overlays on a biome basis. Some applications or readers, however, may find it useful for these climographs to be plotted to a common scale. The interested reader may find this latter version of the climographs in Simpson et al. (2002:Fig. 12).

Climographs (Fig. 14a) for the three characteristic plant assemblages associated with the Arctic tundra biome are shown by the darker colored outlines (line segments used to connect mean monthly (T, P) points). Significant regions of overlap in the (T, P) climographic space, denoted by the lighter-colored solid overlays, exist amongst these assemblages. The dark green overlay (Fig. 14b) shows the geographical distribution of this biome. Analogous data are shown for the boreal forest biome (Fig. 14 c, d), shrublands biome (Fig. 14 e, f) and the biome transition zone (Fig. 14g, h). Although individual precipitation scales were used for these climographs to provide better separation of plant assemblages, the black dashed box in each panel identifies the region of (T, P) space common to them all. The large overlap in (T, P) space amongst these biomes shows that mean monthly values of T and P are not ideal discriminant variables. Mean monthly extrema

TABLE 4. The five Alaskan vegetation biomes, the biome transition zone, and the 19 Alaskan vegetation classes used to characterize them, based on the phenological classification of Fleming (1997, 2000).

Alaskan Vegetation Biomes	Alaskan Vegetation Classes
Alpine tundra and ice fields	Glaciers and snow (permanent snow & ice) Alpine tundra and barren land Dwarf shrub tundra
Arctic tundra	Tussock sedge/dwarf shrub tundra Moist herbaceous/shrub tundra Wet sedge tundra
Shrublands	Shrub/lichen tundra Low dwarf shrub (aleutians) Tall shrub Tall and low shrub (northern)
Boreal forest	Spruce woodland/shrub Open spruce forest/shrub forest Spruce and broadleaf forest Open and closed spruce forest Open spruce and closed mixed forest
Coastal rainforest	Closed spruce and hemlock forest
Biome transition zone	Broadleaf-mixed forest Closed mixed forest Closed spruce forest

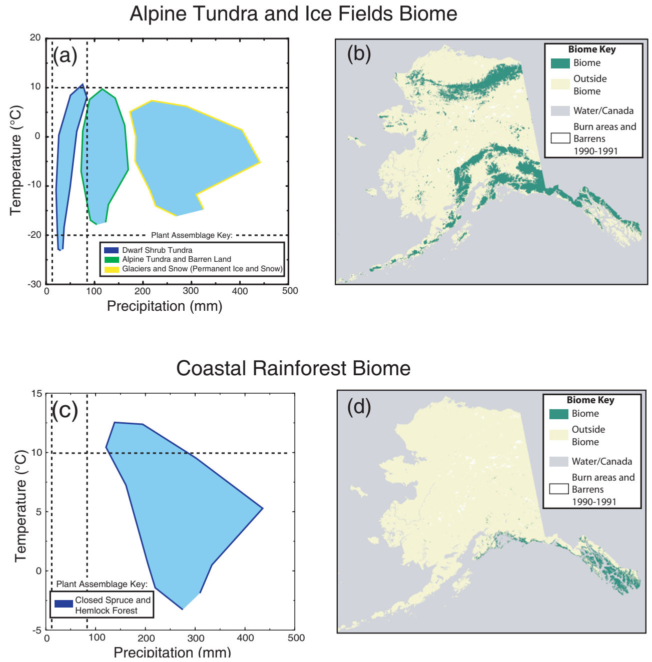


FIG. 15. Analogous to Figure 14 except for the alpine tundra and ice fields biome (panels a, b) and the coastal rainforest biome (panels c and d). No plant assemblage overlap occurs in these two biomes.

in T and P greatly improve classification skill (Tables 2 and 3), a result consistent with the climographs and with earlier Arctic ecological studies (Hopkins, 1959; Ritchie and Hare, 1971; Hare and Ritchie, 1972).

The alpine tundra and ice fields biome (Fig. 15a, b) and the coastal rainforest biome (Fig. 15c, d) are somewhat anomalous with respect to the other Alaskan biomes. The alpine tundra biome has three distinct classes (Table 4), but they have no spatial overlap in their (T, P) space. A recent, detailed study by Jia et al. (2003) of the Arctic Slope of Alaska (north of the crest of the Brooks Range) also includes a region of dry alpine tundra and barrens, which corresponds well with a similar region identified in the Brooks Range area of this biome (Figs. 9b, 15a, b). Overlap is irrelevant for the coastal rainforest biome, since it is characterized by a single plant assemblage. Both these biomes also have an extremely wide range in mean monthly precipitation compared to the biomes shown in Figure 14. However, the coastal rainforest has the smallest and most benign temperature range of all Alaskan biomes.

Comparison between the CCVM and our DA model

The Canadian Climate-Vegetation Model (CCVM) developed by Lenihan and Neilson (1993) is a rule-based equilibrium vegetation model for predicting the distribution of vegetation formation in Canada under current and projected climatic conditions. The model has three data inputs (temperature, precipitation, and soil) and is structured as a rule-based binary tree, in which nodes in the rule base define critical climatic thresholds that physiologically constrain the distributions of major plant types. This model is of particular interest because it was developed and applied in Canadian high-latitude biomes. Because biomes and climate processes follow longitudinal gradients on a global basis, results from our Alaskan study lend themselves well to comparison with those obtained by the CCVM model. The boreal forest biome (Fig. 2, Table 4), for example, is the Alaskan component of the circumpolar taiga (or boreal forest), most of which is found in Canada and Russia. And the coast rainforest biome of southeast Alaska (Fig. 2) is a contiguous extension of the coastal temperate rainforest biome found in British Columbia.

Both the CCVM and the data-driven quadratic discriminant analysis (DA) model presented here do reasonably well when modeling the distribution of vegetation at their respective scales. Both models, however, have problems in areas where climatic variables have large interannual variability, which in turn drives more complicated spatial and temporal patterns of vegetation distribution. A notable point of comparison between the results of the two models is their classification skill. Although these two approaches are rather different, both models attained 74% classification skill relative to their respective ground truth, possibly because many large-scale biomes found in Canada are similar to those in Alaska. Moreover, both the CCVM and the DA model have similar difficulties in areas where either succession or climate dynamics are not stable enough to sustain a true dominant assemblage of climax vegetation. Such areas, associated with large interannual variability in surface temperature and precipitation, occur (for example) within the MAD-defined CTZs (Fig. 11). Fire is of secondary importance to climate within this context (Lenihan and Neilson, 1993), but it still plays an important role in varying vegetation formations in south-central

TABLE 5. The Kappa statistic is used to compute the agreement between the biome truth map (Fig. 9a) and the quadratic discriminant model biome map (Fig. 9b) with the correction for chance agreement included. Column 3 is the agreement rating based on definitions given in Landis and Koch (1977).

Biome	Kappa	Rating
Alpine tundra and ice fields	0.413	fair
Arctic tundra	0.709	very good
Shrublands	0.443	fair
Boreal forest	0.762	very good
Coastal rainforest	0.866	excellent
Biome transition zone	0.019	not meaningful
All biomes	0.636	good

Canada (Halliday, 1937; Bird, 1961; Looman, 1979). In the boreal forest and neighboring biomes of Alaska, fire also plays a role in maintaining and disrupting vegetation formations (Figs. 2 and 13).

The Kappa statistic has previously been used within an ecological context, for example, to compare the agreement between different vegetation maps for a given geographical area (e.g., Congalton et al., 1983; Monserud and Leemans, 1992; Lenihan and Neilson, 1993). Here, the Kappa statistic is used to assess the agreement between the best modeled biome classification map (Fig. 9b), produced by the quadratic discriminant analysis with the most comprehensive input information vector (Table 3, D14), and the truth map (Fig. 9a). Kappa statistics for each biome (Table 5) and an overall Kappa statistic were computed as described earlier. On the agreement scale of Landis and Koch (1977), agreement between the two maps is excellent for the coastal rainforest biome, very good for the boreal forest and Arctic tundra biomes, fair for the shrublands and alpine tundra and ice fields biomes, and not meaningful for the biome transition zone. Lenihan and Neilson (1993) provide Kappa statistics based on the CCVM for two Canadian biomes with Alaskan counterparts: Arctic tundra($\kappa = 0.83$, very good) and boreal forest ($\kappa = 0.73$, very good). These values are similar to those for the corresponding Alaskan biomes shown in Table 5. A global Kappa statistic ($\kappa = 0.636$) indicates an overall good agreement between the discriminant analysis–based biome map (Fig. 9b) and the ground truth map (Fig. 9a) with unmapped soil areas excluded from the analysis.

Environmental Constraints on Alaskan Biomes

Environmental constraints (e.g., mean temperature of the coldest month) have been successfully used to predict the northern limit of boreal tree growth empirically (Ritchie and Hare, 1971) and to separate three primary northern latitude vegetation regions: tundra, interior boreal forest, and coastal rainforest (Hopkins, 1959). Such constraints have also been used in rule-based equilibrium models to determine the spatial distribution of vegetation types on continental and regional scales (Neilson et al., 1992; Lenihan and Neilson, 1993; Neilson, 1995) and on the global scale (e.g., Prentice et al., 1992). Analogous constraints for Alaskan vegetation (e.g., topographic constraints [Rupp et al., 2001]; temperature limitations on treeline advance at the boundaries between boreal forest and either Arctic tundra or alpine tundra [Lloyd and Fastie, 2002, 2003]) have also been reported.

Probability density functions of Alaskan surface temperature, and to a greater extent precipitation, contain statistical outliers (see Simpson et al., 2005: Figs. 4 and 5). Therefore, the data were statistically culled to minimize the potential effects of such anomalous values on statistics derived from individual biomes. After culling of outliers, 99.6% of the surface temperatures and 99% of the precipitation estimates remained to calculate biome-wide environmental statistics for all biomes modeled (Table 6). Only data at pixels where the quadratic discriminant analysis model (Fig. 9b) and the truth map classification (Fig. 9a) agreed were used. All data in Table 6 are temporally averaged over the period 1960–90, but temperatures are reported as either annual averages, monthly averages, or single point values, whereas precipitation values are reported as either average annual totals, average monthly totals, or single point totals. Most entries in Table 6 are also spatially averaged over the appropriate pixels in a given biome. A few spatially unaveraged values in Table 6 appear in bold. These statistics provide quantitative climatic information on the Alaskan biomes studied herein and complement information provided in the studies cited earlier.

CONCLUSION

A quadratic discriminant analysis model, combined with climatic (surface temperature and precipitation) and environmental (topography, permafrost, and soil) information was used to classify Alaska into five biomes (alpine tundra and ice fields, Arctic tundra, shrublands, boreal forest, and coastal rainforest) and one biome transition zone. Model skill is 74% when Fleming's (1997) biome map is taken as ground truth. Kappa statistics between the modeled and ground truth maps confirm the usefulness of the quadratic discriminant analysis model. A multivariate alteration detection (MAD) analysis isolated regions of Alaska with large interannual variability and little or no year-to-year consistency in climatic characteristics. About 55% of the pixels misclassified by the quadratic discriminant analysis occurred in these MAD-defined Climatic Transition Zones, supporting the conclusion that large interannual climatic variability does not favor the development of unique biomes. Results from the MAD analysis were used to distinguish "core biome areas" from "transition biome areas" or ecotones, and the Alaskan biome map of Fleming (1997) was modified to incorporate these results. Disturbance events (e.g., fires and the subsequent long recovery times required for Arctic plant communities to reach climax), coupled with the partial range overlap of

TABLE 6. Biome-wide statistics computed using only data at pixels where the quadratic discriminant analysis model and the ground truth map agree on biome class, and with outliers (< 0.5% for temperature, < 1% for precipitation) removed. The alpine tundra and ice fields biome is undersampled compared to the other biomes because most pixels in this biome were excluded for lack of soil data (e.g., most of the Brooks Range was excluded, black overlay in Figs. 7, 9a). Single point values are in bold. Note: The mean annual total precipitation values shown here are true annual totals (rather than the mean monthly totals shown in Figure 4).

	Alpine Tundra	Arctic Tundra	Shrublands	Boreal Forest Forest	Coastal Rainforest	Biome Transition Zone
a) Temperature (˚C)						
Number of pixels included in computations for each biome	32505	242490	135138	372637	28380	15279
Mean annual mean monthly temperature	-6.08	-9.23	-0.98	-4.60	5.18	0.71
SD[1] mean monthly temperature	4.16	3.68	2.49	1.62	1.03	0.92
Single coldest mean monthly temperature	**-29.00**	**-32.00**	**-27.00**	**-33.00**	**-8.50**	**-18.50**
Single warmest mean monthly temperature	**13.00**	**16.00**	**14.50**	**17.00**	**15.00**	**15.50**
Coldest month mean temperature	-19.04	-25.45	-12.44	-23.11	-2.31	-11.67
SD of coldest month mean temperature	6.56	5.78	5.48	3.08	1.71	2.92
Warmest month mean temperature	9.77	11.02	12.04	14.57	12.57	13.83
SD of warmest month mean temperature	1.30	1.90	1.04	1.20	0.80	1.09
b) Precipitation (mm)						
Number of pixels included in computations for each biome	31880	235634	131943	362133	27648	15139
Mean annual total precipitation	952.32	311.65	803.95	360.92	2907.48	640.21
SD of mean annual total precipitation	684.73	102.38	316.12	84.41	739.26	163.31
Minimum mean annual total precipitation	228.00	150.00	282.00	182.00	1324.00	340.00
Maximum mean annual total precipitation	3916.00	662.00	2066.00	626.00	5184.00	1092.00
Single minimum total mean precipitation in the driest month	**4.00** **(February)**	**2.00** **(March)**	**6.00** **(April)**	**2.00** **(February)**	**56.00** **(June)**	**6.00** **(April)**
Single maximum total mean precipitation in the wettest month	**554.00** **(October)**	**128.00** **(August)**	**268.00** **(September)**	**124.00** **(August)**	**790.00** **(October)**	**160.00** **(September)**
Driest month total mean precipitation	60.46	14.65	40.58	14.40	121.57	27.78
SD of driest month total mean precipitation	66.53	5.48	24.30	5.23	35.94	9.89
Mean wettest month total mean precipitation	105.61	61.25	107.76	66.24	452.77	92.21
SD of wettest month total mean precipitation	103.02	23.41	41.92	20.82	115.75	21.93

[1] SD = standard deviation.

environmental variables used to characterize Alaskan biomes, further complicate biome classification. As the Alaskan biomes studied have extensions or functional equivalents throughout the Northern Hemisphere polar region, the present results are expected to be applicable to other polar regions.

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