Significant climate warming, and drying in certain localities, has been observed in interior Alaska over the last 20 years. For example, the mean daily maximum temperature in the warm season at Fairbanks has been rising sharply (over 3°C per century) since 1949 (Figure 3.07). Perhaps equally significant, the number of days with the warmest extreme of temperatures, 26°C (80°F) or warmer, has increased substantially from just over a week in the early 1950s to nearly 3 weeks in the 1990s (Figure 3.08). The extremes of warm temperatures in the boreal forest are associated with moisture stress to trees and with rapid maturation of insects and their population buildups.

Figure 3.07 Mean daily maximum temperature (°C) at Fairbanks (1949-1996), 1 April to 30 September

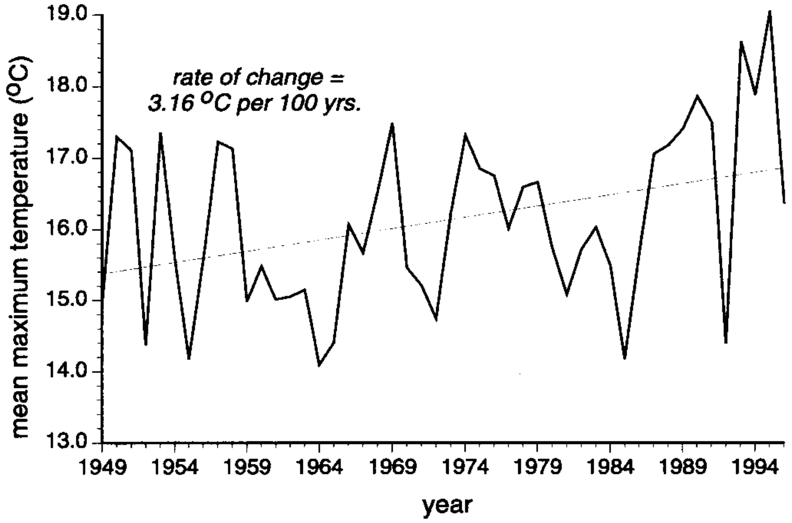
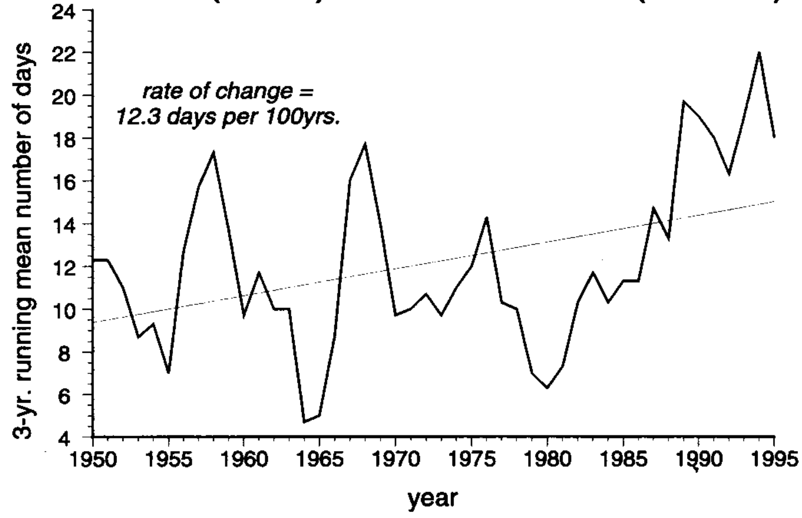
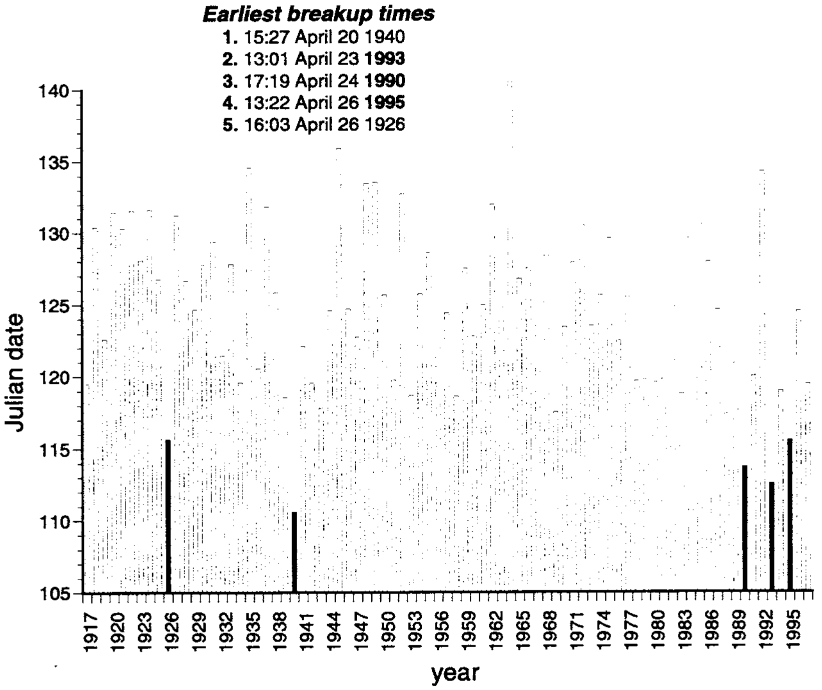


Figure 3.08 Smoothed number of days with maximum temperature 80 °F (26.7 °C) or warmer at Fairbanks (1950-1995)



The warming in interior Alaska has been effective in pushing back the date at which spring and early summer events begin. The earlier start to spring is reflected in the date at which ice breaks up on the Tanana River (Figure 3.09). The trend toward earlier breakup dates is particularly strong in the last 10 years; 3 of the 4 earliest breakup dates in the 81-year record are in the 1990s (Figure 3.09). Warm early spring and summer weather is apparently a necessary trigger factor in the production of the infrequent abundant white spruce cone and seed crops (Alden 1985, Zasada et al. 1992). Until recently the occurrence of a high number of days with warm temperatures in the early summer would be followed predictably the following year by a white spruce cone crop, unless a crop was already being produced in the trigger year. In the last decade or more, greater numbers of warm days than ever have occurred, but crops are not being formed.

Figure 3.09 Breakup date and time on the Tanana River 1917-1997



Earliest breakup times
1. 15:27 April 20 1940
2. 13:01 April 23 **1993**
3. 17:19 April 24 **1990**
4. 13:22 April 26 **1995**
5. 16:03 April 26 1926

Figure 3.10 illustrates how the recent Alaskan warming could be translated into longer growing seasons that begin earlier and terminate later in the year. A standard measure of growing season warmth is growing degree days[2]. A comparison of growing degree days from the most recent 24 years (1973-96) of the Fairbanks Airport climate data compared to the first 24 years (1949-72) shows the expected pattern of warmer and extended growing seasons (Figure 3.11). The average annual total of growing degree days is 10% greater in the most recent half of the Fairbanks record than in the first half (Figure 3.11). Myneni et al. (1997) claim that an increase in growing season length between 1981 and 1991 is detectable from satellite data in the northern hemisphere, concentrated in the area between 45° and 70° N.

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[2] Growing degree days are calculated as the mean of the high and low temperature for the date minus a threshold value such as 0°C (32°F).

Figure 3.10 Effect of recent Alaska climate warming on length of growing season and timing of "shoulder" seasons

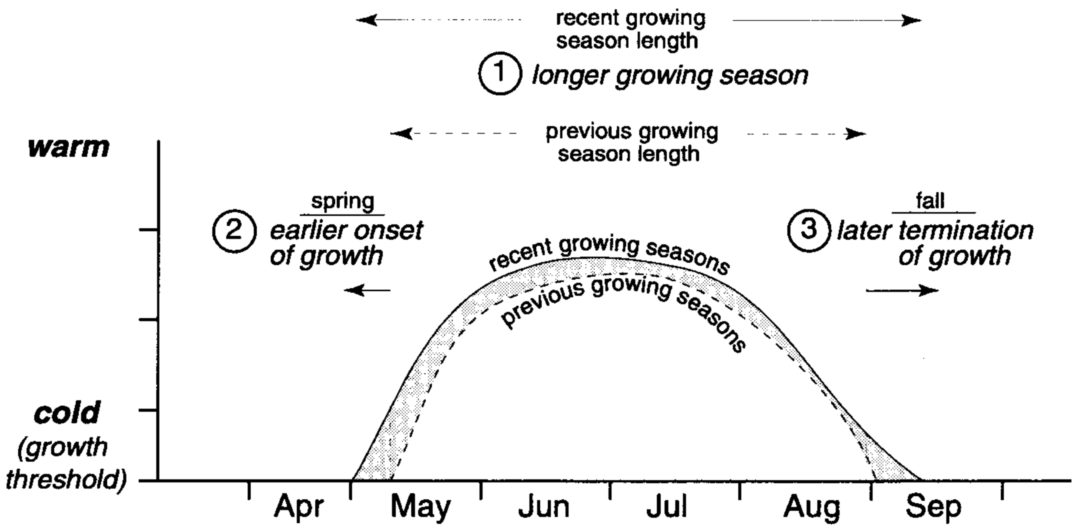
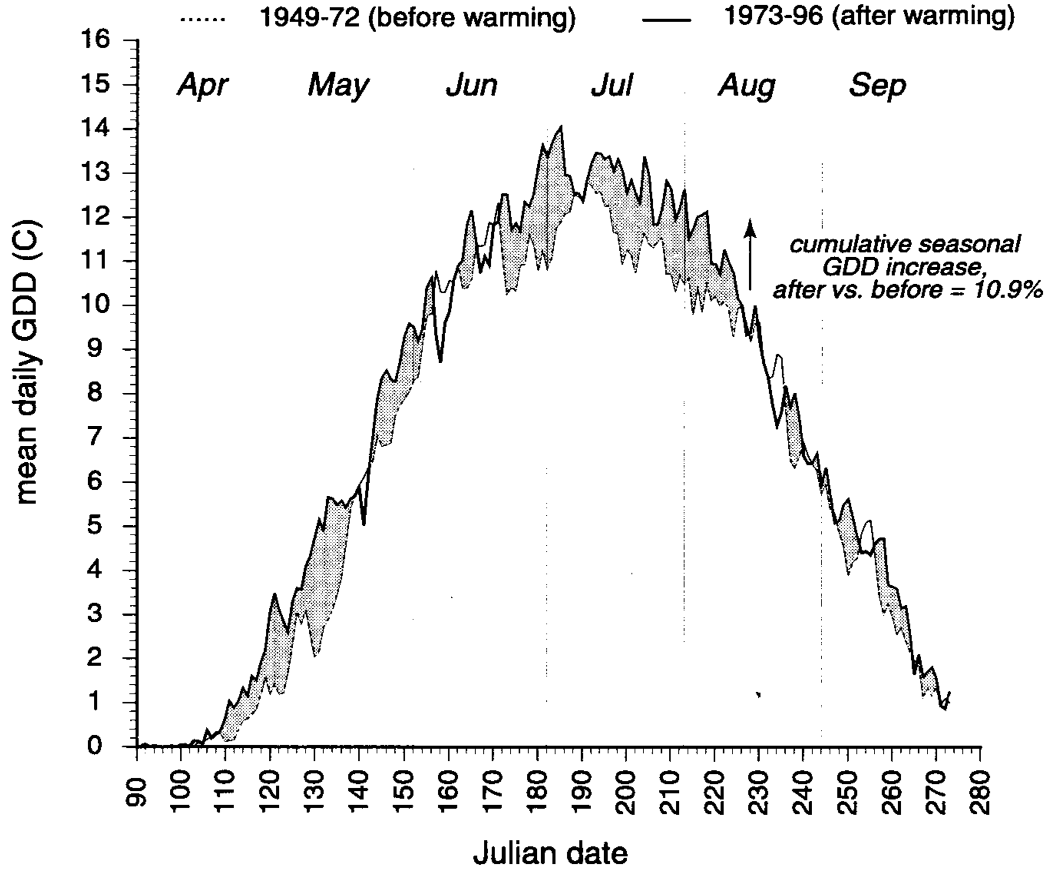
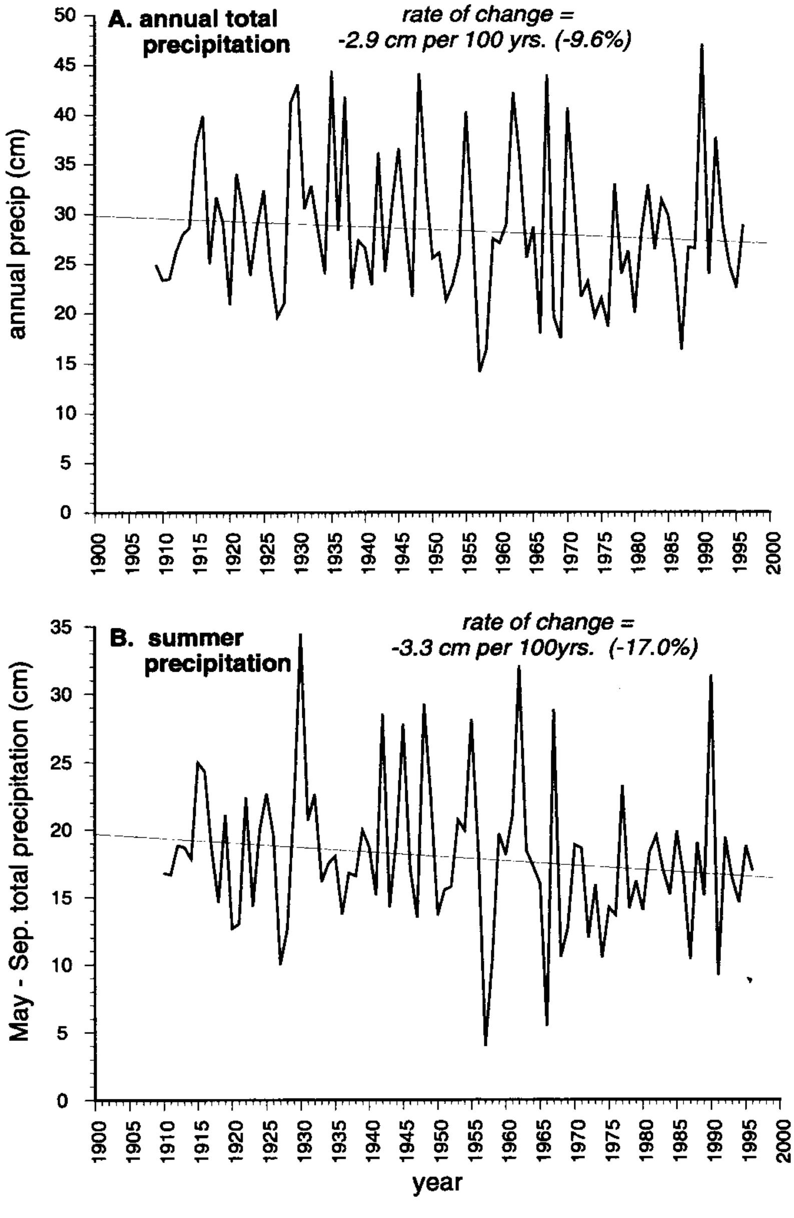


Figure 3.11 Growing season change in mean daily growing degree days (GDD) (4.4° threshold) at Fairbanks before and after climatic warming



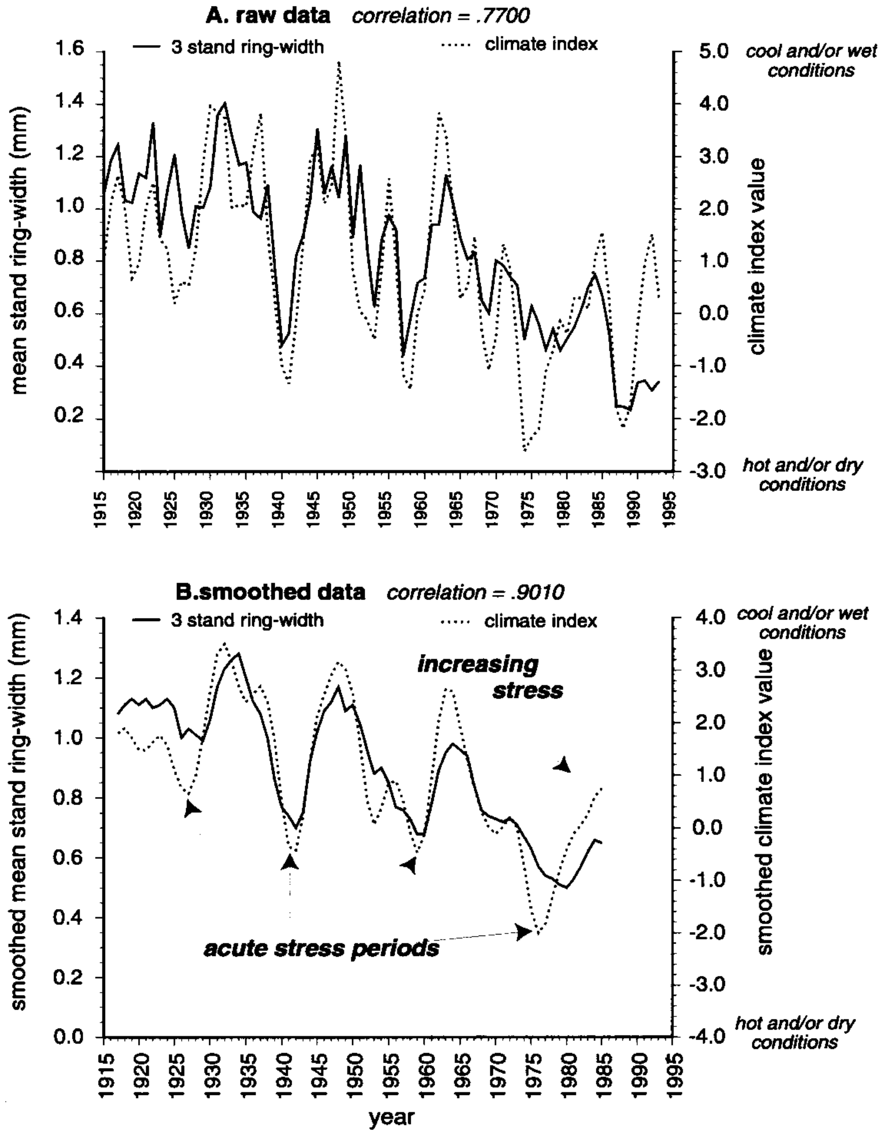
Both annual precipitation (Figure 3.12A) and summer precipitation (Figure 3.12B) have decreased during the entire 81-year (1906-96) period of record in Fairbanks. Summer precipitation, already marginal for forest growth across much of low elevation interior Alaska, has decreased at the rate of 17% per century at Fairbanks. Tree growth generally responds not only to the current year's weather but to several previous years as well. Figure 3.13 shows the trends in the multiple year precipitation and temperature index values that best match white spruce radial growth. White spruce growth is positively related to precipitation (greater growth in wet years) and negatively related to temperature (greater growth in cool years). Since the late 1970s both the precipitation and temperature index values have been moving strongly in an unfavorable direction, warming and drying, for white spruce growth (Figure 3.13). Because recent climate warming has started the growing season earlier and extended growth later, white spruce on productive sites near Fairbanks have become moisture stressed.

Figure 3.12 Precipitation trends at Fairbanks



Radial growth of upland white spruce trees closely follows the temperature and precipitation index derived from the Fairbanks climate data (Figure 3.13A). The smoothed trend of the white spruce climate index shows that the acute stress periods that were previously associated with the production of white spruce cone crops have been lengthened and exceeded by the climate change since the mid 1970s (Figure 3.13B), possibly resulting in less frequent cone crops. The combination of warming and drying are producing severe stress and decreased productivity in boreal forest trees unprecedented in the 20th century (Juday and Barry 1996). Elsewhere in Alaska, trees growing at the tree limit along the margin of tundra, which were previously limited only by warmth, are now limited by moisture stress (Jacoby and D'Arrigo 1995).

Figure 3.13 Relationship of mean radial growth of 3 white spruce stands at Bonanza Creek LTER and multiyear Fairbanks climate index



Wind Disturbance and Abiotic Stress

Coastal forests of Alaska respond not only to temperature and precipitation, but to wind as well. Wind is the primary disturbance agent in these forests (Veblen and Alaback 1996, Harris 1989). Coastal forests are highly susceptible to wind damage due to the combination of shallow root systems, poorly drained soils, and high winds—usually during peak rain intensity (Alaback 1990). Wind disturbance events typically are small-scale and involve single trees or small groups of trees—termed canopy gaps (Alaback 1990, Ott 1997). However, large-scale tree blowdowns do occur, especially along exposed coastlines (Veblen and Alaback 1996). The storms that deliver damaging winds to coastal Alaska are produced by the mixing of cold polar air with the warmer air of the North Pacific. A warmer sea surface intensifies the storm system produced (Salmon 1992). Since the late 1970s, a period of strong warming in southcentral and southeast coastal Alaska, the number of days with fastest wind speed > 50 km/hr (31 mph; moderate gale or stronger) increased dramatically (Figure 3.06).

Forest Insects

Biological disturbance agents of coastal forests respond to climate. The western black-headed budworm (*Acleris gloverana*) feeds primarily on western hemlock buds and current year's needles. This insect periodically defoliates large areas of western hemlock-Sitka spruce forest; it causes reduced tree growth, tree top-kill, and some whole-tree mortality (Hard 1974). Past black-headed budworm outbreaks affected trees over hundreds of thousands of hectares in southeast and southcentral Alaska, where it is one of the most damaging species present (Holsten et al. 1985). Growing season temperature appears to be a major factor controlling this insect's populations in coastal Alaska (Hard 1974). Large outbreaks are triggered by warm, dry summers (Furniss and Carolyn 1977).

The 1996 aerial survey of areas of major forest damage in Alaska identified 1.0 million ha (2.4 million ac) affected by insects (Holsten and Burnside 1997). Alaska contains 49.6 million ha (119 million ac) of forest land, of which about 24% is commercial forest land. Roughly speaking, an area equivalent to about 2% of all forest in Alaska and over 10% of commercial forest displays current or recent significant insect damage. This is an exceptional, if not historically unprecedented, level of damage. The ongoing mortality of spruce in southcentral Alaska caused by bark beetles (*Dendroctonus rufipennis*) currently involves 0.46 million ha (1.1 million ac) and is the largest forest insect epidemic in North America (Werner 1996).

The widespread outbreak of tree mortality in Alaska from stress-related insects[3] is also coincident in time with the onset of climate stress (Juday and Marler 1996). In the Bonanza Creek Long-Term Ecological Research (LTER) site in central interior Alaska, the tree-ring growth reduction caused by a 1993-95 spruce budworm (*Choristoneura spp.*) outbreak is unique in the 200-year record, supporting the view that outbreak levels of this insect are a new phenomenon caused by recent climate warming. In the monitored LTER stands snow breakage events in 1989 and 1990-91 triggered bark beetle attacks that occurred as tree growth was slowing markedly due to warming and drying. This suggests that climate change effects may be multiplicative, as one change (tree breakage from heavy snowfalls) sets the stage for another (insect outbreaks from damaged trees spread to undamaged stands because of warm weather and moisture stress).

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[3] Insects that either cause stress to trees by thier attacks or insects that concentrate their attacks on already stressed trees.

Wildland Fire

Fire is the major natural disturbance agent in the boreal forest. Large scale insect outbreaks can weaken or kill trees over vast areas, often leading to forest fires. Most of the area burned (about 90%) in the Alaskan boreal forest is the result of natural ignition caused by lightning. Figure 3.14 shows the annual area burned in Alaska. In years with prolonged hot and dry periods of summer weather, Alaska experiences millions of hectares burned, mostly in a few very large fires. Peaks in area burned appear about every 10 years, typically with very little area burned between peak years. The trend in annual area burned in Alaska is related to summer warmth (Figure 3.15). The overall trend for the period 1955 to 1996 represents a moderate decline (34%) of average area burned annually. A portion of the decline may be accounted for by the maximum fire suppression effort in the 1960 and early 1970s. Since the mid 1980s about 80% of Alaska has been zoned for limited or no wildland fire suppression. However, because an approximately 10 year cycle of the record of area burned is evident in the Alaska record, care should be taken to compare intervals that start and stop at equivalent positions on the cycle. If estimated fire acreage values typical of the Alaska fire cycle are supplied for 1997-99, then the trendline over the 20th century would yield a 100% increase in average area burned annually.

Several factors operating together suggest that a substantial area should burn in Alaska in the next 1 to 4 years. These include: (1) anticipated greater number of periods of warm and dry weather, (2) a cumulative fuel/soil moisture deficit that has developed in the mid 1990s, and (3) extensive areas of dead vegetation. The relative proportion of area burned as a result of human-caused fire is gradually increasing in Alaska as population and developed area increase. A combination of increased human ignition sources, extensive penetration of forest land by suburban and intensified rural development, and prolonged warmer and drier weather set the stage for highly destructive wildland-urban interface fires. The Miller's Reach-Big Lake fire of 1996 destroyed the largest number of structures by fire in the history of Alaska.

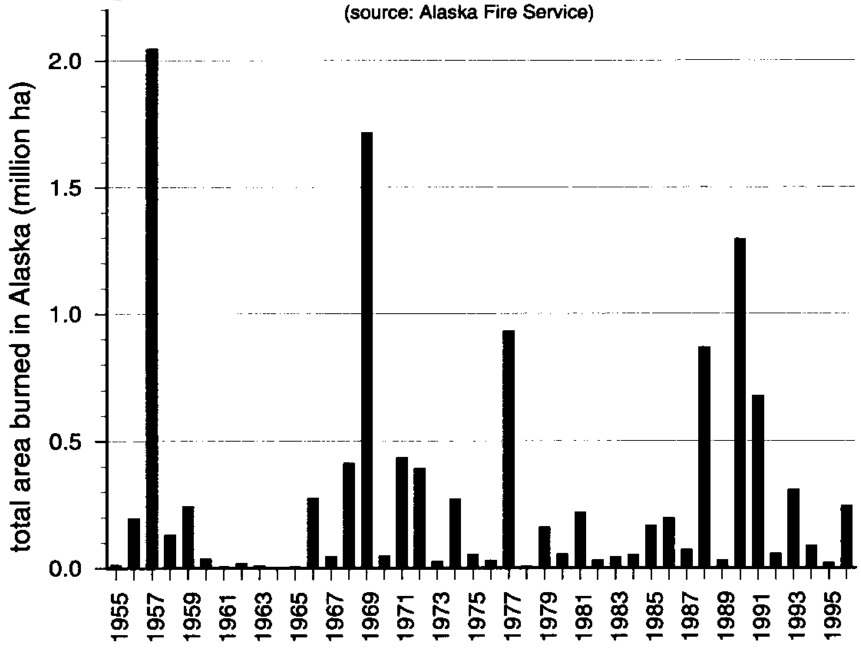
3.3 Future Changes

Coastal Forest

Much of the risk to Alaska coastal forest from climate change scenarios associated with global warming involve (1) destructive winds, (2) tree mortality from insect outbreaks, and (3) changes in forest hydrology.

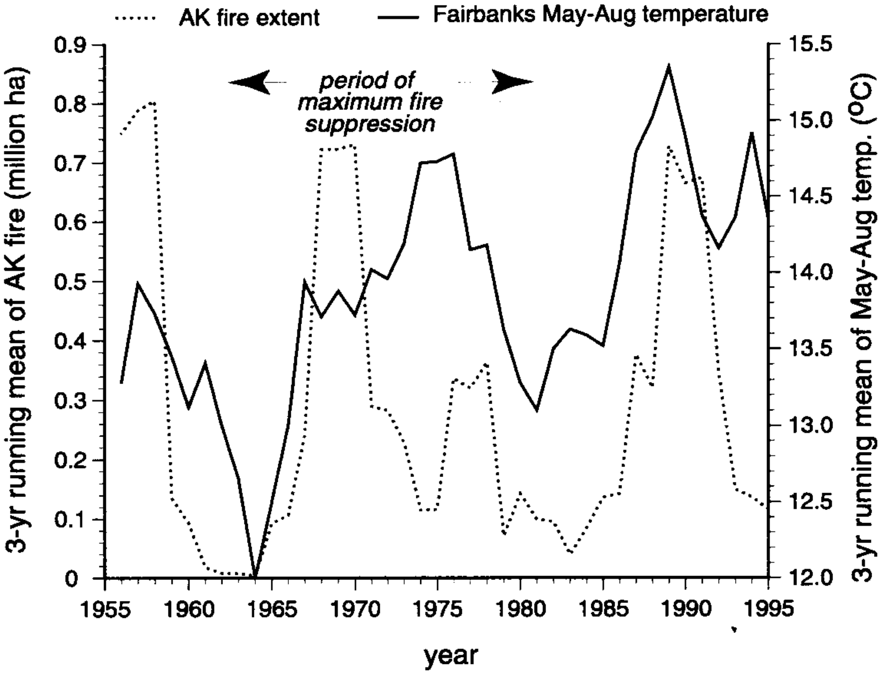
Recent forest mapping in the Tongass National Forest has identified large areas composed of trees that reproduced after the previous forest was flattened apparently by single windstorms in the past. The dramatic increase in gale winds (Figure 3.06) in coastal Alaska since the 1970s suggests that the risk of windthrow of trees will be much greater. To date, the increased frequency of storm does not correspond to an increase in the rate of formation of large-scale blowdowns in southeast Alaska. However, it is possible that canopy gap formation or expansion rates have increased as the number of days with storm winds increased. Additionally, the rate of blowdown around timber harvest units in the Tongass National Forest may have increased, but historic record-keeping systems are not sufficient to produce a reliable long-term time series. For 10 to 15 years following timber harvest, trees along clearcut edges in productive, low-elevation forests are more susceptible to wind disturbance

Figure 3.14 Annual total area burned in Alaska, 1955-1996



(source: Alaska Fire Service)

Figure 3.15 Relationship of mean summer temperature at Fairbanks and extent of area burned in Alaska



compared to trees in closed canopy forest. To date, a relationship between increased days with storm winds and increased formation of small forest canopy gaps or disturbance around the edges of cutting units has not been documented.

As climate warming occurs, insect populations that were previously restrained by marginal climatic conditions can increase rapidly (Fleming and Volney 1995). Insects can increase much more rapidly than the forest can respond, for example by adjusting the age or species distribution of trees. A transition period of increased tree mortality from insect outbreaks is a distinct probability in the Alaska coastal forest.

Most of the forest streams of coastal Alaska have short and steep watersheds resulting from the recent geologic uplift that characterizes most of the area. Precipitation has been so abundant and reliable that many streams with small watershed areas are important salmon producers or municipal or industrial water supplies. As the climate warms, the forest vegetation demands and moves more soil moisture into the atmosphere, reducing groundwater storage available for stream flows. An increase in the number of warm, dry weather intervals can make the problem acute.

Ultimately, a number of positive effects on the coastal forest could be associated with a warmer climate. These involve increased average tree growth and other forms of forest productivity, increased species diversity, and expansion of forest area following glacial retreat and colonization of tundra. These adjustments characteristically take some time, but the degree of intactness of the Alaska coastal forest ecosystem insures a high probability of success as long as the magnitude of change does not exceed the degree of adaptability of the organisms, especially of the vegetation. However, if the climate change is of such a magnitude as to require immigration of species not currently in or immediately adjacent to the region, then the survival challenge is considerably more severe. An increase of the mean annual temperature typical of Anchorage in the 20th century by the amount specified in Weller et al. (Chapter 2) would result in a climate that was no longer typical of boreal forest, but a transition type between boreal and temperate hardwood forest. The nearest source areas for propagules to establish such a vegetation type are located over half a continent away in the northcentral U.S. That would be far too distant to make (unassisted) any practical contribution to establishing elements of the temperate forest in Alaska.

The following potential changes in the Alaska coastal forest under the projected climate change scenarios are summarized according to confidence and degree of impact in Figure 3.16.

- Increased risk of widespread catastrophic windthrow, especially on outer coastal forest landscapes of southeast Alaska.
- More frequent, widespread, and damaging western black-headed budworm outbreaks causing damage to western hemlock.
- Increased windthrow damage of trees around the margin of clearcuts.
- Accelerated and expanded tree colonization of avalanche tracks and subalpine meadows and edges. Eventually, local limitations to Sitka black-tailed deer numbers will occur because of decreased summer subalpine meadow habitat in southern Alaska.

- Accelerated and more widespread tidewater and low elevation glacial retreat and forest and/or shrubland colonization at low elevations in southcentral Alaska. Widespread glacial retreat is followed by mountain hemlock treeline advance at moderate elevations in southeast Alaska.
- Continued and accelerating westward tree advance on the Alaska Peninsula and Kodiak Archipelago. Eventually western Alaska tree limit may be set by strong winds.
- Irregular northward expansion of the distributional limits of tree species currently confined to southernmost southeast Alaska, including western red cedar (*Thuja plicata*), subalpine fir (*Abies lasiocarpa*), Pacific silver fir (*Abies amabilis*), and red alder (*Alnus rubra*). Minor increases in elevation limits for these species will occur as well.
- Increased incidence and duration of warm temperature and/or low flow events in coastal forest streams causing anadromous fish mortality.
- Sustained high populations of Sitka black-tailed deer because of high winter survival resulting in local browse damage to tree regeneration.
- Continued low snow accumulations in most of low-elevation forested southeast Alaska resulting in reduced runoff and earlier peak flows in streams with low or moderate elevation headwaters.
- Continued gradual drying and subsequent oxidation of blanket peatlands accompanied by minor amounts of tree colonization.
- Continued heavy snow accumulations in much of moderate and high-elevation southcentral Alaska resulting in increased freshwater runoff in streams with moderate to high-elevation headwaters.
- Eventually, an increased risk of forest fire in southern southeast Alaska will develop where there is currently no fire history. Over the longer term the highly productive tree species Douglas fir (*Pseudotsuga menziesii*) would colonize such sites from current northern populations in north coastal British Columbia.
- Increased tree growth and average site productivity would be increased (previously non-commercial forest would meet the commercial threshold) as long as other factors, especially moisture, are not limiting. Higher elevation zones in the mountains might both warm sufficiently and experience sufficient precipitation to support these productive forest types.
- Appearance of new tree diseases, especially fungi, increase invasion in areas previously unaffected.
- Increased canopy gap formation from single tree and small group treefalls.
- Reduced abundance of shore pine as blanket peatlands (muskegs) and alpine habitats are reduced in extent.