STATE OF THE CLIMATE IN 2010

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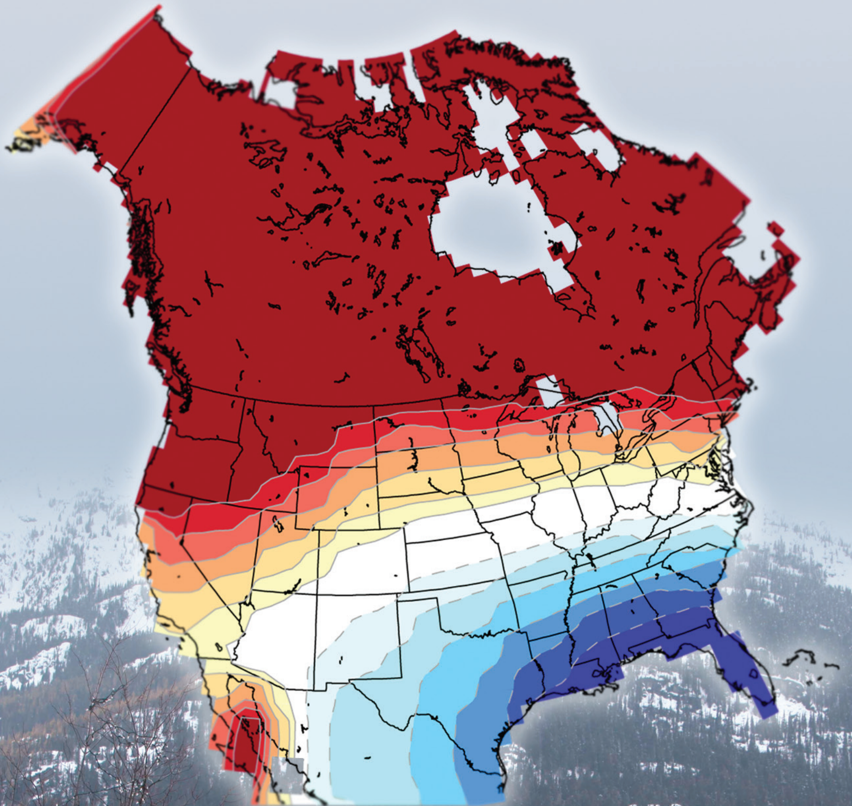

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www.whoi.edu/beaufort) show that the pack ice in the central Canada Basin is changing from a multiyear to a seasonal ice cover.

3) Sea ice thickness

Combined estimates of ice thickness from submarine and satellite-based instruments provide the longest record of sea ice thickness observation, beginning in 1980 (Kwok et al. 2009; Rothrock et al. 2008). These data indicate that over a region covering ~38% of the Arctic Ocean there is a long-term trend of sea ice thinning over the last three decades.

Haas et al. (2010) added to this record with results from a 2009 spring field campaign of airborne electromagnetic sounding surveys of sea ice thickness at multiple locations across the Arctic Basin. Consistent with the sea ice age results presented above, the thickest ice observed was along the coast of Ellesmere Island, Canada. Mean ice thicknesses were as high as 6 m, due to extensive ice deformation along the coast. The thinnest ice was found in the Chukchi and Beaufort Seas, with average thicknesses of 1.7 m to 1.9 m. Overall, the older ice was slightly thicker in 2009 relative to 2007. The 2009 modal thickness of undeformed first year ice was unchanged from 2007.

It is instructive to examine in detail the survey site in the Lincoln Sea north of Ellesmere Island (around 62.5°W and between 83°N and 84°N), which has been part of a sea ice mass balance observation program carried out in the same region since 2004 (Haas et al. 2010). The mean ice thickness in spring 2010 was 4.02 m (± 2.10 m standard deviation), with a modal thickness (representing multiyear ice) of 3.4 m. A comparison with thickness distributions from previous years shows that ice thicknesses were very large and relatively constant from 2004 to 2006. Then, more pronounced interannual variability was observed, with minimum thicknesses in 2008 (mean 4.37 ± 1.95 m, mode 3.2 m) and a temporal recovery in 2009. The more recent variability may be related to the reduced area and decreasing age of old ice north of Ellesmere Island (Fig. 5.12).

Other airborne electromagnetic surveys were performed in April in the Beaufort and Chukchi Seas and in April and August in Fram Strait by the Alfred Wegener Institute, Germany. While there was little change since 2007 in the Beaufort and Chukchi Seas, ice thicknesses in Fram Strait were as much as 0.5 m lower than in 2009 (S. Hendricks 2010, personal communication), which is most likely related to the strong interannual and spatial variability typical for Fram Strait.

e. *Land*

1) Vegetation—D. A. Walker, U. S. Bhatt, T. V. Callaghan, J. C. Comiso, H. E. Epstein, B. C. Forbes, M. Gill, W. A. Gould, G. H. R. Henry, G. J. Jia, S. V. Kokelj, T. C. Lantz, S. F Oberbauer, J. E. Pinzon, M. K. Raynolds, G. R. Shaver, C. J. Tucker, C. E. Tweedie, and P. J. Webber

Circumpolar changes to tundra vegetation are monitored from space using the Normalized Difference Vegetation Index (NDVI), an index of vegetation greenness. In tundra regions, the annual maximum NDVI (MaxNDVI) is usually achieved in early August and is correlated with above-ground biomass, gross ecosystem production, CO_2 fluxes, and numerous other biophysical properties of tundra vegetation (Tucker et al. 1986; Stow et al. 2004). MaxNDVI is obtained each year from a 29-year record of NDVI derived from the AVHRR sensors on NOAA weather satellites (Bhatt et al. 2010).

MaxNDVI has increased during the period of satellite observations (1982–2010) in Eurasia and North America (Fig. 5.13a), supporting model predictions that primary production of Arctic tundra ecosystems will respond positively to increased summer warmth (Bhatt et al. 2008; Lawrence et al. 2008). Despite considerable spatial variation in the magnitude of change in each of the three variables examined, annual MaxNDVI patterns were also positively and significantly correlated with more abundant ice-free coastal waters (Fig. 5.13a) and higher tundra land temperatures (Fig. 5.13b) over most of the Arctic region (Bhatt et al. 2010). Trends in summer open water, summer land-surface temperatures, MaxNDVI, and time-integrated NDVI (TI-NDVI) in the adjacent land areas were calculated for the major sea basins in the Arctic. TI-NDVI is the sum of maximum NDVI occurring in bi-weekly intervals, and provides a perspective that includes the length of the growing season. For example, not only does Baffin Bay have a moderate MaxNDVI increase (13%) but it also has the largest TI-NDVI increase (38%). This indicates that major changes in greenness have occurred over the length of the growing season, likely due to extension of the snow-free and growing seasons (see sections 5e4 and 5f). Several new features are apparent that were not present in the *BAMS State of the Climate in 2009* (Walker et al. 2010). For example, the sea ice changes occurring in the eastern Kara Sea far exceed those elsewhere, but there has been no warming over adjacent lands or a major increase in MaxNDVI, as would have been expected. Instead, the adjacent land areas have cooled slightly and there is only a modest increase in NDVI.

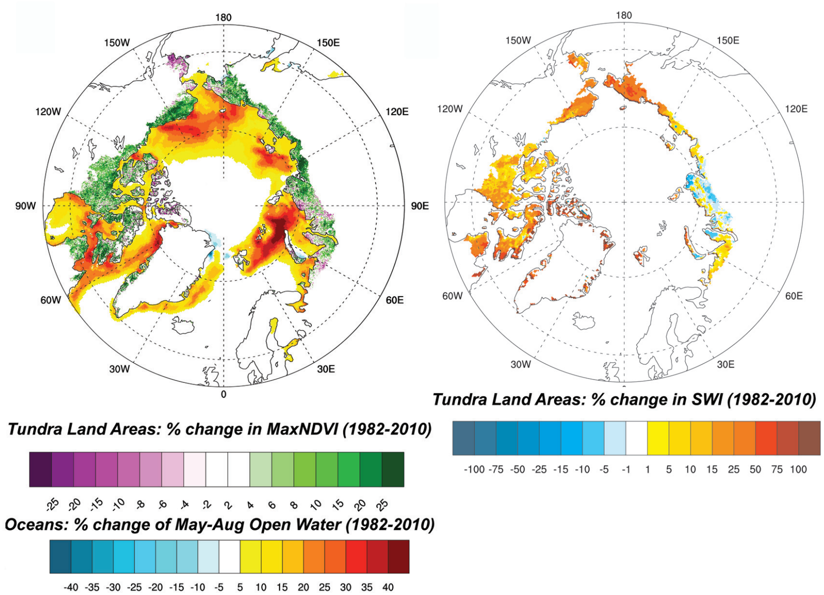

Fig. 5.13. Trends for (a) summer (May–August) open water and annual MaxNDVI, and (b) land-surface summer warmth index (annual sum of the monthly mean temperatures > 0°C) derived from AVHRR thermal channels 3 (3.5–3.9 μm), 4 (10.3–11.3 μm) and 5 (11.5–12.5 μm). Trends were calculated using a least squares fit (regression) at each pixel. The total trend magnitude (regression times 29 years) over the 1982–2010 period is expressed as a percent of the 1982 value.

Temporal changes in MaxNDVI for Arctic areas in Eurasia and North America show positive and nearly parallel increases amounting to a MaxNDVI increase of 0.02 NDVI units per decade (Fig. 5.14a). However, there is considerable variability in the rate of increase in different regions of the Arctic. For example, the MaxNDVI increase adjacent to the Beaufort Sea (+26%) is the most rapid in the Arctic and corresponds to large changes in open water (+31%) and summer land temperature (+17%). On the other hand, the MaxNDVI change in the western Kara Sea is among the smallest (+4.4%), corresponding to smaller changes in sea ice (+20%) and land temperatures (-6%; Fig. 5.14b).

In 2009 there was a circum-Arctic decrease in NDVI (Fig. 5.14a) that corresponded to elevated atmospheric aerosols over the Arctic in the same year (Stone et al. 2010). This coincided with generally lower temperatures across the Arctic in 2009 and 2010 (see section 5b). The elevated aerosols were attributed to an accumulation of pollutants in the upper troposphere from Eurasian industrial centers in combination with volcanic plumes from the eruption of Mount Redoubt in Alaska. The enhanced Arctic haze in 2009 was estimated to have reduced net shortwave irradiance by about 2 W m^{-2}–5 W m^{-2} (Stone et al. 2010).

Bi-weekly NDVI data reveal clear differences in phenological (green-up) patterns in North America and Eurasia (Fig. 5.15). Both regions show a ~0.06 unit MaxNDVI increase over the 29-year record. In Eurasia there is a somewhat more rapid green-up and peak NDVI was reached about 2 weeks earlier during 2000–09 than in the 1980s. In North America there is no significant shift in peak greenness. Neither continent shows a significant trend toward a longer growing season. However, whole-continent data appear to mask changes along latitudinal gradients and in different regions. For example, during 1982–2003, MaxNDVI along the Canadian Arctic climate gradient showed a ~1-week shift in the initiation of green-up and a somewhat delayed onset of senescence in the Low Arctic (Jia et al. 2009). The High Arctic did not show earlier initiation of greenness, but did show a ~1–2 week shift toward earlier MaxNDVI.

The increased Arctic greening observed in the satellite data is also observed in long-term in situ vegetation measurements. For example, the InternationTundra Experiment (ITEX), established in 1990, has made annual measurements of plant growth and

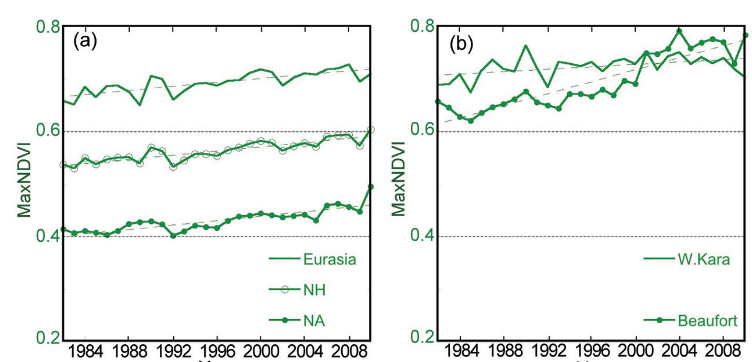

Fig. 5.14. Time series of MaxNDVI during 1982–2010 for coastal tundra in the (a) Northern Hemisphere as a whole, Eurasia, and North America, and (b) western Kara Sea and Beaufort Sea.

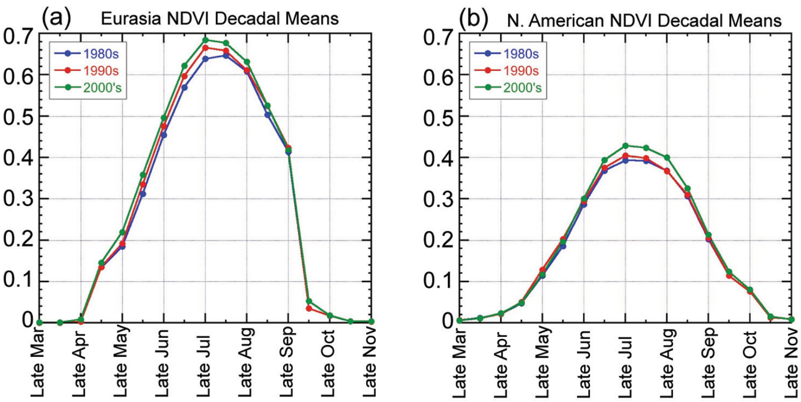

Fig. 5.15. Decadal changes in NDVI-derived phenology in (a) Eurasia and (b) North America.

phenology for up to 20 years using standardized protocols (Henry and Molau 1997). A recent synthesis of the long-term ITEX warming experiments has shown that effects on plant phenology differ by trait, community, and functional types (Elmendorf et al. 2010). Some of these results indicate there have been productivity increases consistent with warming (e.g., Hill and Henry 2011). In others, the links between local climate warming and vegetation change found in the NDVI data were not supported at the plot scale. There is a need for more careful evaluation of the causes of the observed changes, which may be driven by local long-term non-equilibrium factors other than climate warming, such as recovery from glaciation or changes in snow cover or precipitation (Troxler et al. 2010; Mercado-Díaz and Gould 2010).

The Back to the Future International Polar Year project, which revisited numerous Arctic research sites established between 15 and 60 years ago, is revealing decadal-scale changes. These include vegetation change and increases in plant cover at Barrow, Alaska, on Baffin Island, and at multiple sites throughout Beringia (Tweedie et al. 2010). Advanced phenological development and species shifts associated with drying occurred on Disko Island, Greenland. Warming of permafrost was documented in sub-Arctic Sweden, and dramatic changes in pond water column nutrients, macrophyte cover, and chironomid assemblages have been noted near Barrow. NDVI, gross ecosystem production, and methane efflux from wet vegetation types have increased at sites near Barrow, on Baffin Island and at the Stordalen mire in sub-Arctic Sweden. In most cases, air and ground warming appear to be the primary causes of change, but disturbances of various types are causing change at some sites (Johnson et al. 2010). Warming will cause changes in species distributions and biodiversity in the Arctic. Consequently, the Circumpolar Biodiversity Monitoring Program is launching an integrated biodiversity monitoring plan for Arctic land and freshwater ecosystems (McRae et al. 2010).

Other Arctic vegetation changes indirectly related to climate include those associated with landslides, thermokarst, and fires, which are increasing in frequency in several regions (e.g., Goosef et al. 2009; Lantz et al. 2010a,b; Mack et al. 2011 in revision; Rocha and Shaver 2011). Higher soil temperatures, thawing permafrost, more abundant water, and increased nutrients due to such disturbances result in pronounced greening often due to more abundant shrub growth. Increasing air and ground temperatures are predicted to increase shrub growth in much of the Arctic, with major consequences for ecosystems (Lantz et al. 2010b). Several studies have observed increased shrub growth due to artificial warming, although the increases are small and frequently not statistically significant (e.g., Bret-Harte et al. 2002). On the other hand, there is growing evidence for increased shrub abundance at climatically- and anthropogenically-disturbed sites (Lantz et al. 2010a,b; Walker et al. 2011). In the Russian Arctic, erect deciduous shrub growth closely tracks both the recent summer warming of ~2°C over more than half a century and a trend of increasing NDVI since 1981 (Forbes et al. 2010).

2) Permafrost—V. Romanovsky, N. Oberman, D. Drozdov, G. Malkova, A. Kholodov, and S. Marchenko

Observations show a general increase in permafrost temperatures during the last several decades in Alaska (Romanovsky et al. 2007; Osterkamp 2008; Smith et al. 2010), northwest Canada (Couture et al. 2003; Smith et al. 2010), Siberia (Oberman 2008; Drozdov et al. 2008; Romanovsky et al. 2010a) and Northern Europe (Harris and Haeberli 2003; Christiansen et al. 2010).

Most of the permafrost observatories in Alaska show a substantial warming during the 1980s and especially in the 1990s. The magnitude and nature of the warming varies between locations, but is typically from 0.5°C to 2°C at the depth of zero seasonal temperature variations (Osterkamp 2008). However, during the 2000s, permafrost temperature has been