served for warm permafrost in the discontinuous zone, with recent data indicating a negligible change (Romanovsky et al. 2011; Smith et al. 2010). In the high Canadian Arctic, greater warming has been observed, with recent data indicating a continuing steady increase in permafrost temperature since 2000 (Romanovsky et al. 2011; Smith et al. 2010). Permafrost temperature has increased by 1°C – 2°C in northern Russia during the last 30 to 35 years, but this trend was interrupted by colder conditions in summer 2009 and winter 2009/10 at many locations, especially in the western sector of the Russian Arctic. Long-term permafrost temperature records are limited for the Nordic area, with a few beginning at the end of the 1990s. These, however, show recent decadal warming of 0.04°C yr^{-1} to 0.07°C yr^{-1} in the highlands of southern Norway, northern Sweden, and Svalbard, with the largest warming in Svalbard and northern Scandinavia (Isaksen et al. 2011; Christiansen et al. 2010).

Identification of trends in ALT is difficult, as thaw depth responds to interannual variations in summer air temperature (e.g., Smith et al. 2009; Popova and Shmakin 2009). Decadal trends in ALT vary regionally, with a progressive increase in ALT observed in some Nordic countries, e.g., in the Abisko area of Sweden since the 1970s, with an accelerated rate after 1995, and disappearance of permafrost in several mire landscapes (e.g., Åkerman and Johansson 2008; Callaghan et al. 2010). This increase ceased during 2007–10, coincident with drier summer conditions (Christiansen et al. 2010). ALT has increased since the late 1990s on Svalbard and Greenland, but the rates vary spatially and temporally (Christiansen et al. 2010). In the eastern Canadian Arctic, ALT has increased since the mid-1990s, with the largest increase occurring in bedrock of the discontinuous permafrost zone (Smith et al. 2010). Active-layer thickness on the North Slope of Alaska has been relatively stable, without pronounced trends during the last 15 years (Streletskiy et al. 2008; Shiklomanov et al. 2010).

h. *Lake ice*—C. R. Duguay, L. Brown, K.-K. Kang, and H. K. Pour

Lake ice phenology, which encompasses freeze-up (ice-on) and break-up (ice-off) dates, and ice cover duration (ICD), is largely influenced by air temperature changes and is therefore a robust indicator of regional climate (e.g. Duguay et al. 2006; Kouraev et al. 2007; Latifovic and Pouliot 2007). Ground-based observational records have provided evidence of later

SIDEBAR 5.2: CHANGING ARCTIC TUNDRA VEGETATION BIOMASS AND GREENNESS—D. A. WALKER, U. S. BHATT, H. E. EPSTEIN, P. BIENIEK, J. COMISO, G. V. FROST, J. PINZON, M. K. RAYNOLDS, AND C. J. TUCKER

Eighty percent of the non-alpine tundra biome in the Arctic is within 100 km of the Arctic Ocean and adjacent seas, its distribution largely controlled by cold summer air masses associated with the pack ice. It is expected that if sea ice continues to decline the adjacent tundra areas will warm during the summer (Lawrence et al. 2008), and the higher temperatures will increase tundra primary productivity and biomass (Bhatt et al. 2010; Elmendorf et al. 2011; Callaghan et al. 2011; Epstein et al. 2012).

Recently, Raynolds et al. (2012) established a very strong correlation ($r^2 = 0.94$, $p < 0.001$) between zonal (climax)aboveground plant biomass at the peak of the growing season at mesic (moist) sites and the annual maximum NDVI (Normalized Difference Vegetation Index). The latter is an index of vegetation greenness derived from Advanced Very High Resolution Radiometer (AVHRR) data. Derived for zonal/climax vegetation along two transects in North America and Eurasia, the Raynolds et al. (2012) relationship was used by Epstein et al. (2012) to determine that above-ground tundra biomass at representative sites increased by 19.8% during the period of the NDVI record (1982–2010). This has major implications for tundra ecosystems, including active layer depth, permafrost temperature and distribution, hydrology, wildlife, and human use of Arctic landscapes.

The biomass-greenness relationship described above offers the promise of easily determining total above-ground tundra biomass from NDVI. However, since the data were limited to vegetation on zonal sites, and it is not known how well the relationship holds for complex landscapes composed of many plant community types, NDVI continues to be used primarily as a measure of greenness and a proxy for total above-ground biomass.

During 30 years of AVHRR observations (1982–2011), area-averaged MaxNDVI (Fig. SB5.2b) has increased 15.5% in the North American Arctic, with a particularly sharp increase since 2005, and 8.2% in the Eurasian Arctic, although values have been nearly constant since 2001 (Bhatt et al. 2010, updated to 2011). Summer land temperatures in the tundra regions also show different geographic patterns between 1982 and 2011, with the area-averaged Summer Warmth Index (SWI, the sum of mean monthly temperatures > 0°C, or thawing degree months) increasing 10.1% for North America and decreasing 2.6% for Eurasia (Fig. SB5.2a). Large areas of the Eurasian Arctic are apparently cooling during the summer growing season and contributing to the smaller NDVI response. A decreasing NDVI trend is particularly pronounced in the region adjacent to the northern Barents and Kara Seas (Fig. SB5.2b), where an increase in extent and persistence of the open water sea-freeze-up and earlier break-up dates in the Northern Hemisphere, particularly during the second half of the 20th century (e.g., Brown and Duguay 2010). In the last 20 years, however, ground-based lake ice networks have been diminished to the point where they can no longer provide the quality of observations necessary for climate monitoring. Satellite remote sensing is the most logical alternative for Arctic-wide lake ice observing.

Spatial and temporal variability in ice phenology and ICD derived at the pixel level from the NOAA Interactive Multisensor Snow and Ice Mapping System (IMS) 4-km resolution grid daily product (National Ice Center 2008) was analyzed for the 2010/11 ice season and compared to average conditions for the full length of the available satellite historical record (since 2004). The IMS incorporates a wide variety of satellite imagery (AVHRR, GOES, SSMI, etc.) as well as derived mapped products (USAF Snow/Ice Analysis, AMSU, etc.) and surface observations (see Helfrich et al. 2007 for details).

Freeze-up in 2010 was close to the 2004–10 mean throughout much of the Arctic. The major exception was northern and eastern Europe, where freeze-up occurred 20–40 days earlier than mean freeze-up. The most likely explanation for this very early freeze-up is penetration of cold air from the Arctic into Europe in autumn 2011 (see section 5b).

Break-up in 2011 was close to the 2004–10 mean in the North American Arctic. In contrast, a large number of lakes in northernmost Europe and eastern Siberia experienced earlier break-up (10–20 days), while lakes in much of eastern Europe and the southern portion of northern Europe experienced later break-up (10–30 days). The earlier break-up in eastern Siberia is consistent with the record-low June snow cover extent (see section 5d) over Eurasia. The later break-up in eastern Europe and the southern portion of northern Europe is consistent with colder early spring temperatures in this region (see section 5b).

Compared to the 2004–10 mean, ICD (Fig. 5.15) in 2010/11 was ~14 days shorter in central and eastern Arctic Canada and 14–21 days shorter in eastern Siberia. In contrast, ICD was 14–21 days longer in Baffin Island and western Canada/Alaska and as much as 28–42 days longer in northern and eastern Europe. The combination of earlier freeze-up and later break-up due to colder winter/early spring weather explains the longer ICD over Europe.

son in the summer and into the fall could be providing a winter-long source of moisture to these areas, increasing winter snowpack and decreasing winter temperatures (Cohen et al. 2012).

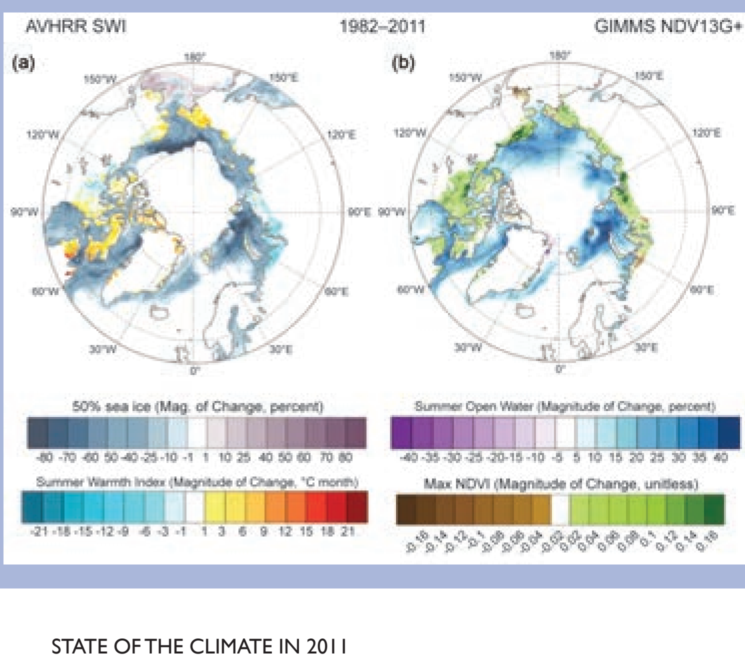

Fig. SB5.2. (a) Magnitude of changes in sea ice break-up (as represented by 50% sea ice concentration) and Summer Warmth Index for land area. (b) Magnitude of changes in summer (May–Aug) open water and tundra MaxNDVI (annual maximum NDVI, usually reached in early August). Magnitude of change is the slope of the simple linear regression trend line multiplied by the number of years of record (30 years: 1982–2011). The sea ice concentration and open water data were derived from SMMR and SSM/I passive microwave records. Ice concentration time series were assembled using data averaged over a three-week period centered on the week when mean concentrations were 50%; the more negative the value on the scale, the earlier 50% ice concentration, or break-up, occurs. Open water indicates the integrated summer open water amount. All the above information was derived from AVHRR data and the Global Inventory, Modeling and Mapping Studies (GIMMS) dataset.