Dating the Growth of Oceanic Crust at a Slow-Spreading Ridge

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Nineteen uranium-lead zircon ages of lower crustal gabbros from Atlantis Bank, Southwest Indian Ridge, constrain the growth and construction of oceanic crust at this slow-spreading midocean ridge. Approximately 75% of the gabbros accreted within error of the predicted seafloor magnetic age, whereas ~25% are significantly older. These anomalously old samples suggest either spatially varying stochastic intrusion at the ridge axis or, more likely, crystallization of older gabbros at depths of ~5 to 18 kilometers below the base of crust in the cold, axial lithosphere, which were uplifted and intruded by shallow-level magmas during the creation of Atlantis Bank.

Slow- and ultraslow-spreading ridges with spreading rates of <55 mm/year (*1*) constitute nearly 60% of the total length of midocean ridges. Results from a variety of studies (*2*–*7*) indicate that slow- and ultraslow-spreading oceanic crust is dominantly created by the emplacement of small magma bodies of up to 500 m in thickness (*7*) into zones of partially solidified crystal mush (*2*, *3*). Conventionally, these magma bodies are thought to be emplaced episodically over a short period of time beneath the axial ridge valley; however, there have been few attempts (*5*) to date the timing or rate of their emplacement. Previous U-Pb geochronologic studies of oceanic crust have either focused on dating continental breakup (*8*) or identifying much older, inherited components (*9*). Here, we provide U-Pb age determinations using sensitive high-resolution ion microprobe reverse geometry (SHRIMP-RG) of lower oceanic crust exposed at the tectonically denuded Atlantis Bank oceanic core complex (57°E) on the Southwest Indian Ridge (SWIR).

The SWIR separates the Antarctic and African plates (Fig. 1, inset). Atlantis Bank lies ~100 km south of the SWIR rift valley, where the seafloor spreading half rate is ~8.5 mm/year for the Antarctic plate (*10*, *11*). Our samples are from the footwall of a dissected, long-lived detachment fault system (*12*). Sea-surface magnetic anomalies suggest that oceanic crust at Atlantis Bank formed over a period of ~3.0 million years (My) (table S1). Atlantis Bank consists of variably deformed and denuded lower oceanic crust and upper mantle (*7*, *10*, *12*–*16*). Rocks from Ocean Drilling Program (ODP) Hole 735B and from submersible dives at Atlantis Bank include olivine gabbro, olivine gabbronorite, and oxide gabbro with minor felsic veins (*7*). Fractionated rocks, including oxide gabbro, comprise ~25% of Atlantis Bank and commonly host trace minerals (e.g., zircon) suitable for U-Pb isotopic dating (*17*). Pb/U zircon ages from ODP Hole 735B range from 11.3 million years ago (Ma) (*18*) to 11.93 ± 0.14 Ma (*17*).

We selected 17 zircon-bearing samples of lower oceanic crust (tables S1 and S2) for U-Pb SHRIMP analysis, and these samples yielded 19 Pb/U ages (including one older core age). Samples were collected by both manned submersible and remotely operated vehicles (76%) and dredge (24%). Zircon is concentrated in the more evolved rock types, but was found in olivine to oxide gabbro and in felsic veins. Weighted average $^{206}Pb/^{238}U$ ages of the samples range from 10.6 to 13.9 Ma, with errors of 0.1 to 0.6 My (0.9% to 4%). In general, Pb/U ages young to the north and are consistent with magnetic isochrons over Atlantis Bank (*10*, *11*, *19*). However, four samples (648-20, 467-8, JR31 12-68, and JR31 29-2) record significantly older zircon ages (0.7 to 2.5 My), relative to their predicted magnetic age, and one sample (645-17) has zircons with inherited cores as much as 1.5 My older than their corresponding rims. There is no observed correlation between age and rock type (table S1), and the anomalously old samples are not from any specific part of Atlantis Bank; they appear to be randomly distributed among the nonanomalous age samples and come from different structural depths (Fig. 1). Of the anomalously old samples, JR31 12-68 and 467-8 are two of the northernmost samples, and the differences between the Pb/U and the predicted magnetic ages are dependent on the location of the relatively long-lived C5n magnetic polarity epoch (*19*). Even accounting for errors associated with the location of this chron, samples JR31 12-68 and 647-8 are still significantly older than their predicted magnetic age.

Zircons in sample 645-17 have inheritance in the form of statistically older cores with ages of 12.7 to 13.6 Ma. These cores typically have higher U concentrations and Th/U ratios than their corresponding rims, indicating that crystallization of cores and rims occurred in different chemical environments. The oldest core ages (~13.6 Ma) are interpreted to reflect the true age of the igneous precursor, and the slightly younger core ages (~12.7 to 12.9 Ma) (Fig. 2) are an artifact of the primary ion beam overlapping older and younger components during spot analysis. This overlap was confirmed by detailed backscattered-electron imaging of the zircon pits after ion probe analysis (fig. S2). The inherited zircon cores are 1.5 My older than the predicted magnetic age for this portion of Atlantis Bank (*19*). In contrast, the weighted-average age of the four rims (12.12 ± 0.29 Ma) is consistent with the magnetic age and is interpreted to reflect the timing of crustal accretion at ~12.0 Ma. The observed inheritance likely represents magmatic assimilation during the primary crust-forming event.

To determine whether differences in mineral chemistry exist between the samples with inherited zircon and those without, we made electron microprobe traverses across clinopyroxene and plagioclase crystals (core to rim). The sample with inheritance (645-17) exhibits a wider range in composition for both plagioclase (An_{26-50}) and clinopyroxene (Mg_{54-72}) than do samples without inheritance (467-8 and 460-15) (table S3). X-ray mapping and microprobe analyses of plagioclase crystals in sample 645-17 (fig. S4) reveal multiple irregularly shaped, rounded, and embayed cores (An_{42-50}) surrounded by compositionally uniform mantles (An_{35-37}). The transition from core to mantle is marked by a sharp boundary ~30 μm in width. These complex zoning patterns are not observed in plagioclase crystals from samples 467-8 and 460-15. One possible explanation for these zoning patterns is that the cores are relict grains that were resorbed during infiltration of new melt. This interpretation is consistent with the inheritance recognized in this sample.

The Pb/U zircon ages reported here, together with the age reported in (*17*), allow us to place absolute constraints on the time scale for crustal growth at Atlantis Bank. In all, at least 15 (75%) of these 20 ages plot within error of their expected magnetic age (Fig. 3). However, 5 (25%) of our samples are significantly older (up to 2.5 My), indicating that construction of any given piece of slow-spreading oceanic crust may take as long as 2.5 My. This time for the growth of slow-spreading oceanic crust is an order of magnitude greater than expected in conventional

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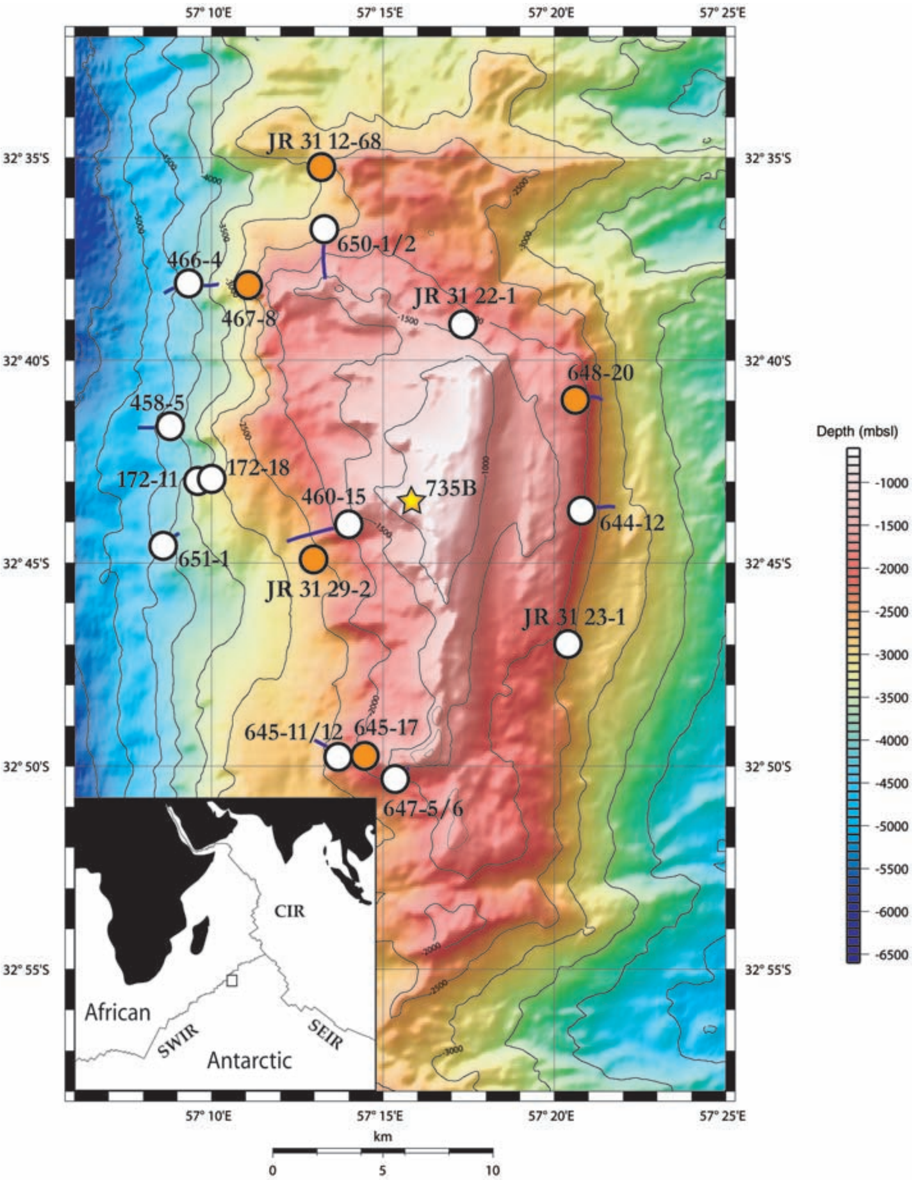

Fig. 1. Bathymetric map of Atlantis Bank depicting location of dive tracks (solid blue lines), sample locations (white and orange circles), and ODP Hole 735B (yellow star). Anomalously old Pb/U ages are indicated by orange circles. SWIR, SEIR, and CIR refer to Southwest Indian Ridge, Southeast Indian Ridge and Central Indian Ridge.

models for crustal accretion at midocean ridges (~100,000 to 200,000 years) (*5*).

The existence of both significantly older zircon-bearing rocks and inherited zircon cores as much as 1.5 My older than their corresponding rims (Figs. 2 and 3) requires a mechanism to incorporate older gabbroic material into lower oceanic crust and provides evidence that assimilation of preexisting gabbroic rocks took place during accretion of Atlantis Bank. One possibility is that the locus of magmatism/tectonism shifted (i.e., ridge jump), resulting in the intrusion of new gabbro into preexisting material. Along the Mid-Atlantic Ridge, documented ridge jumps involving migration of the spreading axis are characterized by derelict features including anomalous seafloor bathymetry and fossil rift valleys (*20*), neither of which has been recognized in the vicinity of the Atlantis Bank. It is also difficult to explain the random spatial distribution of anomalously older ages by a ridge-jump model. The observation that ~25% of the material is older further argues that assimilation occurred on a relatively small scale, in contrast to what might be expected from a jump of the spreading ridge beneath older, preexisting crust.

A second possibility is that magmatism varied stochastically in space and time over the full width of the rift valley, resulting in the entrapment of portions of older lower crust by subsequent intrusions. Thus, the older ages that we observe could be from remnants of earlier intrusive bodies, which were temporarily trapped beneath the rift valley before being transported away as part of the heterogeneous crust that forms Atlantis Bank. Although this process may account for some of the younger anomalously old ages, it is difficult to envision portions of the lower crust being trapped for 2.5 My (the oldest anomalous age recorded by our samples).

Uplift and assimilation of previously crystallized gabbroic rocks in the lithospheric upper mantle beneath the axial valley is another mechanism to incorporate older material into a younger crust (Fig. 4). Assuming that the present-day mean, half-spreading rate at the SWIR (7.0 mm/year) roughly corresponds to mantle upwelling rates, a zircon-bearing rock that crystallized at a depth of ~18 km in the mantle beneath the ridge axis would take ~2.5 My to reach the base of the crust. If this rock were assimilated by a shallow-level magma at 11.4 Ma, original zircons would record an age of ~13.9 Ma, corresponding to the oldest age recorded by our samples. Thus, if the spreading rate were constant during the formation of Atlantis Bank, the difference in time between the U-Pb zircon crystallization age and the magnetic age is a proxy for the depth at which zircon crystallized. The age range of our anomalously old samples (0.7 to 2.5 myr) would therefore record crystallization over depths of ~5 to 18 km below the base of the crust. The deduction that crystallization may occur over a range of depths below the ridge axis requires that the proportion of entrapped gabbros increases upward toward the base of the crust as the axial lithospheric mantle is uplifted (Fig. 4).

The above argument assumes that the ambient temperature of the uppermost ~18 km of mantle was less than the nominal zircon closure temperature (*21*, *22*). Although cooling rates for lithospheric mantle below midocean ridges are poorly constrained, calculated and predicted cooling rates for lower oceanic crust close to the Moho are ~10^4 °C/My (*23*, *24*). Cooling rates in the lithospheric mantle are likely less than 10^4 °C/My; nonetheless, a 100-μm zircon with a cooling rate of 10^3 to 10^4 °C/My would have a closure temperature in excess of 1000°C, consistent with thermal and rheological models of thick lithosphere at slow- and ultraslow-spreading ridges (*25*). Thus, zircon crystallized at shallow depths in an ascending portion of the lithospheric mantle is likely to record original crystallization ages without substantial Pb loss.

Crystallization of ephemeral melt intrusions may be a common feature within the axial lithosphere of slow- and ultraslow-spreading midocean ridges (*26*). Although there is little data on their size, evolved gabbroic bodies (meters to several hundred meters in thickness) are present in the upper mantle beneath the Mid-Atlantic Ridge at 15°N, having equil-

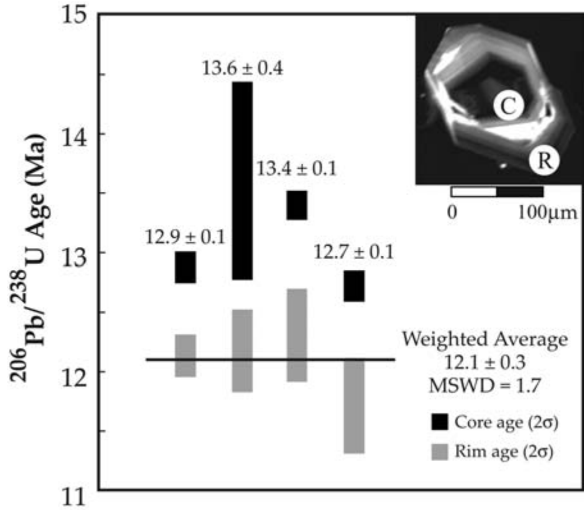

Fig. 2. Weighted $^{206}Pb/^{238}U$ ages of four zircon grains from 645-17. Core ages are statistically older than their corresponding rims, indicating a second period of growth at 12.1 Ma. The age of the cores is interpreted to be ~13.6 My, with slightly younger core ages reflecting sampling of older and younger components during spot analysis. A representative cathodoluminescence image is shown with the location of spot analyses. C, core; R, rim.

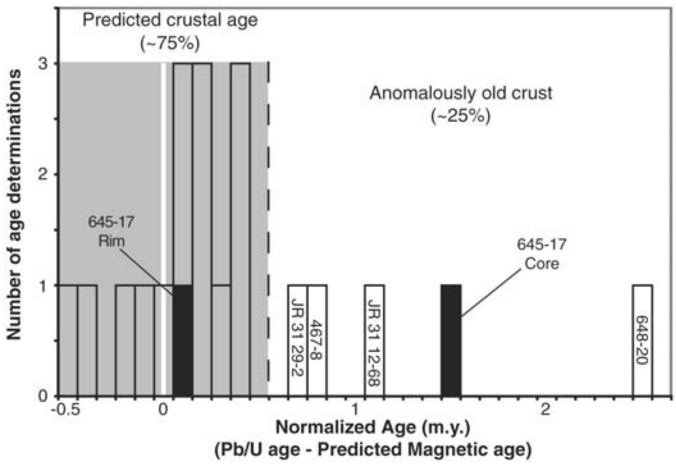

Fig. 3. Bar chart showing number of samples versus normalized age, including one data point from John *et al.* (*17*). Gray field encompasses uncertainties (±0.5 My) associated with U-Pb and magnetic age data. About 75% of the analyzed samples plot within error of the predicted crustal age, whereas 25% display anomalously older ages.

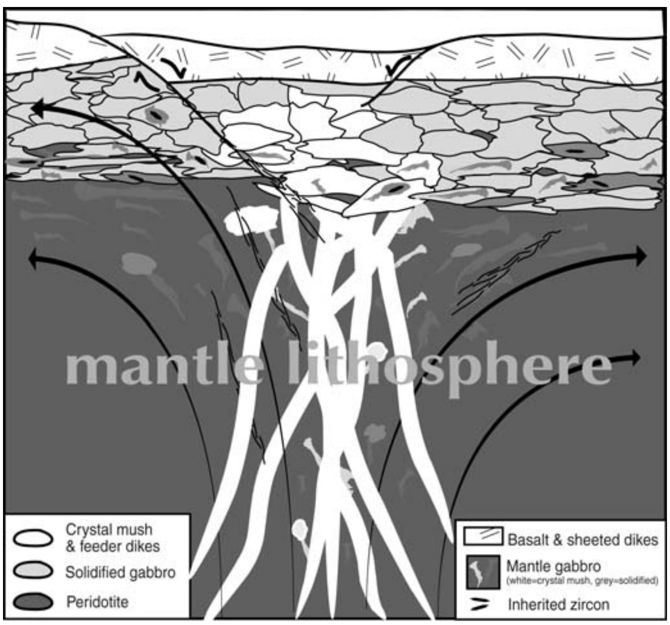

Fig. 4. Schematic cross section drawn at ~1:1 scale through axial lithosphere at a slow-spreading midocean ridge. Old gabbroic bodies (white) crystallize in cold lithospheric mantle, are uplifted, and become incorporated/assimilated into the lower crust by shallow-level crust-forming magmas. These older gabbroic bodies constitute up to 25% of lower oceanic crust and likely form a major component of the lithospheric mantle in slow-spreading environments.

ibrated at depths of 15 to 20 km (*27*). Trapped gabbroic bodies have been argued to form a considerable portion of the upper mantle beneath slow-spreading oceanic crust, where melt extraction is inhibited by reduced spreading rates (*28*, *29*).

These observations are corroborated by the absence of primitive lower crustal rocks sampled near the crust-mantle transition along the western flank of Atlantis Bank (e.g., sample 651-1) (*15*, *16*). The presence of disequilibrium plagioclase (sample 645-17) and augite (*30*) in gabbroic rocks from Atlantis Bank is also consistent with early crystallization of preexisting gabbroic rocks within the upper mantle, which subsequently underwent melt-rock interaction and dissolution by later crust-forming magmas. If gabbroic rocks are emplaced within the axial region of upwelling mantle at slow- and ultraslow-spreading ridges, incorporation of these gabbroic bodies is an important process in the growth of oceanic crust.

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Materials and Methods
Figs. S1 to S4
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Role of Land-Surface Changes in Arctic Summer Warming

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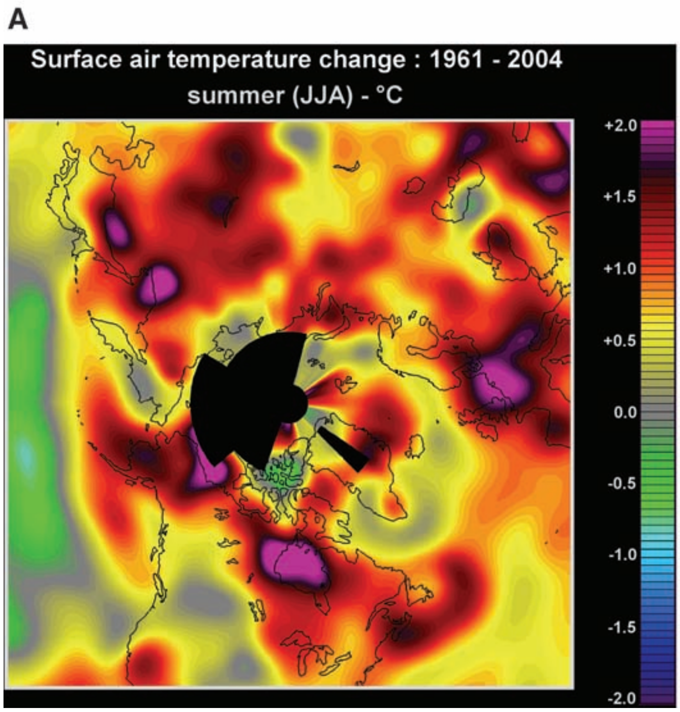
A major challenge in predicting Earth's future climate state is to understand feedbacks that alter greenhouse-gas forcing. Here we synthesize field data from arctic Alaska, showing that terrestrial changes in summer albedo contribute substantially to recent high-latitude warming trends. Pronounced terrestrial summer warming in arctic Alaska correlates with a lengthening of the snow-free season that has increased atmospheric heating locally by about 3 watts per square meter per decade (similar in magnitude to the regional heating expected over multiple decades from a doubling of atmospheric CO_2). The continuation of current trends in shrub and tree expansion could further amplify this atmospheric heating by two to seven times.

The Arctic provides a test bed to understand and evaluate the consequences of threshold changes in regional system dynamics. Over the past several decades, the Arctic has warmed strongly in winter (*1*). However, many Arctic thresholds relate to abrupt physical and ecological changes that occur near the freezing point of water. Paleoclimate evidence, which is mostly indicative of summer conditions, shows that the Arctic in summer is now warmer than at any time in at least the past 400 years (*2*). This warming should have a large impact on the rates of water-dependent processes. We assembled a wide range of independent data sets (surface temperature records, satellite-based estimates of cloud cover and energy exchange, ground-based measurements of albedo and energy exchange, and field observations of changes in snow cover and vegetation) to estimate recent and potential future changes in atmospheric heating in arctic Alaska. We argue that recent changes in the length of the snow-free season have triggered a set of interlinked feedbacks that will amplify future rates of summer warming.

Summer warming in arctic Alaska and western Canada has accelerated from about 0.15° to 0.17°C decade^{-1} (1961–1990 and 1966–1995) (*1*, *3*) to about 0.3° to 0.4°C decade^{-1} (1961–2004; Fig. 1). There has also been a shift from summer cooling to warming in Greenland and Scandinavia, more pronounced warming in Siberia, and continued summer warming in the European Russian Arctic.

The pronounced summer warming in Alaska cannot be readily understood from changes in atmospheric circulation, sea ice, or cloud cover. Changes in the North Atlantic Oscillation and Arctic Oscillation are linked to winter warming over Eurasia. Variations in the Pacific North American Teleconnection,



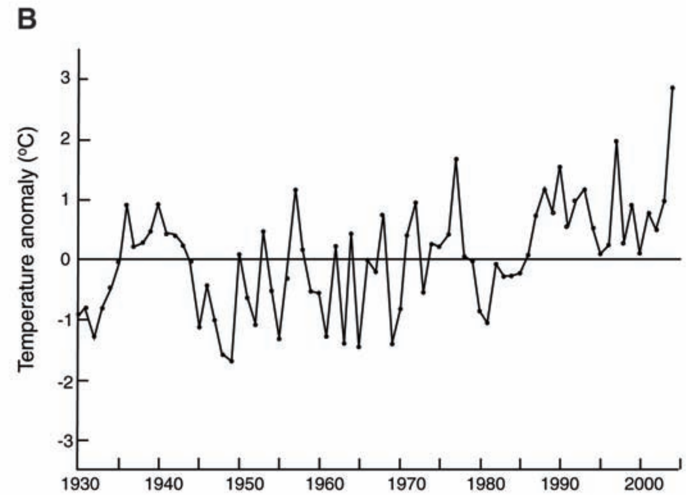


Fig. 1. (**A**) Spatial pattern of high-latitude surface summer (June to August) warming (in °C over 44 years, 1961 to 2004) and (**B**) the temporal air temperature anomaly (deviation from the long-term mean) in Alaska. The spatial pattern of temperature increase was estimated from monthly anomalies of surface air temperature from land and sea stations throughout the Northern Hemisphere (*42*), updated from Chapman and Walsh (*3*). The temporal pattern of temperature is specifically for the Alaskan domain from 1930 to 2004.