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Iceland as a heat island

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[1] Iceland is a strong localized source of non-eruptive volcanic warming and cooling. Temperature trend maps show that this phenomenon is localized to an area of about twice that of Iceland. With altitude the area remains constant but the phenomenon weakens and changes sign upon passing through the tropopause. The effect's magnitude implies a large positive feedback, according to a conventional climate forcing estimate. This phenomenon is unique in that it is not observed for the other major volcanic islands. **Citation:** Douglass, D. H., V. Patel, and R. S. Knox (2005), Iceland as a heat island, *Geophys. Res. Lett.*, *32*, L03709, doi:10.1029/2004GL021816.

1. Introduction

[2] Earth's average surface temperature has been studied extensively over the last 25 years. While greenhouse gases (GHGs) are involved in the observed changes in temperature, in order to determine the extent of their influence one must first account for various geophysical phenomena that may have a larger effect. *Christy and McNider* [1994] showed that volcanoes and El Niño can change the temperature worldwide by fractions of a degree. *Douglass and Clader* [2002] and *Douglass et al.* [2004a] have most recently examined the effects of changes in solar radiance. These and other natural phenomena create variations in climate that can be larger than the observed trends. A candidate for study not previously considered in this context is heat flow from the interior of the Earth, whose global average flux is 82 mW/m^2 [*Fowler*, 1990]. Such a flux at the surface contributes a warming of 27 mK, in an approximation that omits feedback [*Knox*, 1999].

[3] Icelandic records from 1931 to 2000 show fluctuations in temperature about a mean value of approximately 4.5 K with no discernable long-term trend. However, the temperatures since 1979 do show an increase of about 1.0 K. In this paper we study this localized temperature anomaly, which has an observed decadal variation itself many times larger than 27 mK and much larger even than one expects on the basis of the local geothermal fluxes. This is an unresolved puzzle.

2. Data

[4] The data used in our analysis were obtained from the following sources and processed as noted.

[5] [MSU] Tropospheric temperature records sensed at various altitudes by satellite-borne microwave sounding units (MSUs) [*Christy et al.*, 2000] (data available at http://vortex.nsstc.uah.edu/data/msu/t2lt). Earth is uniformly sampled, with about 40,000 measurements per day at a mean pressure of 770 hPa (altitude about 2 km).

[6] [NNR] The reanalysis project of the National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) [*Kistler et al.*, 2001] (data available at http://dss.ucar.edu/datasets/ds090.2/data/monthly/). The abbreviation NNR stands for NCEP-NCAR Reanalysis. This study produced retroactive records of temperatures at various pressures (altitudes), covering more than 50 years of global analysis of atmospheric fields. Using a reanalysis model various climate variables were computed at standard times and spatial intervals based on inputs from many measurement systems, such as radiosondes and satellite sounders. This yielded monthly temperature values for each grid cell at the chosen pressures. We used temperature data available for levels 850, 700, 500, and 200 hPa, and one designated as "tmp.2m" corresponding to the very low altitude of 2 meters.

[7] [IMO] Surface temperature records from eight meteorological stations in Iceland (Iceland Meteorological Office, http://www.vedur.is/english, 2000). Locations of these stations are shown in Figure 1d and they are described in Table 1.

[8] [NMI] Surface temperature records from one station in Jan Mayen (Norwegian Meteorological Institute, Jan Mayen data, http://met.no, 2003).

[9] To characterize temperature changes, we compute the best fit regression line of the temperature data for a specific time period for each data cell. The slopes of these lines, expressed in mK/decade, are called *trends*. The temperature maps shown in this paper are the maps of trends associated with the corresponding data sets.

[10] We truncate all data at 1996 because the El Niño of 1997–98 was particularly strong. *Douglass and Clader* [2002] showed that the trend estimate is severely distorted by the effects occurring near the end of the temperature record.

3. Results

3.1. World and Regional Maps

[11] Figure 1 is a series of 1979–1996 temperature trend maps obtained from MSU data, at a pressure of 770 hPa (altitude approximately 2 km). It zooms from a global view (1a) to a local view (1d). Warming and cooling regions appear at mid-latitudes (30° to 60°) with highs and lows located at particular longitudes on both the hemispheres. We designate these regions with N or S for the hemisphere and odd numbers for warming regions. For example, N1 denotes

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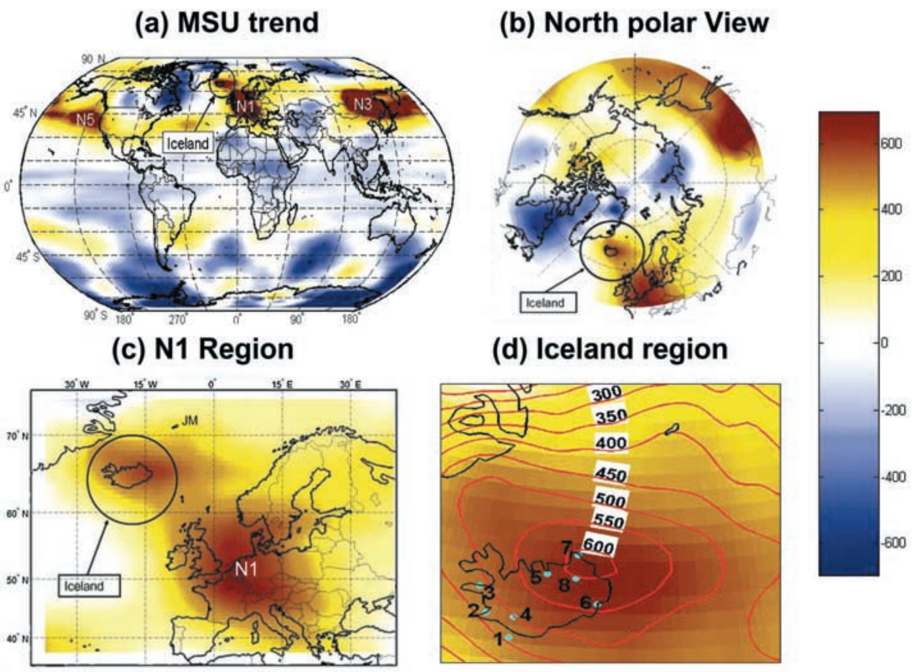

Figure 1. MSU temperature trend maps, 1979–1996. The color bar scale is in mK/decade. (a) World in Robinson projection. (b) World in north polar projection. (c) View centered around region N1. (d) Iceland view. Trend contours are shown in mK/decade. See Table 1 for identification of the stations.

the warming region over Germany/Netherlands. In this paper we concentrate on the clearly anomalous small warming spot northwest of N1, centered on Iceland.

3.2. Iceland Temperature Trends, 1979–1996

[12] Figures 2 and 3 provide a more detailed look at trends in the region of Iceland and Jan Mayen for this recent period. All these maps are drawn to the same scale.

[13] Figure 2a shows results from the NNR 2-m data set (altitude "2 meters"), which has a high resolution (2.5° × 2.5° cells). The contours show the peak to be bifurcated such that one part is north of Iceland and second is around the island of Jan Mayen; the maximum trend is 1100 mK/decade. Figure 2b shows the NNR data at a higher altitude at pressure 850 hPa. Here the maximum trend at the peak is 700 mK/decade, but we see no evidence of the peak around Jan Mayen. This could be due to the fact that this data set has one-fourth the resolution of the 2-m data set. Figure 2c shows the NNR data at an even higher altitude at pressure 500 hPa with a maximum of 375 mK/decade. Finally,

Table 1. The Icelandic Meteorological Stations[a]

Index	Station Name	Surface Data Trend (mK/decade)	MSU Trend at 770 hPa (mK/decade)
1	Stórhöfdi	373	470
2	Reykjavík	566	470
3	Hæll	570	500
4	Stykkishólmur	607	480
5	Akureyri	715	580
6	Teigarhorn	748	560
7	Raufarhöfn	792	615
8	Grímsstadir	820	600

[a] Trends are computed from 1979–1996 MSU trends at the location of the station. Index identifies stations by location (Figure 1d).

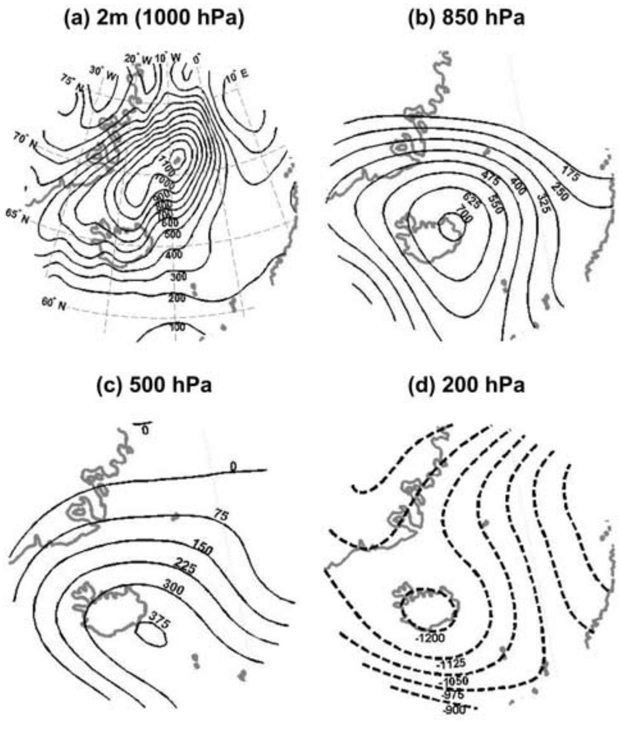

Figure 2. Temperature trend contour maps centered around Iceland (1979–1996). Each map corresponds to a different pressure (altitude) as indicated on the figure. Contours show mK/decade. All data are from NNR. Positive values (a, b, c) are indicated in solid curves and negative values (d) are dashed curves. Cells for the 2-m data set are 2.5° × 2.5°, the others 5° × 5°.

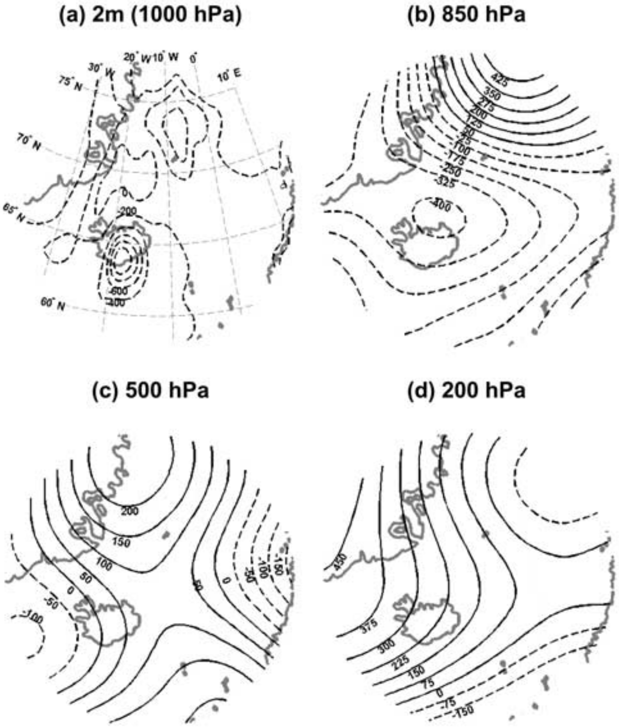

Figure 3. Maps for 1959–1978. Scales, cell sizes, and data source are the same as in Figure 2. Positive values (b, c, d) are solid curves and negative values (a, b, c) are dashed curves.

Figure 2d corresponds to pressure 200 hPa (altitude ca. 12 km), where the trendlines now have negative slope with a contour minimum of −1200 mK/decade. This altitude is above the tropopause, where the physical properties of the atmosphere are different.

3.3. Iceland Temperature Trends, 1959–1978

[14] There are no MSU data for this time period, so we examine the NNR data. The four maps in Figure 3 refer to the same four altitudes as those in Figure 2, but show a reversed pattern of minima and maxima. At 2-m altitude (Figure 3a) a minimum is located at southern edge of Iceland with the value of about −1100 mK/decade. At the next two pressure levels 850 hPa and 500 hPa the minimum moves slightly off the island and becomes weaker, −375 and −100 mK/decade, respectively. At 200 hPa (ca. 12 km) the contours near Iceland have changed from negative to positive. The value at Iceland is 225 mK/decade.

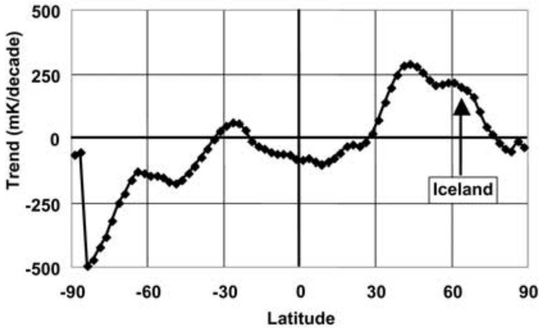

Figure 4. Average over latitude zones of width 2.5°. The trend features of Figure 1 produce the maxima and minima seen here.

4. Analysis

4.1. Latitude Dependence

[15] We computed global averages of MSU data over longitude within latitude zones of width 2.5°, with the result shown in Figure 4. The maximum in Figure 4 around 45°N is due to the warming regions N1, N3 and N5. The shoulder, at latitude ∼60°, which has been observed before but not identified [*Douglass et al.*, 2004b], is clearly due to Iceland. Because of the small area of Iceland these warming effects have a small influence on the global average trend. We estimate the area of the region defined by the contour at half maximum to be about twice the surface area of Iceland, or about 4×10^{-4} of Earth's surface. Taking the half maximum value of 600 mK/decade leads to a contribution of about 0.24 mK/decade to the global average, to be compared with the global average of 65 ± 12 mK/decade determined by *Douglass and Clader* [2002].

4.2. MSU-Iceland Weather Stations Comparison

[16] There are eight stations in Iceland located as shown on the map, Figure 1d. Figure 5 shows, as an example, the 1955–96 temperature data for station 6 at Teigarhorn. The period 1959–78 shows a negative trend and the period 1979–96 shows a positive trend. Table 1 lists the eight stations, their temperature trends and the corresponding trends of MSU as in Figure 1d for the period of 1979–1996. We plotted the eight surface trends against the eight MSU trends and found that [MSU trend] = 0.80 × [surface trend]. The coefficient 0.80 differs from 1.0 because the MSU measurements are at the higher altitude (∼2 km) (see below). This result strongly suggests a local forcing of the lower tropospheric temperatures by the local geothermal flux in the Iceland region.

4.3. Altitude Dependence of Trends

[17] Table 2 shows the values of the extremal trends *vs.* pressure/altitude found from the various maps (Figures 1 and 2). Figure 6 shows the extremal values of the trend *vs* pressure (altitude). For the period 1979–96, one notes a monotonic decrease from 1100 mK/decade to negative values above the tropopause. For 1959–78 there is nearly a mirror image of the first curve, with a monotonic increase from about −1100 mK/decade, changing to positive values above

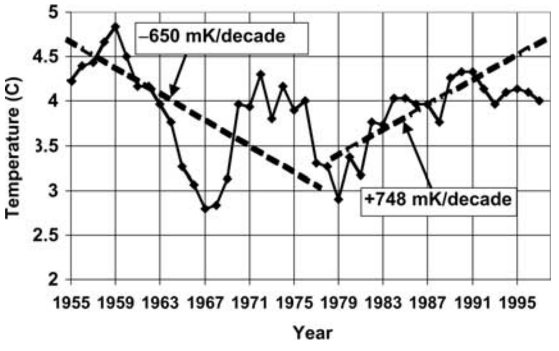

Figure 5. Temperature history of Iceland station 6 with trendlines (see Figure 1d and Table 1).

the tropopause. *Douglass et al.* [2004b] have given similar curves showing the altitude dependence of the global trend.

5. Conclusions

[18] We find that the Iceland area, uniquely among volcanic islands, is a significant source of recent cooling and heating, and that the phenomena extend well into the atmosphere. Since both Iceland and the neighboring island of Jan Mayen are formed of lava from previously erupted volcanoes, we suggest that the atmospheric heating and cooling around Iceland are due to time variations in local geothermal activity.

[19] While our results show a large effect on the Iceland region microclimate, these non-eruptive volcanic activities affect the global average temperature trend by only about 0.24 mK/decade. As one can see in Figure 1, other volcanic islands such as Hawaii and New Zealand have no trends similar to those around Iceland and Jan Mayen. In the absence of numerous similar cases, we can conclude that no measurable part of the global temperature trend is originating from non-eruptive activity. On the other hand, the activity around Iceland is of considerable intrinsic interest both as to its persistence and magnitude.

[20] The heating/cooling area at half maximum/minimum is about twice the size of Iceland in the contour maps. The locations of the maxima and minima vary somewhat with altitude but the area seems to be about the same; i.e., the disturbance is confined to a cylinder of constant cross-section. We are reminded of the observation by *North et al.* [1981] about the Budyko empirical rule [*Budyko*, 1969] connecting the outgoing longwave radiation with the surface temperature directly beneath. They call the rule "miraculous." Both Budyko's rule and our observations suggest that localized time-averaged climate phenomena may be independent of lateral transport in the lowest approximation. The magnitudes of both the maximum and minimum become weaker as the altitude is increased. This "thermal cylinder" even extends across the tropopause where the effect changes sign.

[21] The temperature trends are unusually large. One can make a rough estimate of the temperature change (ΔT) associated with a forcing (ΔF) by using the standard expression $\Delta T = \lambda \Delta F$ [*Shine et al.*, 1995]. With an assumed no-feedback sensitivity λ of 0.3 K/(W/m^2), a typical Iceland trend 500 mK per decade implies a flux trend of 1.6 W/m^2/decade. The total geothermal flux over the surface of Iceland is 30 GW [*Ragnarsson and Helgason*, 2004], resulting in an average flux $(3 \times 10^{10}$ W$)/(1.03 \times 10^{11}$ m$^2) = 290$ mW/m^2. Compared with this, a ten-year flux change of 1.6 W/m^2 is enormous and much larger than average global values, and there is no evidence that the Iceland geothermal flux is varying widely. Therefore, the temperature trends we observe must be due to complex persistent microclimate effects that do not conform to simple forcing theory and which involve quite large positive feedbacks.

Table 2. "Iceland" Extremal Trends at Various Pressure Altitudes

Data Source	Pressure (hPa)	Trend 1979–96 (mK/decade)	Trend 1959–78 (mK/decade)
IMO	1000	820	−600
NNR 2 m	1000	1100	−1100
NNR 850	850	700	−375
NNR 700	700	525	−150
MSU	770	600	–
NNR 500	500	375	−100
NNR 200	200	−1200	200
NMI	1000	659	−330

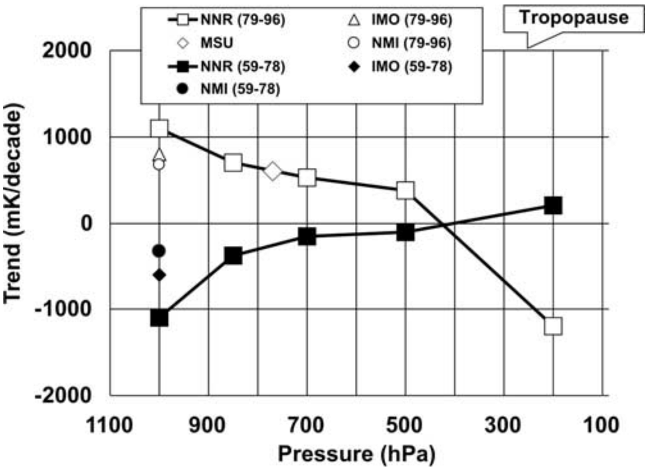

Figure 6. Iceland temperature trend maxima *vs.* pressure.

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References

Budyko, M. I. (1969), A global climate model based on the energy balance of the Earth-atmosphere-system, *Tellus*, *21*, 611–619.

Christy, J. R., and R. T. McNider (1994), Satellite greenhouse signal, *Nature*, *367*, 325.

Christy, J. R., R. W. Spencer, and W. D. Braswell (2000), MSU Tropospheric temperature: Dataset construction and radiosonde comparisons, *J. Atmos. Oceanic Technol.*, *17*, 1153–1170.

Douglass, D. H., and B. D. Clader (2002), Climate sensitivity of the Earth to solar irradiance, *Geophys. Res. Lett.*, *29*(16), 1786, doi:10.1029/2002GL015345.

Douglass, D. H., B. D. Clader, and R. S. Knox (2004a), Climate sensitivity of Earth to solar irradiance: Update, paper presented at 2004 Solar Radiation and Climate Meeting on Decade Variability in the Sun and the Climate, Meredith, N. H. (Available at http://arxiv.org/abs/physics/0411002.)

Douglass, D. H., B. D. Pearson, and S. F. Singer (2004b), Altitude dependence of atmospheric temperature trends: Climate models versus observation, *Geophys. Res. Lett.*, *31*, L13208, doi:10.1029/2004GL020103.

Fowler, C. M. R. (1990), *The Solid Earth: An Introduction to Geophysics*, 234 pp., Cambridge Univ. Press, Cambridge, UK.

Kistler, R., et al. (2001), The NCEP_NCAR 50-year reanalysis: Monthly means: CD-ROM and documentation, *Bull. Am. Meteorol. Soc.*, *82*, 247–267.

Knox, R. S. (1999), Physical aspects of the greenhouse effect and global warming, *Am. J. Phys.*, *67*, 1227–1238.

North, G. R., R. F. Cahalan, and J. A. Coakley Jr. (1981), Energy balance climate models, *Rev. Geophys.*, *19*, 91–121.

Ragnarsson, A., and P. Helgason (2004), *Energy in Iceland: Historical Perspective, Present Status, Future Outlook*, Natl. Energy Auth. of Iceland, Reykjavík.

Shine, K. P., et al. (1995), Radiative forcing, in *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC 1992 IS92 Emission Scenarios*, edited by J. T. Houghton et al., pp. 167–203, Cambridge Univ. Press, New York.

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