Warming is Faster at Higher Elevations?

Zhenzhong Zeng[1], Anping Chen[2], Philippe Ciais[3], Yue Li[1], Laurent Z. X. Li[4], Robert Vautard[3], Hui Yang[1], Liming Zhou[5], Shilong Piao[1,6,*]

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[4] Laboratoire de Météorologie Dynamique, Centre National de la Recherche Scientifique, Université Pierre et Marie Curie-Paris 6, 75252 Paris, France
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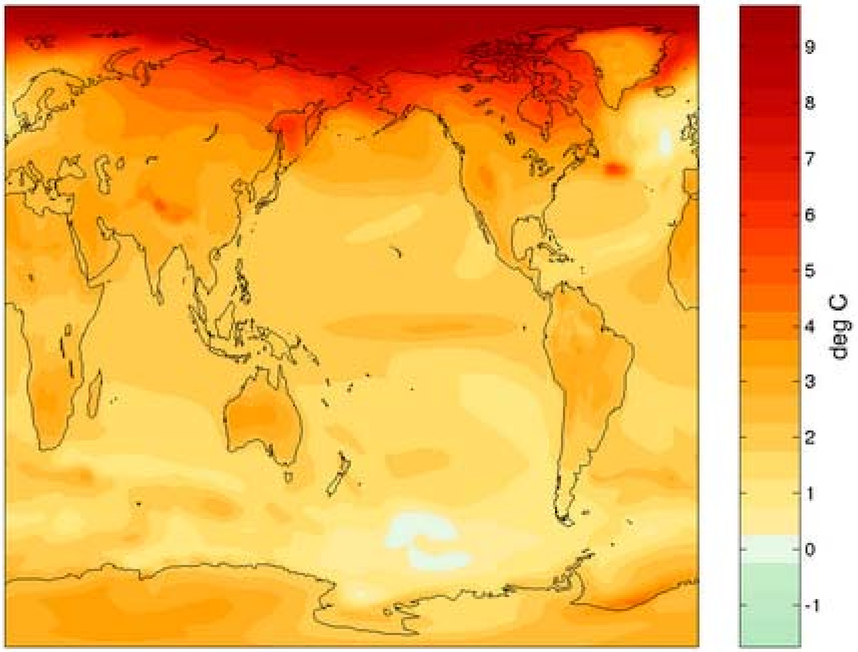
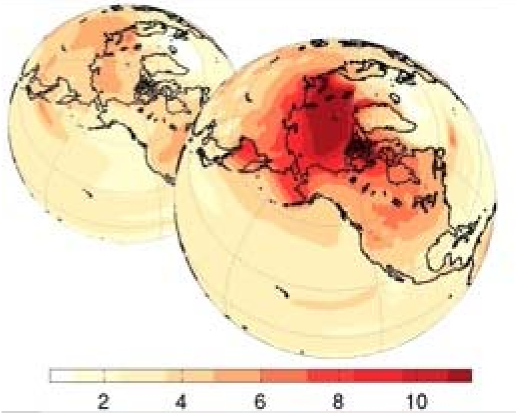
- Polar Amplification

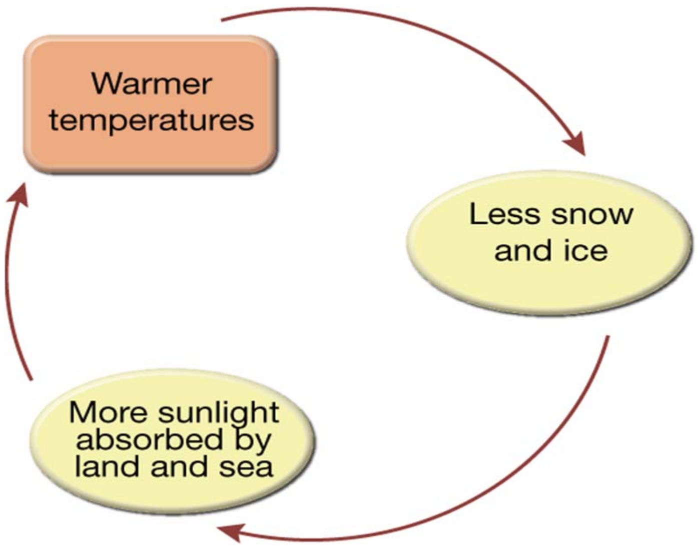




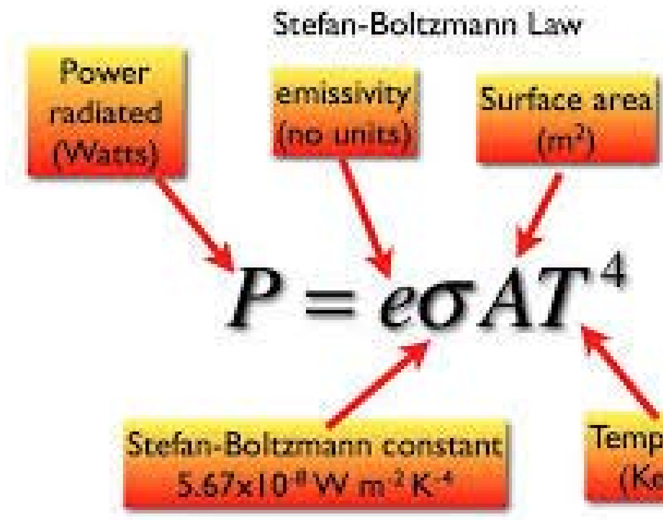
e.g. Moritz *et al.*, 2002; Polyakov *et al.*, 2002; Masson-Delmotte *et al.*, 2006; Holland and Bitz, 2013; IPCC, 2013

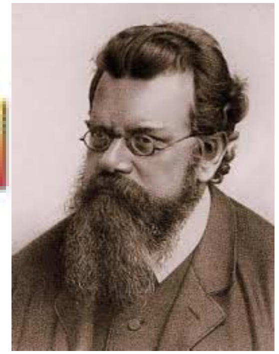
- Mechanisms for Polar Amplification

Snow/ice albedo feedback



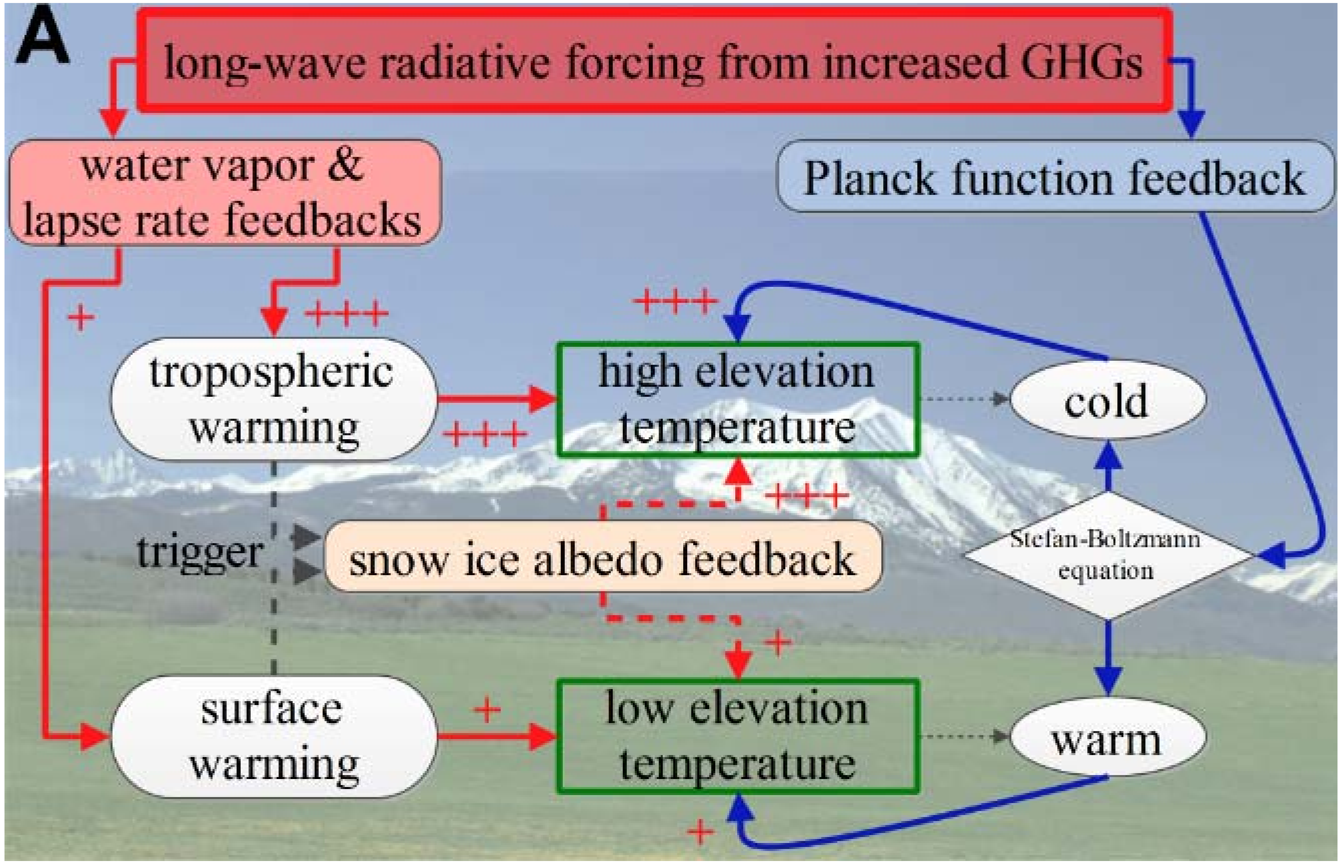
Planck function feedback





e.g. Pepin and Lundquist, 2008; Rangwala and Miller, 2012; Ohmura *et al.*, 2012; Rangwala *et al.*, 2013; Wang *et al.*, 2013; Field *et al.*, 2014

Does temperature increase faster at higher elevations?



e.g. Douglass *et al.*, 2004; Santer *et al.*, 2005; Pepin and Lundquist, 2008; Rangwala and Miller, 2012; Ohmura *et al.*, 2012; Rangwala *et al.*, 2013; Stocker *et al.*, 2013; Wang *et al.*, 2013; Field *et al.*, 2014

Mountain Amplification should be as robust as Polar Amplification!

Zeng *et al.*, 2015 GRL

- Global climate models (GCMs) predict a rather uniform faster warming trend at higher elevations as a consequence of increasing greenhouse gases (GHGs) .

e.g., Giorgi *et al.*, 1997; Fyfe and Flato 1999; Santer *et al.*, 2005; Kotlarski *et al.*, 2012; Rangwala *et al.*, 2013; Stocker *et al.*, 2013; Mountain Research Initiative, 2015

Elevation Dependency of the Surface Climate Change Signal: A Model Study

Filippo Giorgi, James W. Hurrell, and Maria Rosaria Marinucci
National Center for Atmospheric Research, Boulder, Colorado*

Results are presented fr
regional climate model. T
mostly during the winter a
elevations. This is caused
snow–albedo feedback. T
years over the Alpine reg
detection tool for global w
and water budgets, also sh
in high elevation regions.

1. Introduction

Beniston and Rebetez (1996) h
face climate change associated
might show an elevation signal,
at high elevation sites would be
at low elevations. Their hypoth
analysis of wintertime minimum
from 88 Swiss stations, which
altitudinal dependency except at

Elevation gradients of European climate change in the regional climate model COSMO-CLM

S. Kotlarski · T

Received: 17 Janua
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Abstract A tran
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Climate change in mountains: a review of elevation-dependent warming and its possible causes

Imtiaz Rang

Received: 25 Ap
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Abstract Ava
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OPEN ACCESS
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Environmental Research Letters
Environ. Res. Lett. 8 (2013) 024040 (9pp)
doi:10.1088/1748-9326/8/2/024040

Amplified warming projections for high altitude regions of the northern hemisphere mid-latitudes from CMIP5 models

Imtiaz Rangwala[1,2], Eric Sinsky[1] and James R Miller[1]

[1] Department of Marine and Coastal Sciences, Rutgers University, 71 Dudley Road, New Brunswick, NJ, USA
[2] Western Water Assessment/Cooperative Institute for Research in Environmental Sciences, 325 Broadway, R/PSD NOAA ESRL, Boulder, CO, USA

E-mail: Imtiaz.Rangwala@noaa.gov

- AGU SECTION:

"Accelerated Warming at High Elevations: Evidence, Processes, and Future Projections" (2013-12-9, San Francisco, AGU Fall Meeting, A11A).

New Search | Return to Search Results

A11A. Accelerated Warming at High Elevations: Evidence, Processes, and Future Projections Posters

Date: Monday 9 December

Time: 8:00 AM - 12:20 PM

Location: Moscone South, Hall A-C

Section/Focus Group:

Atmospheric Sciences (A)

Co-Sponsor(s):

Biogeosciences (B)

Cryosphere (C)

Global Environmental Change (GC)

Hydrology (H)

Index Terms:

[0736] CRYOSPHERE / Snow

[1610] GLOBAL CHANGE / Atmosphere

[1630] GLOBAL CHANGE / Impacts of global change

Recent warming amplification over high elevation regions across the globe

Qixiang Wang · Xiaohui Fan · Mengben Wang

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Temperature trends at high elevations: Patterns across the globe

N. C. Pepin[1] and J. D. Lundquist[2]

Received 17 March 2008; revised 7 May 2008; accepted 28 May 2008; published 16 July 2008.

[1] Most climate models suggest amplification of global warming in high mountains, but observations are less clear. Using comprehensive, homogeneity-adjusted temperature records from over 1000 high elevation stations across the globe, we examine the causes of changing temperature trends with elevation, assessing the roles of free atmospheric change, topography (exposure and aspect), and cryospheric feedback. The data show that observed 20th century temperature trends are most rapid near the annual 0°C isotherm due to snow-ice feedback. Mountain summit and freely draining slope sites are dominated by free-air advection and thus have consistent trend magnitudes, with reduced inter-site variance in comparison with incised valley sites where local factors are more important. Thus, while there has been no simplistic elevational increase in warming rates, some generalizations can be made. Water resources and ecosystems near the 0°C isotherm in the extratropics are at increased risk from accelerated warming. The data also suggest that exposed mountain summits, away from the effects of urbanization and topographic sheltering, may provide a relatively unbiased record of the planet's climate. **Citation:** Pepin, N. C., and J. D. Lundquist (2008), Temperature trends at high elevations: Patterns across the globe, *Geophys. Res. Lett.*, *35*, L14701, doi:10.1029/2008GL034026.

patterns, local topography, and snow-ice feedbacks can explain where on the Earth's surface we see the strongest temperature trends.

[4] Prior work has been inconclusive about whether high elevations around the globe have been warming faster or slower than nearby lower elevations or global averages [*Beniston et al.*, 1997; *Seidel and Free*, 2003]. *Diaz and Bradley* [1997] analyzed surface temperature records at 116 sites and found that many (although not all) high elevation sites showed enhanced 20th century warming. This has been substantiated by many regional examples including work in Tibet [*Liu and Chen*, 2000] and in the Swiss Alps [*Beniston and Rebetez*, 1996]. However, other studies show a decreased warming rate at high elevations [*Pepin and Losleben*, 2002; *Vuille and Bradley*, 2000] or the lack of any clear relationship between trend magnitude and elevation [*Vuille et al.*, 2003; *Pepin and Seidel*, 2005; *Liu et al.*, 2006; *You et al.*, 2008].

[5] On the other hand, nearly all global climate models report increased sensitivity to warming at high elevations [*Giorgi et al.*, 1997; *Chen et al.*, 2003] because melting snow and ice result in lower surface albedo, which in turn enhances further warming. This feedback should not consistently increase with elevation but should be strongest around 0°C. Because GCMs are run until equilibrium is

- However, meteorological records do not show a uniform acceleration of warming with elevation [e.g. *Beniston et al.*, 1997; *Pepin and Lundquist*, 2008; *Rangwala and Miller*, 2012].

- **Positive** [e.g. *Beniston and Rebetez*, 1996; *Liu et al.*, 2009; *Wang et al.*, 2013], **non-significant** [e.g. *Pepin and Lundquist*, 2008; *You et al.*, 2010] or **negative** [e.g. *Vuille and Bradley*, 2000; *Lu et al.*, 2010] correlations between air temperature trends and elevation have been diagnosed from station data.

WHY?

Importance on whether Warming Accelerated at High Elevations

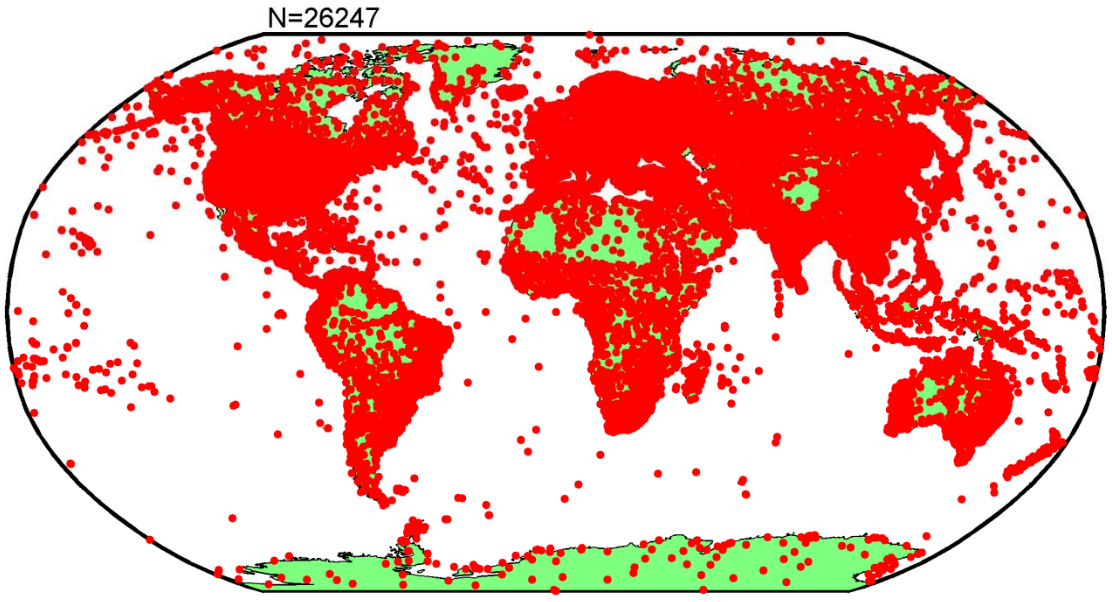
- Mountains are among the regions most sensitive to climate change. Mountains provide freshwater to half of the world's population and are home to half of all global biodiversity hotspots.
- Elevation-dependent warming, if it exists, has important implications for the mass balance of the high-altitude cryosphere and associated runoff; for ecosystems and farming communities in high-mountain environments; and also for species that reside in restricted altitudinal zones within a mountain range.
- In addition, the potential ***inconsistency*** between model projection and *in-situ* observations raises the question about the ability of current climate models to accurately describe regional climate change patterns.

e.g. Inouye *et al.*, 2000; Becker and Bugmann, 2001; Kohler and Maselli, 2009; IPCC, 2013; Mountain Research Initiative, 2015; Zeng *et al.*, 2015

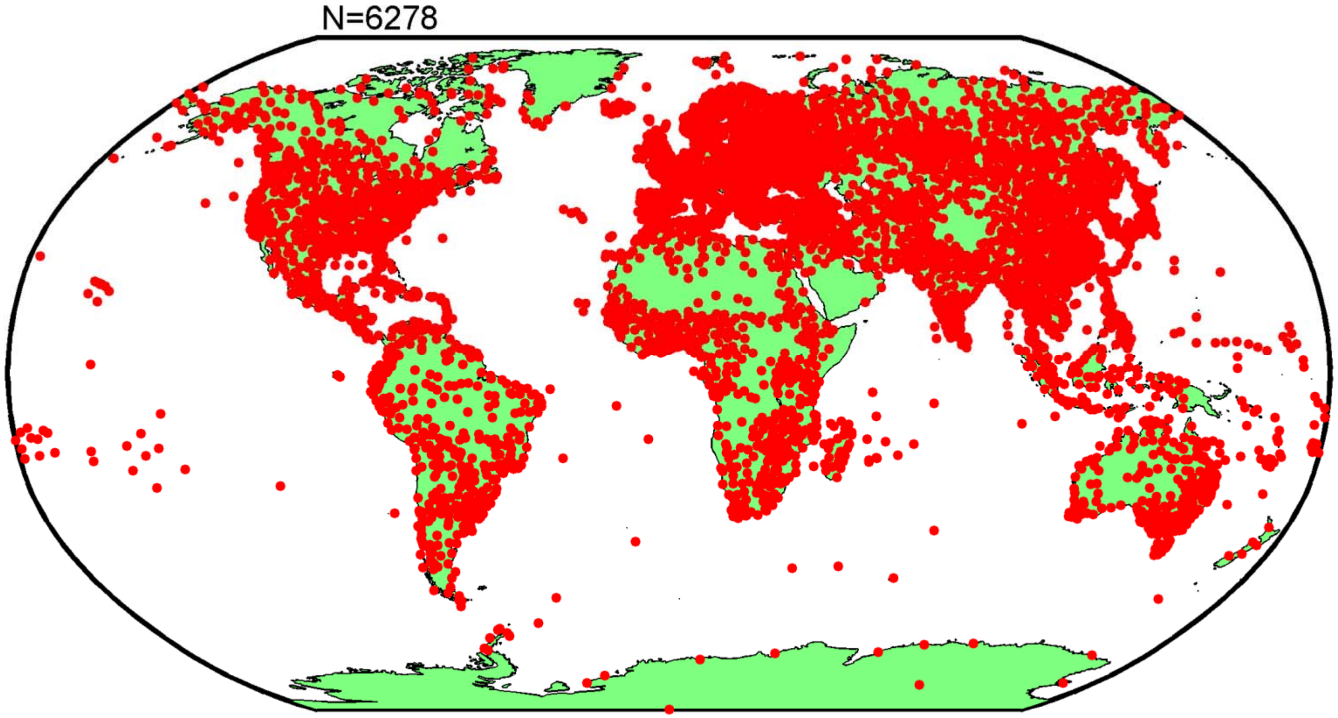
- Here, we use a large dataset of meteorological station data to document the relationship between air temperature trend and elevation in the Northern Hemisphere during the last 30 years.

- **The goals of the study are to detect regions with positive or negative correlations between warming and elevation, and to discuss plausible mechanisms that can explain the sign of these regional correlations.**

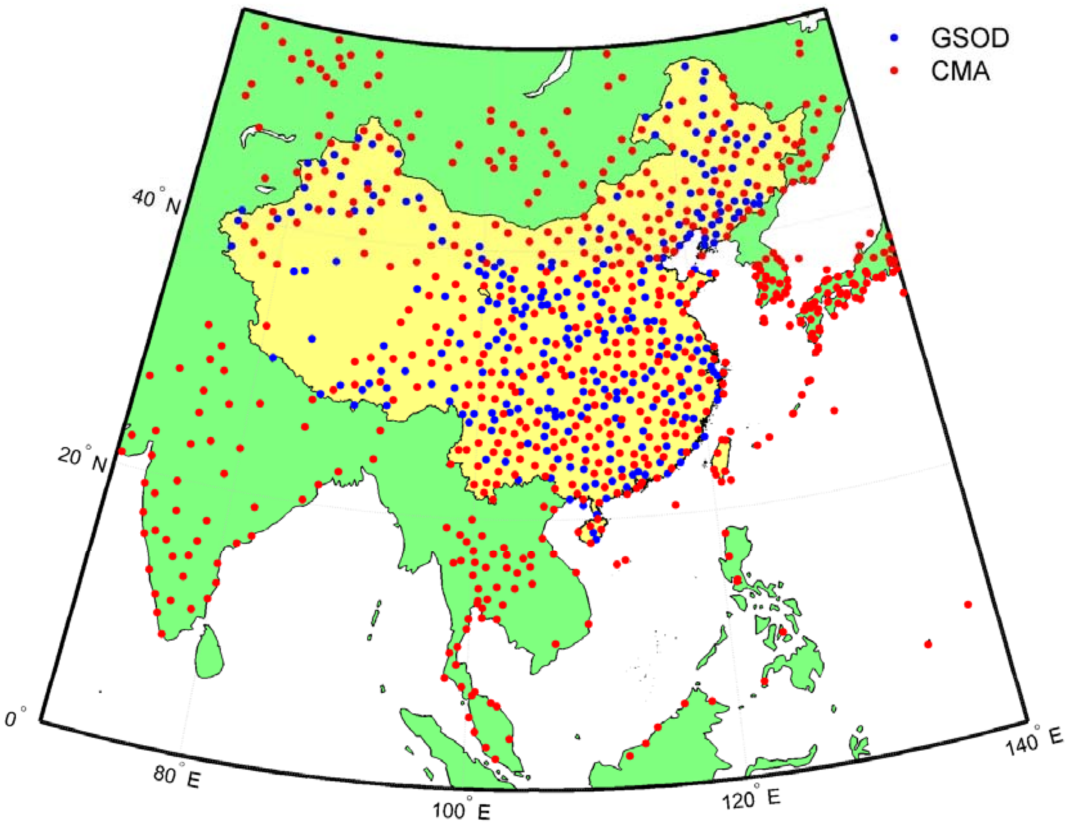
The dataset of meteorological station observations has been retrieved from 1) the Global Surface Summary of the Day collection archived at the National Climatic Data Center (**GSOD**; ftp://ftp.ncdc.noaa.gov/pub/data/qsod).



2) The Global Historical Climate Network Monthly Version 3 (**GHCN**; [*Lawrimore et al.*, 2011]).

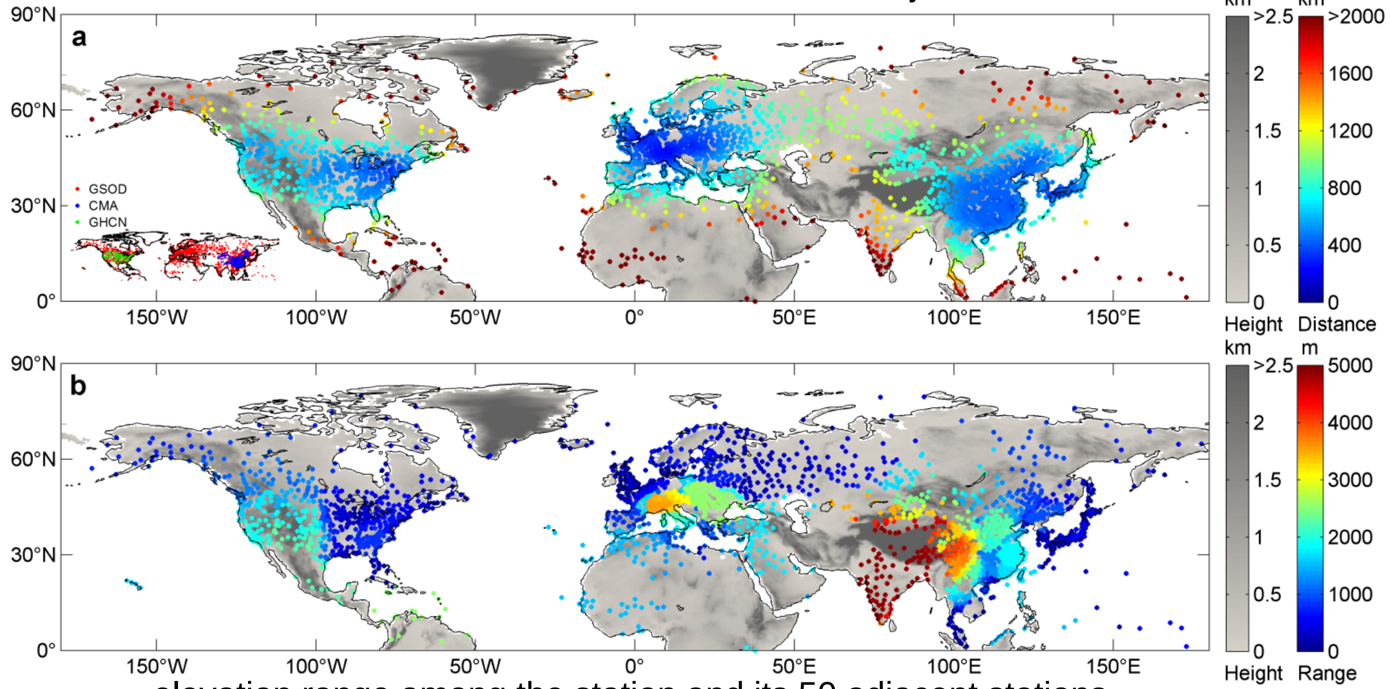


3) The Monthly Surface Climate Variables of China catalog derived from the National Meteorological Information Center of the China Meteorological Administration (**CMA**; http://cdc.cma.gov.cn).



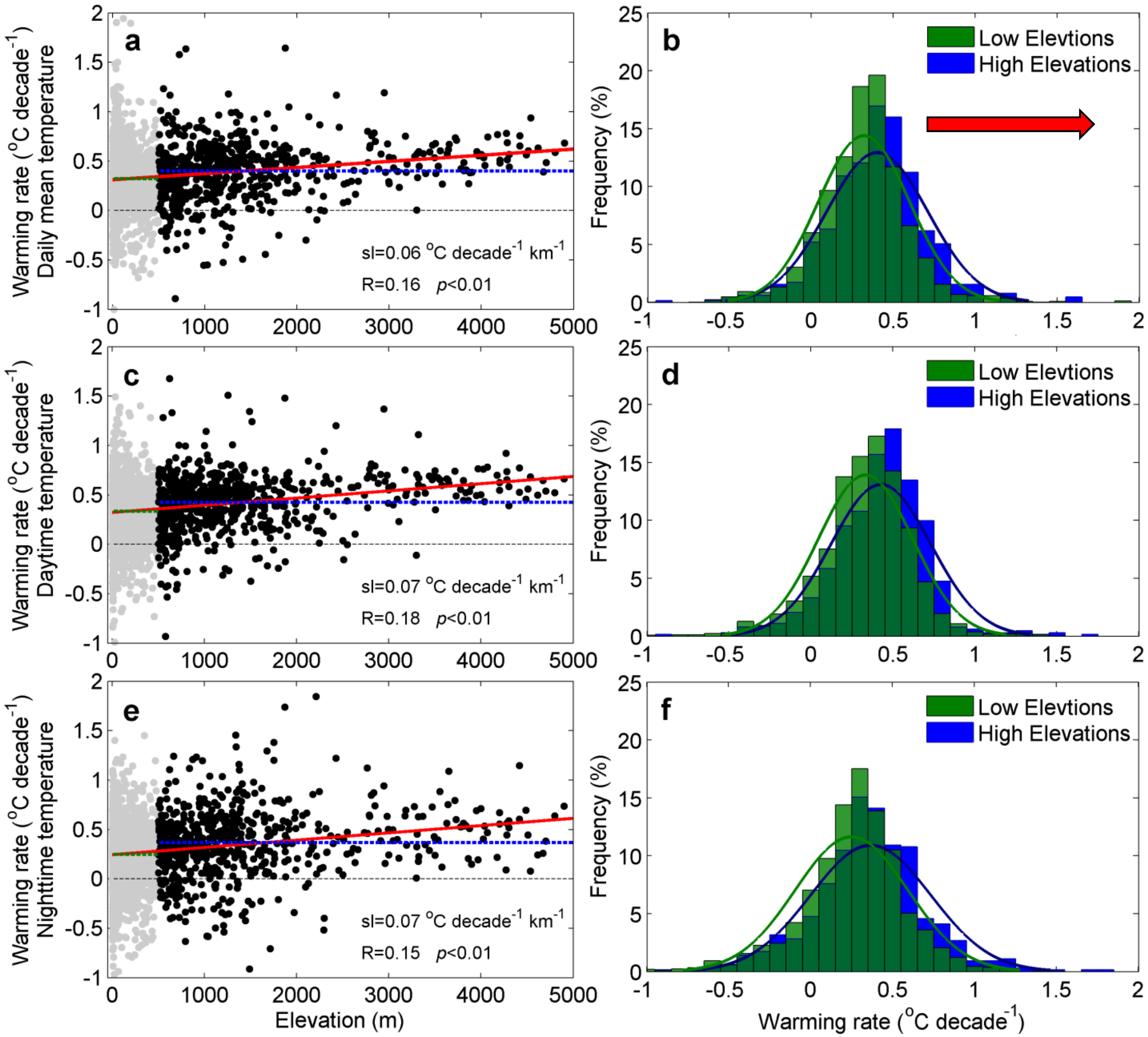
- In total, from the dataset above, we selected 2660 meteorological stations across the NH, with ***continuous*** records of monthly mean temperature, maximum temperature (a proxy of daytime temperature) and minimum temperature (a proxy of night-time temperature) between 1982 and 2010.

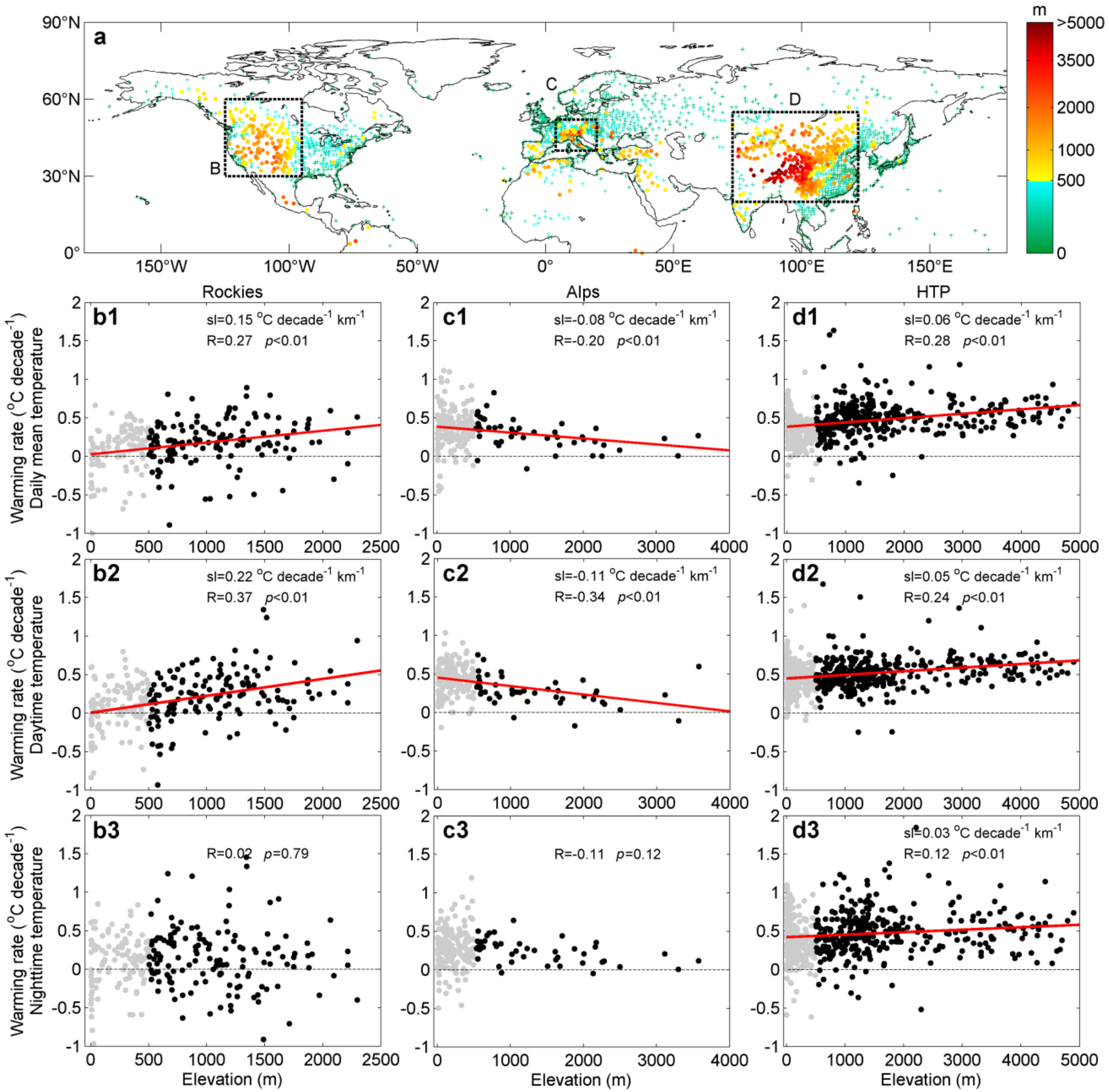
distance between the station and the 50th adjacent station



elevation range among the station and its 50 adjacent stations

Zeng *et al.*, 2015 GRL


a
b
c
d
e
f
Warming rate (°C decade⁻¹) Daily mean temperature
Warming rate (°C decade⁻¹) Daytime temperature
Warming rate (°C decade⁻¹) Nighttime temperature
Frequency (%)
Low Elevtions
High Elevations
sl=0.06 °C decade⁻¹ km⁻¹
R=0.16 p<0.01
sl=0.07 °C decade⁻¹ km⁻¹
R=0.18 p<0.01
sl=0.07 °C decade⁻¹ km⁻¹
R=0.15 p<0.01
Elevation (m)
Warming rate (°C decade⁻¹)


a
90°N
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30°N
0°
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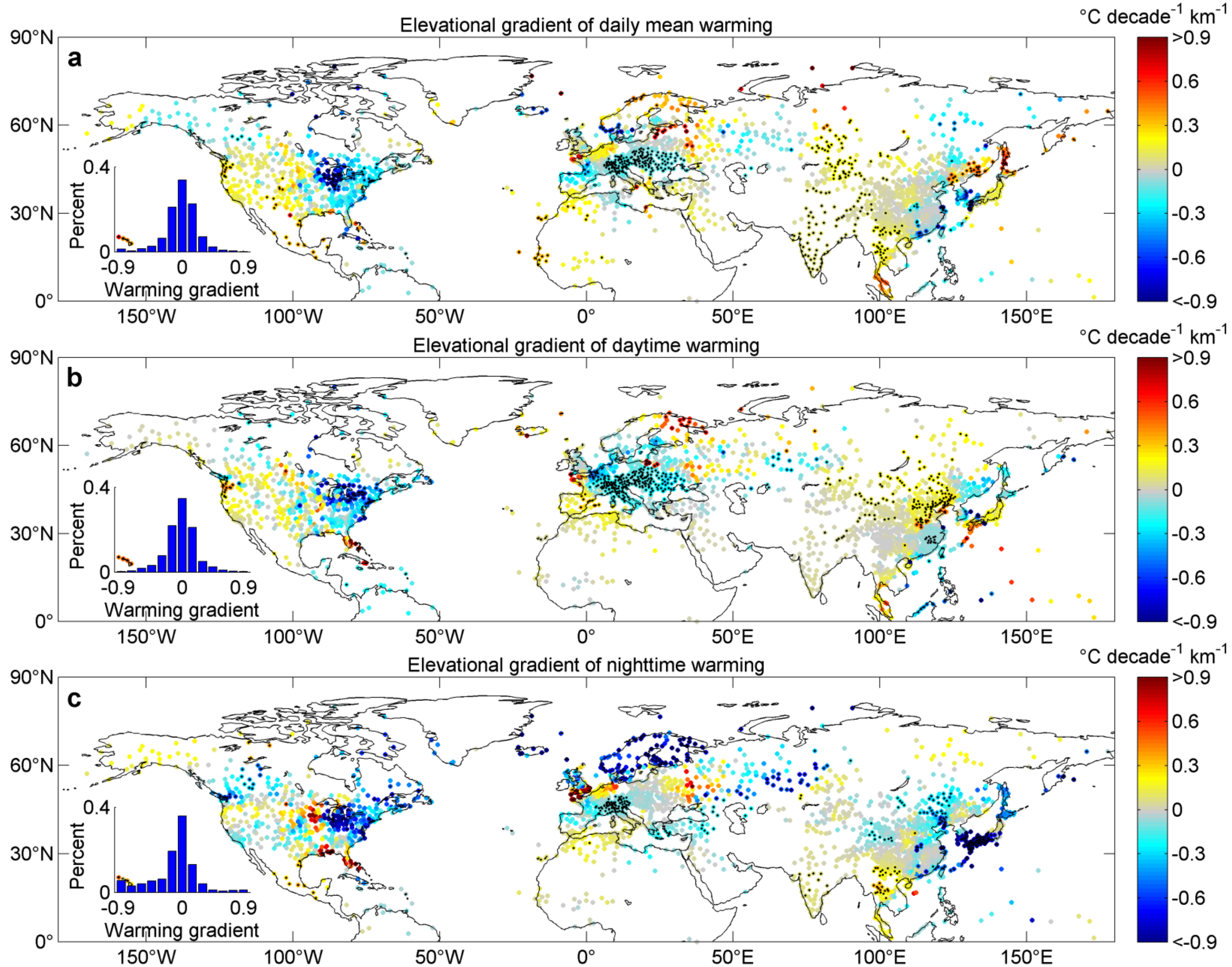
50°W
0°
50°E
100°E
150°E
B
C
D
m
>5000
3500
2000
1000
500
0
Rockies
Alps
HTP
b1
sl=0.15 °C decade-1 km-1
R=0.27 p<0.01
c1
sl=-0.08 °C decade-1 km-1
R=-0.20 p<0.01
d1
sl=0.06 °C decade-1 km-1
R=0.28 p<0.01
b2
sl=0.22 °C decade-1 km-1
R=0.37 p<0.01
c2
sl=-0.11 °C decade-1 km-1
R=-0.34 p<0.01
d2
sl=0.05 °C decade-1 km-1
R=0.24 p<0.01
b3
R=0.02 p=0.79
c3
R=-0.11 p=0.12
d3
sl=0.03 °C decade-1 km-1
R=0.12 p<0.01
Warming rate (°C decade-1) Daily mean temperature
Warming rate (°C decade-1) Daytime temperature
Warming rate (°C decade-1) Nighttime temperature
Elevation (m)
Elevation (m)
Elevation (m)

a regional-pair-based robust multiple linear regression

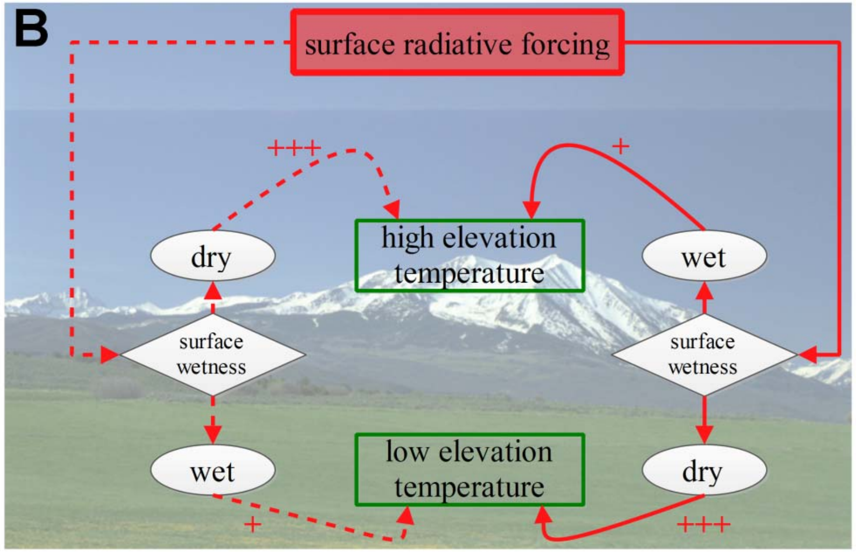
$$Y = k_0 + k_1 \text{Elev} + k_2 \text{Lat} + k_3 \text{Lon}$$

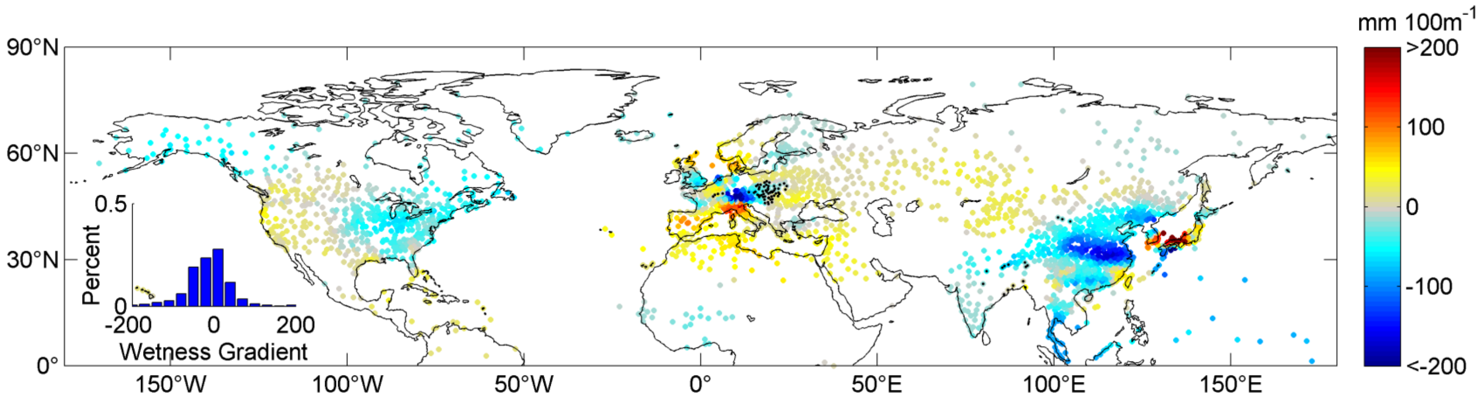


- The prevailing negative elevation-warming relationship over central Europe and eastern North America led us to ask which factors modify the GHG induced positive warming-elevation relationship over these regions. To address this question, we postulate three possible mechanisms:

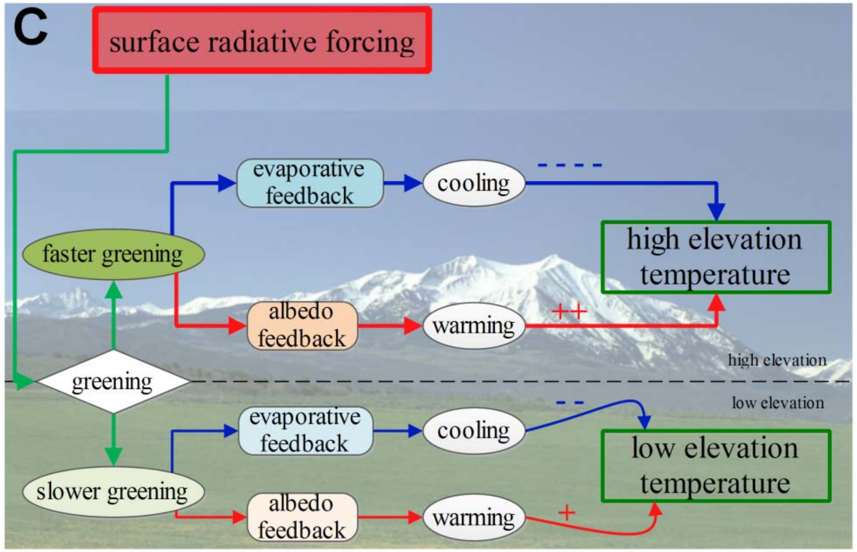
- M1 **wetness**: postulates that wetter surface conditions (soil moisture and air humidity) reduce the warming rate in mountains (Fig. 4*B*).
- M2 **vegetation**: involves a negative feedback on from vegetation-climate interaction, so that increased plant transpiration has cooled mountain regions (Fig. 4*C*).
- M3 **brightening and dimming**: supposes that lowland central Europe and eastern North America are receiving more short-wave surface forcing due to decreasing aerosols and clouds and have thus warmed faster than mountains (Fig. 4*D*).

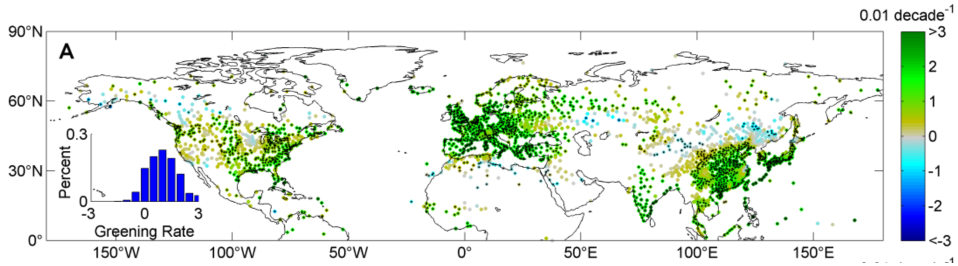
M1: Wetter land surface reduces the warming rate in mountains

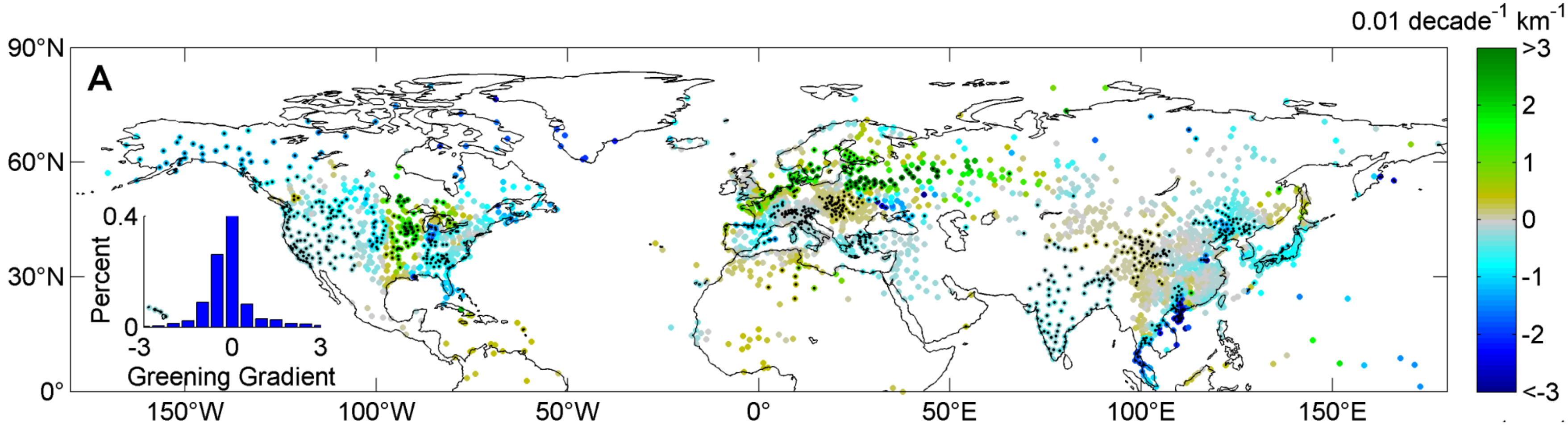




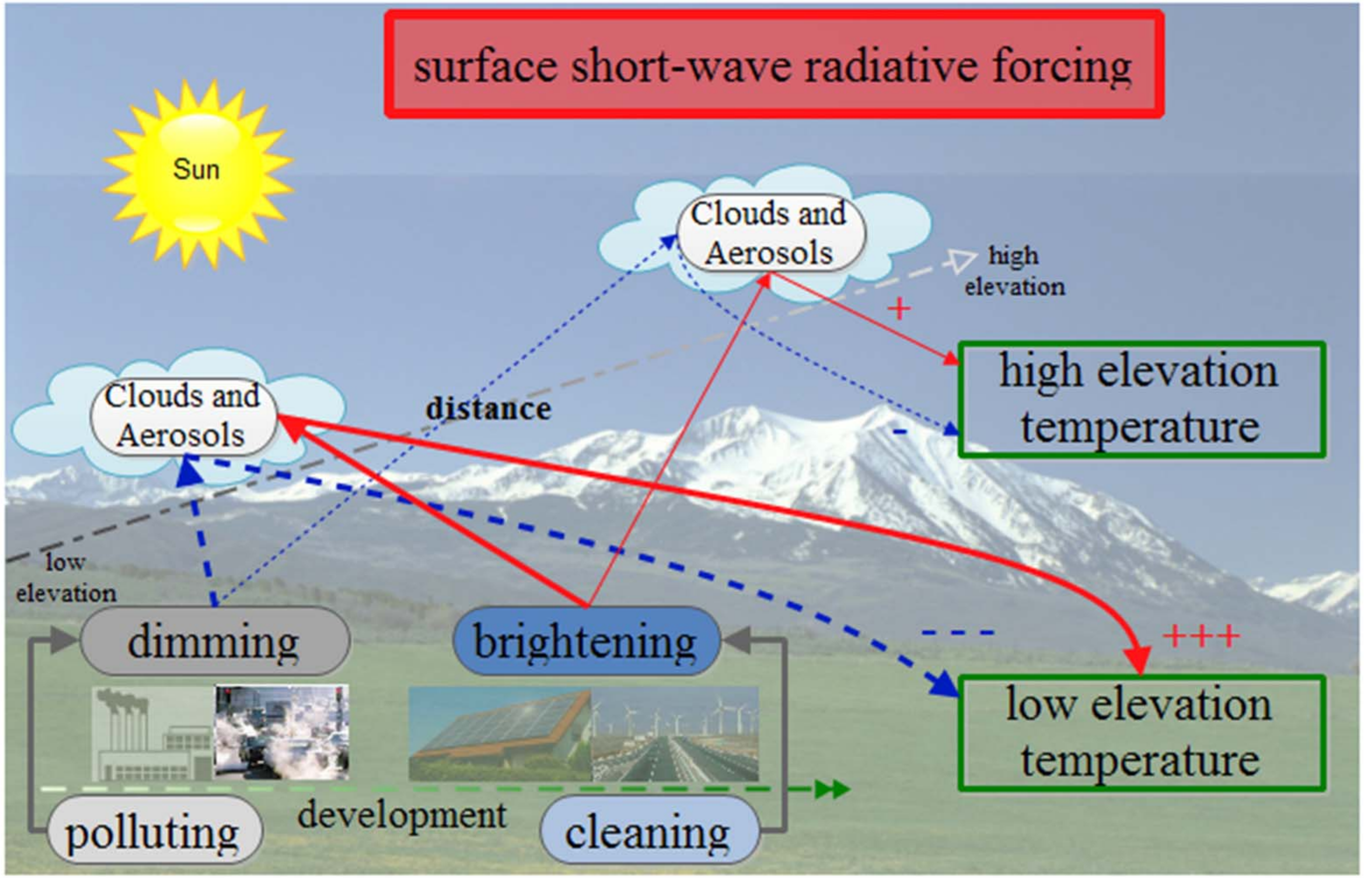
M2: Increased transpiration over mountain regions





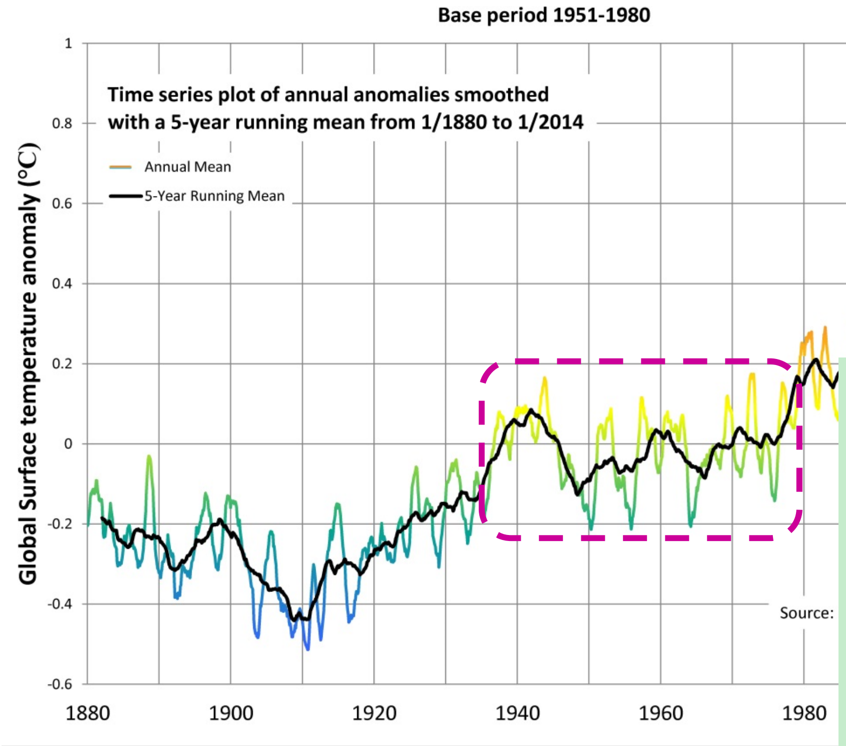


M3: Changes in aerosols and clouds modify the relationship



Zeng *et al.*, 2015 GRL

M3: Changes in aerosols and clouds modify the relationship



Key words:
Dimming & Brightening
Solar radiation at surface
Atmospheric aerosol loading

Wild et al., Science 2005
Wild et al., GRL 2007
Wang et al., Science 2009
Wild, JGR 2009 ......
Wild, BAMS 2012
Wang and Dickinson, PNAS 2013
Nabat, GRL 2014

Contribution of anthropogenic sulfate aerosols to the changing Euro-Mediterranean climate since 1980

Pierre Nabat,[1] Samuel Somot[1], Marc Mallet[2], Arturo Sanchez-Lorenzo[3] and Martin Wild,[4]

Corresponding author: P. Nabat, Météo-France, CNRM-GAME, UMR3589 - 42, avenue Gaspard Coriolis 31057 Toulouse, France, pierre.nabat@meteo.fr

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[2]Laboratoire d'Aérologie, UMR5560 - 16, avenue Edouard Belin, Toulouse, France

the global water cycle, melts away snow and ice, and enables photosynthesis and associated plant growth ...

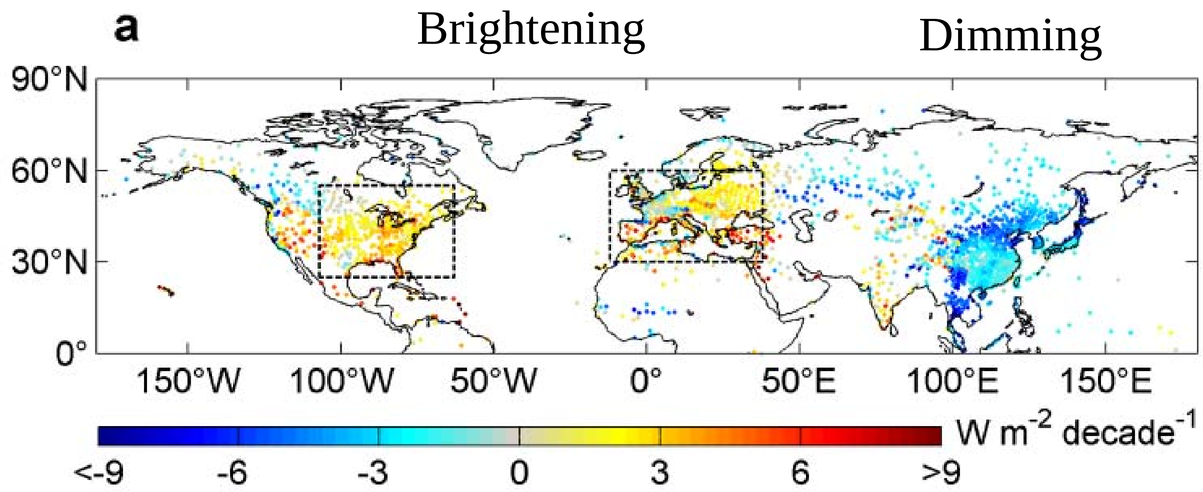
provided by measurement of solar radiation incident at the surface (*1*) and by estimation of emissions by fossil fuel combustion (*2*). The

and may profoundly affect our environments. This evidence comes from the worldwide networks of ...

of Day (GSOD) database collected from about 3250 meteorological stations from 1973 to 2007. It is multiplied by a scaling factor of 1.0 km, as

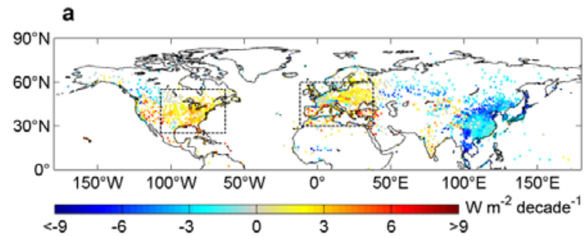
M3: Changes in aerosols and clouds modify the relationship

Condition 1: brightening effect



the NASA/GEWEX Surface Radiation Budget (SRB) Release-3.0 dataset

• Air quality improvement in Europe



Aerosol and cloud effects on solar brightening and the recent rapid warming

Christian Ruckstuhl,[1] Rolf Philipona,[2] Kl
Bruno Dürr,[4] Alain Heimo,[2] Christian Mä
Laurent Vuilleumier,[2] Michael Weller,[3] C

Received 9 April 2008; accepted 22 May 2008; publishe

[1] The rapid temperature increase of 1°C c
Europe since 1980 is considerably larg
temperature rise expected from anthropogeni
gas increases. Here we present aerosol c
measurements from six specific locations
irradiance measurements from a large numbe
sites in Northern Germany and Switz
measurements show a decline in aerosol cor
up to 60%, wh
increase of solar
1980s. The me
show that the dir
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aerosol and oth
cloud induced su

nature geoscience
LETTERS
PUBLISHED ONLINE: 18 JANUARY 2009 | DOI: 10.1038/NGEO41

Decline of fog, mist and haze in Europe over the past 30 years

Robert Vautard[1]*, Pascal Yiou[1] and Geert Jan van Oldenborgh[2]

Europe[22], especially in urban areas,
een given so far. In general, the typ
hether they are due to global or regic
has not yet been determined.
horizontal-visibility (v) series prov
this investigation. Phenomena induc
fog ($v \leqslant 1$ km), mist ($v \leqslant 2$ km)
rom 342 meteorological stations ac
comparison, the evolutions of colloca
carried out. Observations are provi
, 15 and 21 UT. Data and quality con
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ected stations, a strong general declin
bility phenomena is found over the
r visibilities lower than 2 km, the tr
nn–winter (Jan.–March and Oct.–D
ner (April–Sept.), both a 50% reduct
l is larger for higher thresholds, v

Twenty-five years of continuous sulphur dioxide emission reduction in Europe

V. Vestreng[1], G. Myhre[2], H. Fagerli[1], S. Reis[3], and L. Tarrasón[1]

[1]Air Pollution Section, Research Department, Norwegian Meteorological Institute, Oslo, Norway
[2]Department of Geosciences, University of Oslo, Oslo, Norway
[3]Atmospheric Sciences Section, Centre for Ecology & Hydrology, Edinburgh, Scotland

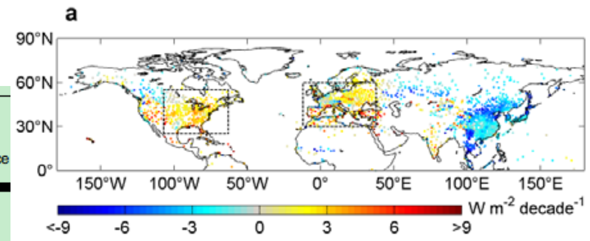
Received: 9 February 2007 – Published in Atmos. Chem. Phys. Discuss.: 11 April 2007
Revised: 4 July 2007 – Accepted: 4 July 2007 – Published: 12 July 2007

Abstract. During the last twenty-five years European emission data have been compiled and reported under the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP) as part of the work under the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP). This paper

processes. The majority of European countries have reduced their emissions by more than 60% between 1990 and 2004, and one quarter have already achieved sulphur emission reductions higher than 80%. At European level, the total sulphur target for 2010 set in the Gothenburg Protocol (16 Tg) has apparently already been met by 2004. However, still half

• Air quality improvement in United States

the 1970 Clean Air Act Amendments in the United States [Dominici *et al.*, 2007]



American Journal of Epidemiology

Advance

Original Contribution

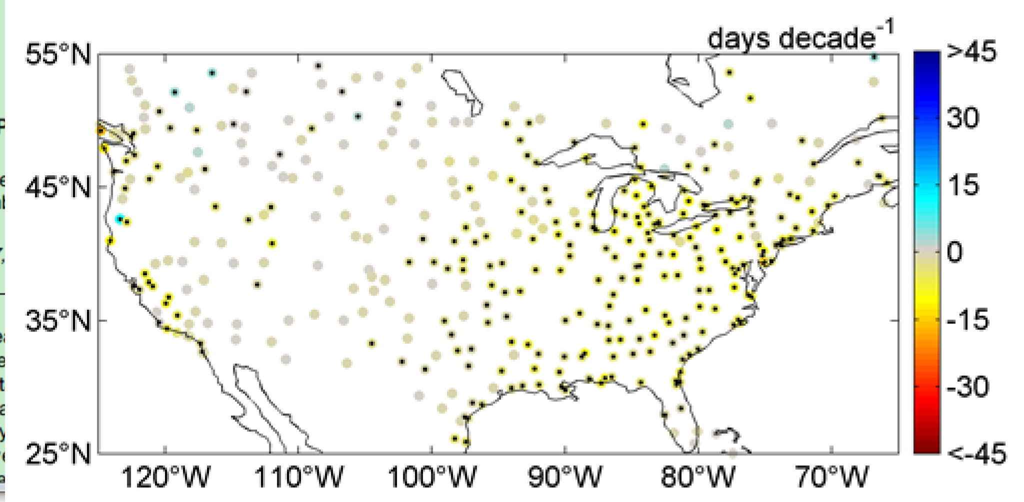
Particulate Air Pollution and Mortality in the United States: Did the Risks Change from 1987 to 2000?

Francesca Dominici[1], Roger D. P

[1] Department of Biostatistics, Bloombe
[2] Department of Epidemiology, Bloomb

Received for publication September 7,

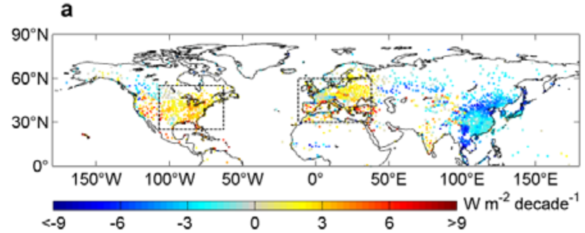
Evaluation of the public he
increasingly viewed as a nece
present an example of account
particles over a period of increa
toxicity of these particles. They
Study to estimate national ave
diameter on all-cause, cardiova



Trends of the number of days with meteorological visibility <5 km (1982-2010; days decade^{-1}) in the United States

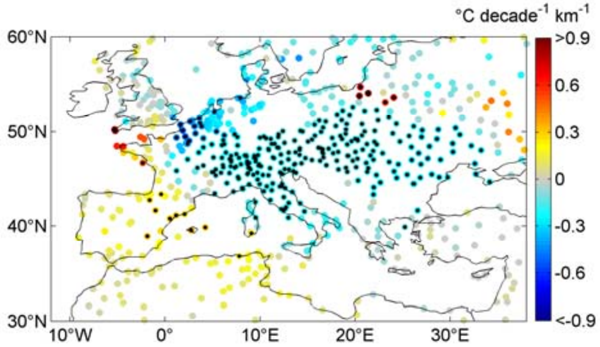
- Air quality deterioration in China

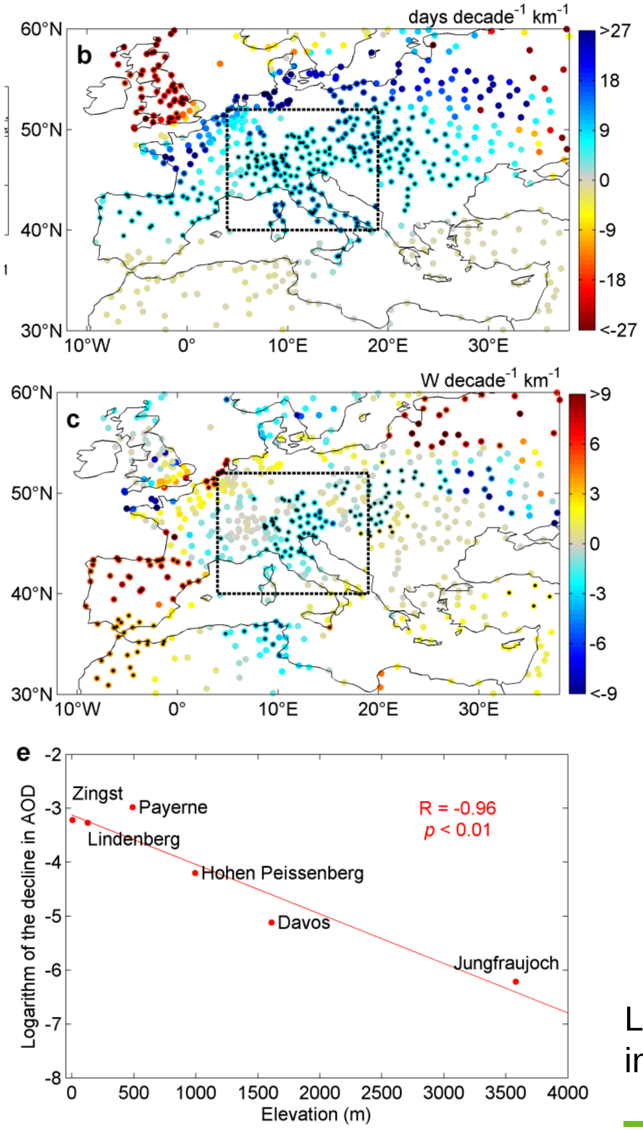
Reform and Opening Policy since 1978.



M3: Changes in aerosols and clouds modify the relationship

Condition 2: more brightening in lowland





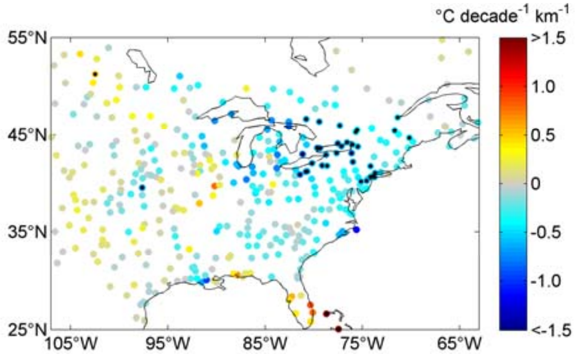
Gradients of the trend of number of days with visibility <5km

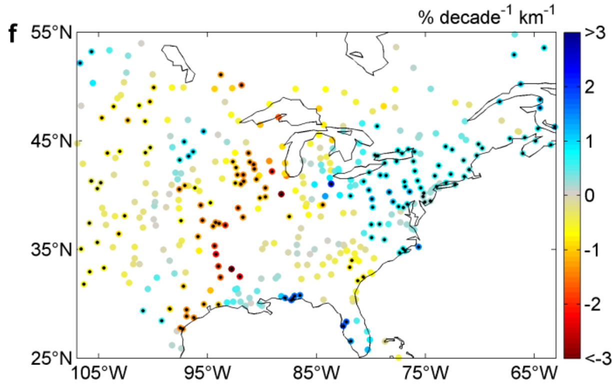
Gradients of the incoming surface radiation trend

Logarithm of the decline in aerosol optical depth

Ruckstuhl *et al.*, 2008; Philipona, 2013

M3: Changes in aerosols and clouds modify the relationship





Gradient of cloud fraction trend

- In Eastern North America, the brightening is attributed to the decreasing trend in cloudiness [*Augustine and Dutton, 2013*; *Wang and Dickinson*, 2013].
- The decreasing trend in cloudiness is partly due to the improved air quality after the 1970 Clean Air Act Amendments in the United States through the indirect effect of aerosols (i.e., acting as cloud condensation and ice nuclei).
- **We do find a positive elevational gradient of the cloud fraction trend.**

Zeng *et al.*, 2015 GRL

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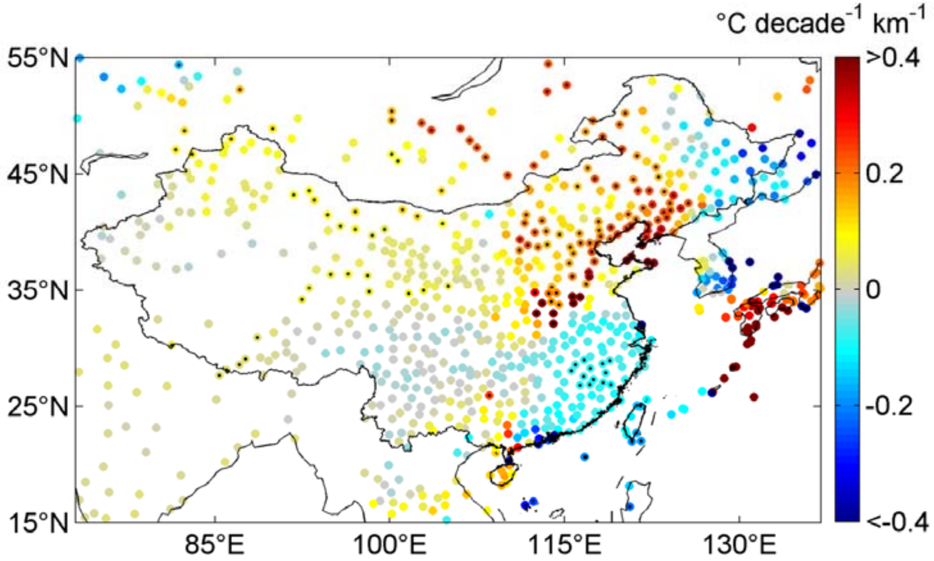
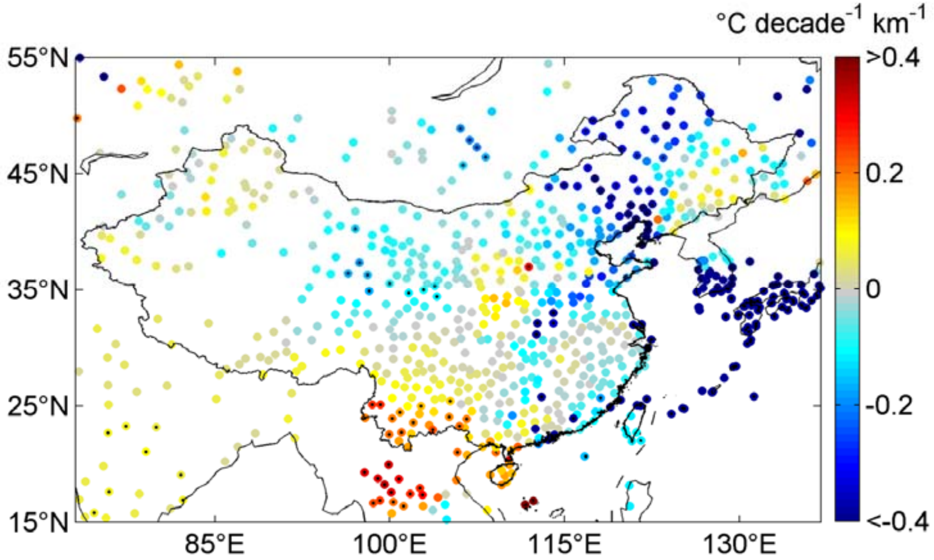
Daytime



Nighttime



- Take home message

- Altitudinal differences in brightening, with observations showing more short-wave radiation received at low altitudes than at mountain stations, have modulated the otherwise uniform effect of the long-wave forcing of GHG on the elevation-dependent warming.

Zeng et al., 2015 GRL
Regional air pollution brightening reverses the greenhouse gases induced warming-elevation relationship