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ON THE ROLE OF TROPOSPHERIC CIRCULATION IN RECENT CLIMATE CHANGES IN THE ANTARCTIC PENINSULA REGION

Abstract: The state of tropospheric circulation in the West Antarctic sector (WAS) is considered during 1990s, the warmest decade in the Antarctic Peninsula (AP) region. Regional warming has progressed almost coherently with the second phase of global warming and is related to oceanic variability, specifically PDO-ENSO conditions. Atmospheric circulation in 1990s comprises a prevailing cyclogenesis west of the Antarctic Peninsula sector along with frequent weather modifications (the winter season in particular is examined) and the ridge of high pressure to the east. Predominant atmospheric circulation types for the recent decade are found to be stable in time causing smaller air temperature oscillations on different time scales. The circulation background responsible for the stabilization of air temperature growth in the AP region immediately after the turn of the millennium is shown.

Key words: regional warming, Antarctic Peninsula, predominant circulation type, criterion of similarity.

Introduction

Two-phase warming has been observed during the last century in the lower troposphere in planetary scale, and was most clearly displayed in both polar regions and the extratropics including Alaska, Arctic, Central Siberia, and most of Europe (Rogers et al. 1995; Alekseev 2003; Hinzmann et al. 2005; Turner et al. 2005). Regional warming in the Antarctic Peninsula (AP) re-

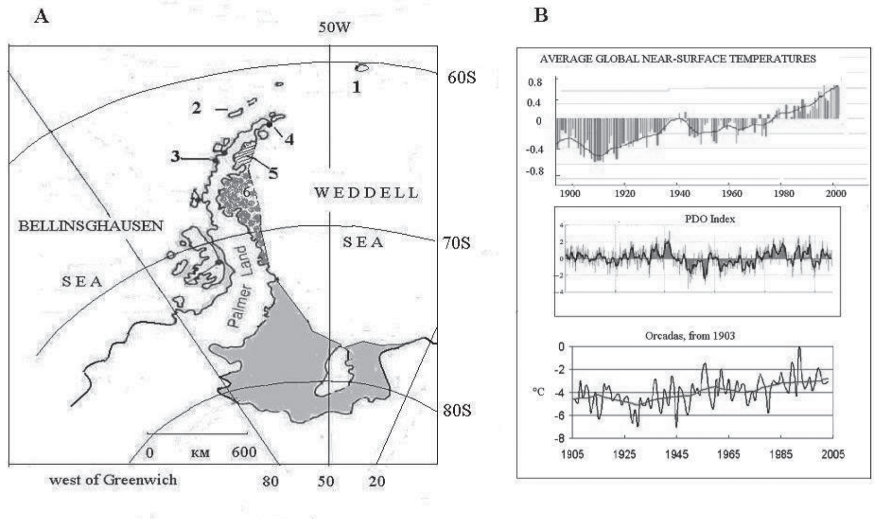

Fig. 1. A – Antarctic Peninsula and research stations, 1 – Orcadas, 2 – Bellinsghausen, 3 – Faraday, 4 – Esperanza; 5 – part of the Larsen ice shelf that collapsed in 2002; B – centennial changes in: global air temperature anomaly, PDO Index and annual mean air temperatures at Orcadas, 1904–2003

gion and the surrounding Subantarctic Islands can also be considered as part of more general global changes (Fig. 1) contrasting to weak cooling in continental Antarctica (Kejna 2002; Turner et al. 2005). A recent warming episode, which started in the AP region in the late 1970s or early 1980s against a background of the transition of the Pacific Decadal Oscillation (PDO) to a positive phase, has significantly exceeded global warming rates and caused numerous after-effects in regional glaciation, sea-ice and ecosystems etc. (Vaughan et al. 1996; Yuan et al. 2000; Tymofeyev et al. 2002).

Many indications of climatically important changes in atmospheric circulation were detected elsewhere, e.g., intensification of cyclonicity in the North Pacific or North Atlantic with an eastward shift of NAO system (Jung et al. 2002), as well as changes in blocking activity and storm-tracks in the Southern Hemisphere (Sinclair 1996; Connolley 1997; Turner et al. 2002; Fyfe 2003). Important conclusions were drawn on the dependence of regional climates on ENSO conditions (Turner 2004), with alternative pressure anomalies in austral extratropics in years with different ENSO events. Considerable attention was paid to variability in the Southern Annular Mode and regional warming; however atmospheric circulation mechanisms of recent climate change in the AP region have still not been thoroughly studied. It is well-known that intensification of eastward air flows becomes a characteristic feature of the recent warming period (Marshall 2003; Marshall et al. 2006) but changes in regional circulation patterns have not yet been shown. A number of weather types obtained in such studies as Lynch et al. (2006) allow us to describe atmospheric circulation in considerable detail, though it remains difficult to compare changes over different years. The main purpose of our research was to obtain a few circulation types of different probabilities and to try to explain the reasons for recent climate variability in the Antarctic Peninsula region.

Data and method

Mean sea-level pressure (MSLP) and geopotential fields of ERA-40 reanalysis (ECMWF) are used as well as data from the Antarctic Peninsula stations with the longest uninterrupted records in the READER database (http://www.antarctica.ac.uk/met/READER/surface/stationpt.html). The main stations are Vernadsky, Ukraine, 65°2'S, 64°2'W, formerly known as Faraday, UK, as well as Orcadas (60.7ºS, 44.7ºW), Bellingshausen (62.2° S, 58.9ºW), Esperanza (63.3ºS, 56.8ºW) (Fig. 1).

The state of atmospheric circulation was studied by identifying so-called 'etalon' weather patterns, obtained using a statistical approach which classifies MSLP fields by their probability (as shown below).

Recent warming in the Antarctic Peninsula region

Although the meteorological records of the majority of Antarctic Peninsula stations are significantly shorter than those in the Northern Hemisphere they cover the period of relative cooling in the mid-twentieth century and the most progressive warming from the early 1980s; the 1990s are the warmest decade. The most significant warming is observed at Vernadsky and Bellinsghausen (King-George Island), with annual rates exceeding 2.5°C over the last 30 years. Figure 2 shows how frequency distributions of near-surface air temperatures (SAT) in winter months (JJA) at Faraday-Vernadsky have changed between the coldest and warmest decades. The distribution for coldest 1960s is bi-modal and that for 1990s is one-modal and much closer to Gauss distribution with mean -3.7ºC and mean squared deviation of 4.6ºC.

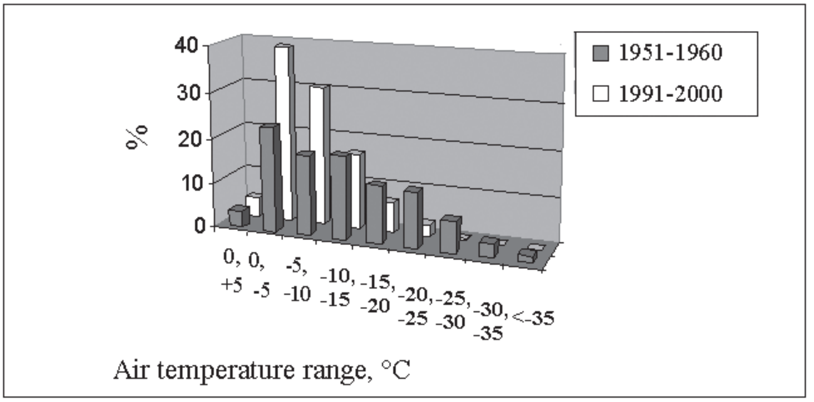

Fig. 2. Air temperature ranges for winter months in the periods 1951–1960 and 1991–2000, Faraday-Vernadsky base. (Data from instrumental measurements in 8 daily synoptic hours are used)

According to the data from Vernadsky, warming in the winter months is mainly connected with the annual growth of SAT and is accompanied by a decrease in annual, seasonal and daily ranges of surface air temperatures and a significant increase in minimum ones. The greatest smoothening of year-to-year SAT amplitudes can be noted in autumn and winter in the course of warming, especially in April (Fig. 3). Summer warming, being much smaller (0.65˚C/30 years), is potentially of greater significance for ablation in conditions of constantly expanding period of daily temperatures exceeding freezing point (it has increased by about one month between the 1960s and 1990s) and greater probability of rains.

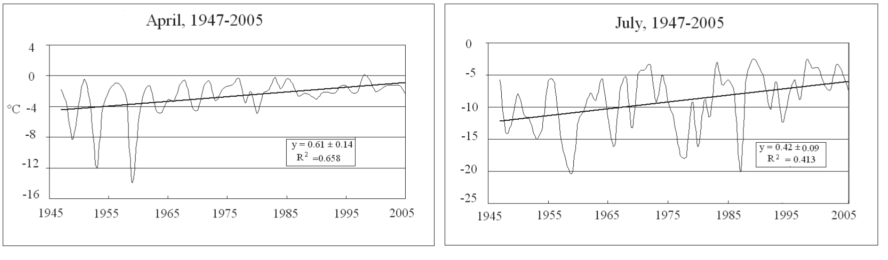

Fig. 3. Multi-annual course of monthly mean air temperatures, April, July 1947–2005, Faraday-Vernadsky. Equation of linear trend and sum of squared residuals are shown in separate box.

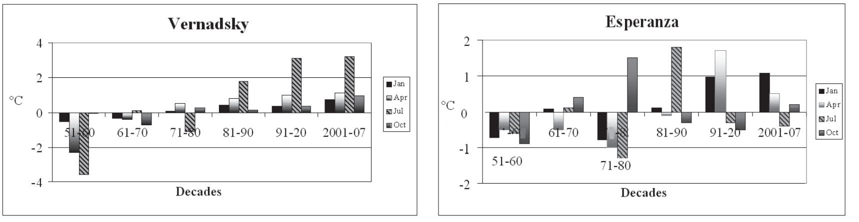

Fig. 4. Anomalies of monthly mean air temperatures for central months of seasons for decades from the 1950s onwards and for the period 2001–2007 at Vernadsky and Esperanza. Anomalies were calculated in relation to monthly averages during the period 1961–1990

Seasonal air temperature growth at Vernadsky has progressed more or less evenly between decades whereas it has occurred more erratically on east coast AP stations, where air temperatures are colder and the topography is more complicated (Fig. 4). Esperanza, for example, experienced more intensive winter warming in the 1980s and summer warming in the 1990s. The temperature records from recent years showed a weakening of the SAT growth in most AP stations although they still significantly exceeded figures from the period 1961–1990. Annual mean SAT values at Vernadsky are range only from 2.0 to -3.7ºC in the past decade; seasonal anomalies in the 2001–2007 are comparable in terms of magnitude with those of the 1990s. Weak cooling in July in Esperanza is registered along with weaker positive SAT anomalies in other months during the period 2001–07 (Fig. 4). Weak cooling is also noted during this period in different seasons at the Orcadas base (not shown here).

Spatial correlations of monthly air temperatures at regional stations are found to be greatest in winter and weakest in summer, most probably because of the more homogenous winter atmospheric circulation. The correlations between temperatures for winter and summer months, for example, are greatest between Vernadsky and Bellingshausen (0.93 and 0.75, statistically significant to a level of 95%), and weakest between Vernadsky and Esperanza (0.56 and -0.08 respectively). So the radius of the best correlations is directed north from Vernadsky towards King George Island; liaison has increased during the recent period of warming.

Winds have intensified in the mid- and lower troposphere during the recent warming episode, with predominant west-north-westerlies. Besides, regional modifications of air flows crossing the Peninsula are found to contribute to warming to some extent, because of the more frequent warm Fohn winds registered by Vernadsky measurements (see the description below of responsible circulation background).

Changes in atmospheric circulation

Distinguishing predominant weather patterns (method)

Predominant circulation patterns (i.e. those which are most probable) were distinguished on the basis of statistical method developed by Martazinova (2005). One of the most effective criteria that allow us to geometrically distinguish MSLP fields is the similarity criterion calculated on the basis of the sign of anomaly of MSLP fields (Bagrov 1969]:

$$\rho = \frac{n_+ - n_-}{K},$$

where n+ is a number of points with coinciding anomalies in pressure fields,
n – is a number of points with opposite anomalies, and K the total number of gridpoints.

The choice of a representative averaging period is the most important matter to bear in mind when performing the calculations, because one can obtain only positive or negative anomalies – and hence big errors in ρ – if some old climatic norms are used. In this study, monthly averages were used for each individual year.

Magnitudes of ρ for the Southern Hemisphere are higher than for the Northern Hemisphere, reflecting a simpler circulation (Martazinova 2005). Criterion ρ can be transformed to correlation coefficient R as follows: R = 1.57 ρ (for $|\rho| < 0.4$) and like correlation coefficient, $-1 \leq \rho \leq 1$. If ρ = 0.30 it means that 70% of gridpoints are similar by the sign of anomaly; if ρ ≥ 0.50 it means that fields are almost identical with close positions of centers of high and low pressure._

Another traditional criterion of similarity is a mean squared distance between K fields:

$$\eta = \frac{1}{K}\sum_{i=1}^{K}(x_{ij} - x_{l})^2 ;$$

Where $(x_{ij} - x_l)$ are departures of MSLP (geopotential) from mean value in the corresponding gridpoints

The MSLP field having the highest degree of similarity with all other fields (assessed by maximum magnitude of aggregated or mean ρ), provided ρ exceeding 0.30, and also having a minimum η, is called the most probable field, or the 'etalon'. In the event of a couple or several MSLP fields having similar ρ (it is unheard of!), they are averaged and a new ρ is re-calculated. It is also possible to calculate weather patterns of intermediate probability for the rest MSLP fields having $0 < \rho < 0.30$ (Martazinova 2005). The rarest class of MSLP fields is recognized when $\rho < 0$, and these are typically responsible for extreme weather events. In the case of a high degree of homogeneity of atmospheric circulation daily, MSLP fields show great similarity, especially in summer (no $\rho < 0$) and one can divide large-scale circulation patterns on 2 different types, of greater and lower probability.

Finally, the skill probability of 'etalon' MSLP fields was estimated by re-calculation of the criterion of similarity of MSLP of an etalon day with other MSLP fields in given month (season); those fields with $\rho > 0.3$ were recognized as similar and the share of similar MSLP fields among all fields is given in percentages.

The most probable and rare MSLP fields in the Antarctic Peninsula sector during the period of the recent warming

The most probable and rarest synoptic patterns are presented below for the winter months in the 1990s and other important years. Calculations were made for the area 40–75°S and 180–40°W that comprise 3 main regions with cyclogenesis in the austral extratropics.

The most probable MSLP fields for 3 winter months (June-August) and the most probable 500 hPa geopotential field for July in the 1990s are presented in Figure 5. Etalon MSLP fields are found in many respects to be similar in all months, with predominant cyclogenesis in WAS and the Bellinshgausen Sea, and the subtropic wedge close to the longitudes of the AP or east of it. The wedge separates areas of climatic cyclones at the Bellinshgauesen and Weddell seas, creating meridionality and sometimes a blocking effect, typically in August. Graham Land is under the influence of prevailing warm N-NW winds in forepart of depression or series of cyclones; signifi-

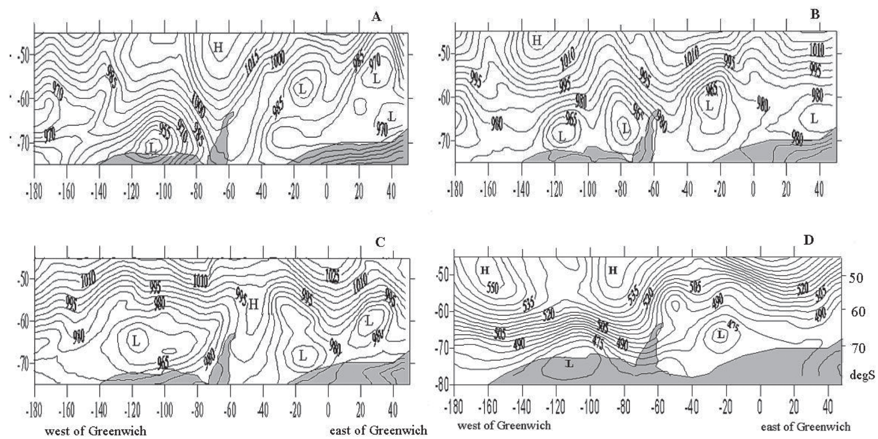

Fig. 5. Most probable MSLP fields, 1990s, June (A), July (B), August (C), and 500 hPa level (July, D). Contour of the Antarctic continent is shaded

cant cold spells from the Antarctic interior are rare under such a type of circulation. This is also confirmed by the most probable mid-tropospheric geopotential field at a level of 500 hPa representing strong zonal gradients (frontal zone) west of the Antarctic Peninsula, with some deflection north at 60–80 W (Fig. 5D). As a result of the strengthening effect of wind, regional weather modifications in the AP region (mainly Fohn winds by data of Vernadsky) have became frequent over the warming episode because of general intensification of winds crossing the mountain ridge.

Synoptic types of rare probability in winter are characterized by significant meridionality in WAS on account of the well-developed wedge between 60–100W, and deep cyclones in the Ross and Weddell seas (Fig. 6). Such a circulation pattern causes southern winds to AP, bringing air temperatures below climatic norms, and in dependence on positioning of the wedge the weather is colder in anticyclonic conditions or a bit warmer but windy and with precipitation in the rear part of cyclone. The probability of such pattern is lower than 10% in each winter month.

Comparison with the winter season in 1987, coldest of the last 30 years, shows that a similar weather pattern was predominant (Fig. 7). Stable south and southeast inflows in July 1987 brought in very cold air and the mean July temperature dropped as low as -20ºC. Analysis of predominant patterns for 2001 and 2002 showed that high pressure has again amplified in WAS,

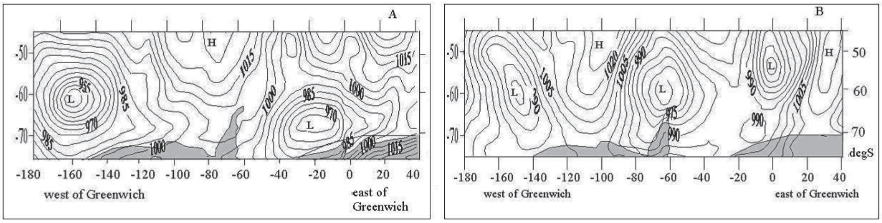

Fig. 6. Rare (least probable) MSLP fields: July (A), August (B), 1990s

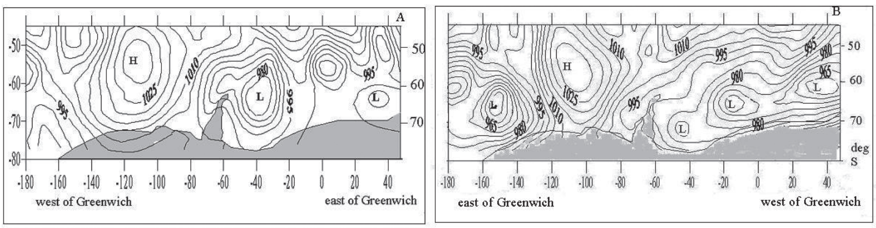

Fig. 7. Most probable MSLP fields for July, 1987 (A) and July, 2001 (B)

although with weaker gradients in the AP region, and not so cold weather: -9.4 June, -7.2, July and -7.5°C in August. This reveals some change in atmospheric circulation to have taken place after warmest 1998, explaining the slowing down in the warming in the AP region.

The ranges of both criteria of similarity are different in different seasons and in the same seasons with alternative air temperature anomalies, and can be used to estimate the homogeneity of circulation in the first approach. The greater the value of criterion ρ, the more statistically 'reliable' the most probable field is; the greater the range of ρ, the more homogeneous we can expect circulation to be.

A significant similarity between the etalon MSLP field and adjacent days is detected, with magnitudes of $\rho > 0.50$ during at least 3–4 adjacent days, and > 0.30 during 7–10 adjacent days (Fig. 8, correlations are calculated in relation to the monthly etalon MSLP field). The greatest similarity is noted in warmer years with series of cyclones, showing a great stability of predominant weather patterns in austral extratropics and explaining less significant daily, monthly and seasonal air temperature amplitudes.

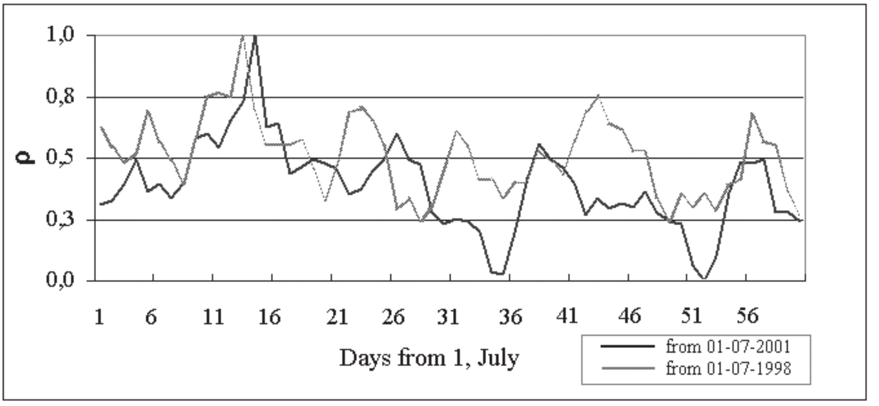

Fig. 8. Course of similarity criterion ρ calculated between each day within July-August, 1998 and 2001, and the most probable MSLP field for the corresponding period

The temporal variability of the similarity criterion ρ calculated for any given day resembles autocorrelation and reveals regular peaks connected with some periodicities in the atmospheric circulation. A synoptic periodicity of about 10–14 days is easier to ascertain for a warm year (1998) with a series of cyclones; this can also be seen in Figure 8. The periodicity is slightly longer in a colder year (2001) with predominant high pressure slowing down the movement of cyclones and amounting to 14–20 days. These periodicities can be used in medium-range weather forecasting.

Discussion

The hierarchy of etalon MSLP fields of different probabilities describes details of atmospheric circulation for a given month, season or year showing the typical position of the main weather-making pressure patterns including teleconnections.

Changes in atmospheric circulation can be detected by analyzing the predominant MSLP fields, which in turn are responsible for the prevailing air inflows. Warmest 1990s in AP stations were characterized by predominant cyclogenesis in the West Antarctic sector and specifically in the Bellingshausen Sea; further stabilization of regional warming was accompanied by intensification of anticyclogenesis.

Anticyclones with like-blocking effects are intensified in the WAS under warmer ENSO episodes, whereas depressions are typically developed under La-Niña (Turner 2004). Cold events are rare in the recent years, however. It is believed that connections between ENSO and weather and climate anomalies in the AP region are rather more complicated because the AP lies near the boundary of main circulation systems.

Other authors (Bertler et al. 2004) found that ENSO has a different influence on the climate in the Ross Sea region suppressing warming. According to our conclusions, intensification of cyclonicity in the western Antarctic sector results in different types of advection to its marginal parts: colder air inflow predominates in the Ross Sea region and warmer N-NW winds prevail in the northern Antarctic Peninsula, causing alternative near-surface air-temperature conditions.

Additionally, climate anomalies are found to be coherently registered in the North and South Pacific during mature ENSO events, e.g., intensification of anticyclogenesis in both extratropics and/or polar regions along with weakening of the subtropical highs is typical during warmer ENSO events. Recent warming episode in the Antarctic Peninsula region agreed to temporal frames of warming in Alaska, its geographical counterpart.

Conclusions

The recent warming episode in the Antarctic Peninsula region has progressed in line with time frames of global warming and is accompanied by a decrease in air temperature ranges over different timescales from annual to daily. Maximum rates of warming are noted in the stations on the west coast of the peninsula; after one of the warmest 1998 the rate of warming has somewhat decreased. Multi-years' growth of near-surface temperatures occurred differently in seasons on stations with different topographies, with the most variety at north-east Graham Land.

Recent warming in the AP region is characterized by specific regional atmospheric circulation with predominant cyclogenesis west of the Antarctic Peninsula, along with frequent regional weather modifications because of general intensification of winds. The warmest 1990s were characterized by prevailing of cyclogenesis in the West Antarctic sector; the great temporal stability of predominant circulation patterns produced lower air-temperature oscillation on a variety of time scales.

The stabilization of air temperature increases by atmospheric circulation in the AP region is noted right after the turn of the millennium, providing a background for a new climate shift to emerge in the region.

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