Extratropical Southern Hemisphere Cyclones: Harbingers of Climate Change?

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ABSTRACT

In concert with a poleward shift in baroclinicity, the synoptic environment south of 40°S appears to have changed significantly over recent decades. South of 40°S and north of the Antarctic Ocean the number of cyclones has dramatically decreased, while over the Antarctic Ocean a modest increase has occurred. A global climate model with anthropogenic forcing produces similar historical changes, and under a ''business-as-usual'' emissions scenario predicts that the number of sub-Antarctic Ocean cyclones will drop by over 30% between now and century's end.

1. Introduction

The Southern Hemisphere (SH) high-latitude tropospheric circulation appears to have undergone pronounced changes over recent decades (Folland et al. 2001). These changes can be interpreted as a bias toward the high-index polarity of the SH annular mode, a large-scale pattern of variability that dominates climate variability in the region (Thompson et al. 2000). While the root cause(s) of these changes remain unknown, observational and modeling evidence points to photochemical ozone losses in the stratosphere (Thompson and Solomon 2002; Sexton 2001) and/or anthropogenic greenhouse gas gains in the atmosphere (Fyfe et al. 1999; Kushner et al. 2001) as plausible candidates. Here, we describe dramatic changes occurring in the high-latitude SH synoptic environment, and offer modeling evidence that increasing anthropogenic greenhouse gas concentrations may be a contributing cause.

2. Data and methods

We use sea level pressure (SLP) data from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996), as well as from the Canadian Centre for Climate Modelling and Analysis (CCCma) global climate model (GCM; Flato et al. 2000). The atmospheric component of the GCM is a global primitive equation spectral model with T32 triangular truncation and 10 unequally spaced vertical levels with the top level at 12 hPa. The ocean component is a global primitive equation gridpoint model with 1.875° resolution and 29 vertical levels. An ensemble of three transient climate change simulations for the period 1850–2100 is available. The GCM employs observed effective greenhouse gas forcing changes from 1850 to 1990, and projected changes based on the IS92a scenario from 1990 to 2100. The direct effect of sulfate aerosols is included by varying the surface albedo. Also available is a 500-yr control simulation with fixed preindustrial forcing.

All the data were averaged to daily values (leap days excluded) and transformed to spherical-harmonic coefficients with a triangular truncation at 32 waves. The coefficients were subsequently transformed to polar stereographic grids with a spacing of about 381 km at 60°S, yielding analysis boxes of area of about 135 000 km^2. Here, cyclones are identified as the minima on these daily polar-stereographic grids. This SLP-based cyclone detection method is simple and intuitive but is potentially sensitive, particularly in low and midlatitudes, to changes in the background SLP climatology (Sinclair 1994). We do not believe this to be an issue in this study for two reasons: 1) our focus is on high latitudes where the cyclones are intense and the background SLP weak, and 2) our results are consistent with Simmonds and Keay (2000, hereafter SK) who employ a much more complicated scheme that expressly minimizes this potential sensitivity. Further to this, we purposefully define cyclone depth for a given geographical location and time period as the difference between the period-average cen-

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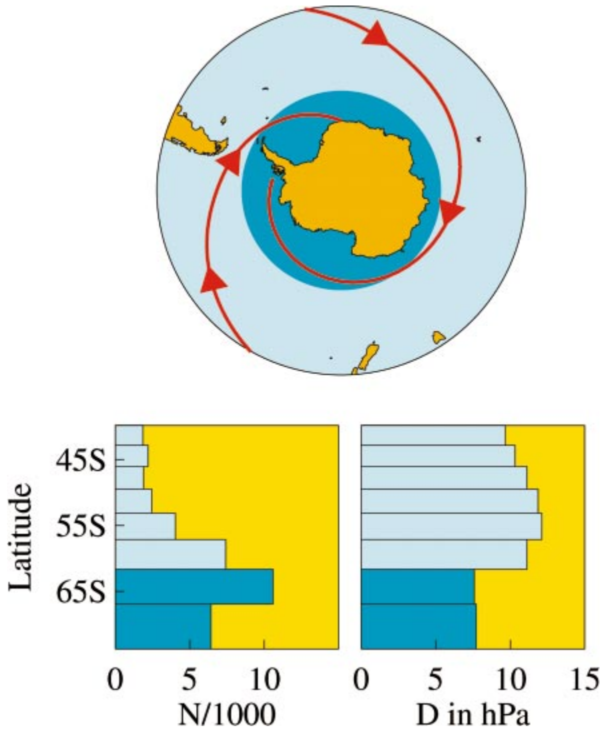

FIG. 1. (top) Schematic of primary cyclone tracks in the high latitudes of the SH. (bottom) Climatological (1960–99) number of cyclones per decade (N) and mean depth (D) in each equal-area latitude band. The dark and light blue shading define the Antarctic Ocean and sub-Antarctic Ocean regions, respectively.

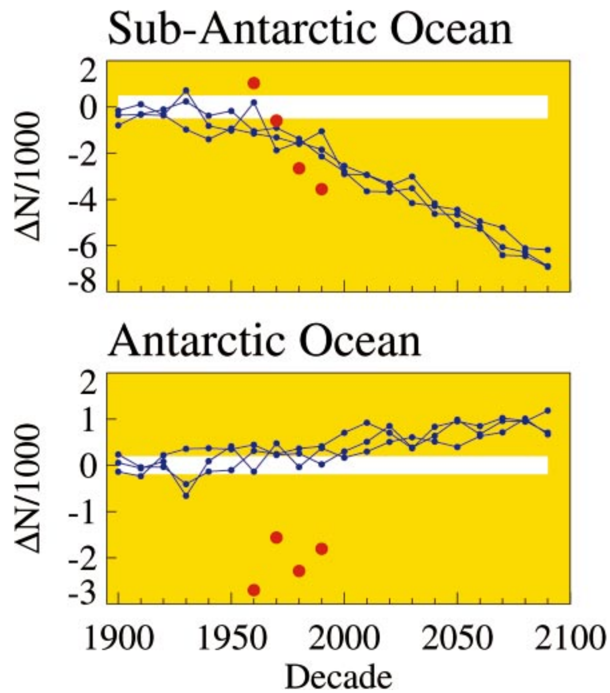

FIG. 2. Number of cyclones in each decade relative to a 500-yr control simulation. Red dots represent NCEP–NCAR reanalysis and blue dots GCM simulations. The white shading is the 95% acceptance region for the null hypothesis that the decadal means under the control and transient conditions are equal.

tral SLP of the cyclones and the period-average SLP. As discussed in Simmonds and Wu (1993) this diagnostic usefully removes the influence of a changing background SLP distribution.

Finally, we note that our analysis is focused on two regions: 1) the Antarctic Ocean, consisting of the ocean surrounding Antarctica up to a northern boundary at 60°S and 2) the sub-Antarctic Ocean, consisting of the ocean immediately to the north in the 40°–60°S latitude band.

3. Results

Cyclones in the SH track through high latitudes primarily in two spiral branches (Fig. 1, top). These originate in the Pacific and Atlantic Oceans, and terminate in the circumpolar trough (Jones and Simmonds 1993). Figure 1 (bottom) shows the number per decade, N, and mean depth, D, of cyclones for the NCEP–NCAR reanalysis for the 1960–99 period. According to this estimate cyclones are climatologically most populous around 65°S, and deepest around 55°S. The GCM cyclone climatology (not shown) is in very close agreement, except over the Antarctic Ocean where N and D are overestimated by around 10%.

Figure 2 (red dots) shows the change in the number of cyclones per decade from the NCEP–NCAR reanalysis over the 1960–99 period. The changes are relative to the control simulation. The NCEP–NCAR reanalysis shows that over this period the number of cyclones dramatically decreased over the sub-Antarctic Ocean, whereas a modest increase over the Antarctic Ocean is seen. This confirms a recent analysis based on the same dataset but a different cyclone finding scheme (SK). It is unclear, however, whether these are real physical changes, or whether they are the consequence of increasing data availability in and around the Antarctic (Kistler et al. 2001; Hines et al. 2000). Based on circumstantial evidence, as well as corroborating studies with independent data, SK argue that the decline in cyclones north of 60°S may well be real. More of a concern is the *rise* in cyclones over the Antarctic Ocean, which is a region especially devoid of observations and hence particularily sensitive to increases in the quality and quantity of Antarctic observations. It is remarked in SK that changes in sea ice specification, as well as increased deployment of automated weather stations over the continent, may be behind the apparent rise in Southern Ocean cyclones in the NCEP–NCAR reanalysis.

Figure 2 (blue dots) also shows the change in the number of cyclones per decade from the ensemble of climate change simulations (again, relative to the control simulation). Beginning early in the 1900s the climate change simulations show cyclone number declines over

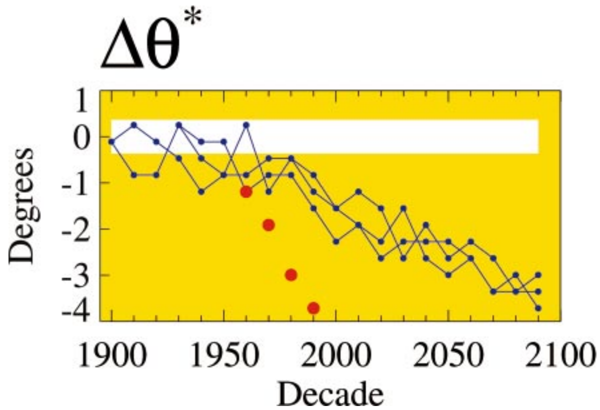

FIG. 3. Latitudinal position of the maximum decadal- and zonal-average 500-hPa meridional temperature gradient relative to a 500-yr control simulation (where $\theta^* \approx -47°$). Red dots represent NCEP–NCAR reanalysis and blue dots GCM simulations. The white shading is the 95% acceptance region for the null hypothesis that the decadal means under the control and transient conditions are equal.

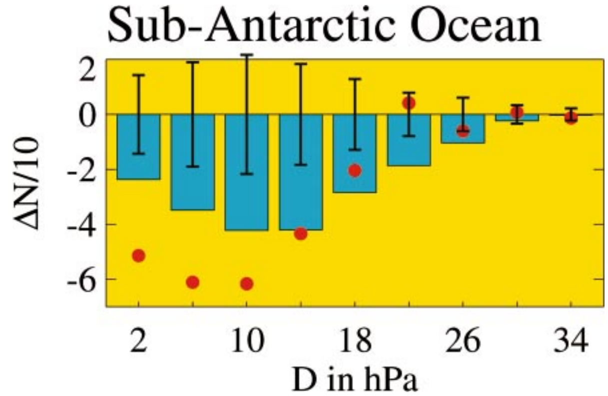

FIG. 4. Mean depth distribution change (1980–99 minus 1960–79) for the NCEP–NCAR reanalysis (red dots) and ensemble-average of the GCM simulations (blue bars). The black bars indicate the 95% acceptance region for the null hypothesis that the means under the control and transient conditions are equal.

the sub-Antarctic Ocean and rises over the Antarctic Ocean. That these changes emerge above the range of natural variability (white shading) so early on in the simulations suggests that high-latitude SH cyclones may be useful harbingers of anthropogenic climate change. Over the 1960–99 period the simulated and observed changes compare reasonably well, giving us some degree of confidence that the cyclone number changes seen in the NCEP–NCAR reanalysis may indeed be real. It should be noted, however, that the simulated changes over this period are somewhat underestimated relative to the NCEP–NCAR reanalysis, which suggests that processes not represented in the GCM (e.g., photochemical ozone losses in the stratosphere) may also be important. As for the future, the GCM predicts that the number of sub-Antarctic Ocean cyclones will drop by over 30% between now and century's end. Finally, we note the absence of significant seasonality in these, and the observed, changes in cyclone statistics (not shown).

Synoptic disturbances primarily result from baroclinic instability of the mean state of the atmosphere. A determining parameter for baroclinic instability is the meridional gradient of zonal-average temperature. Here, we consider the decadal average of this parameter on the 500-hPa pressure surface ($\overline{T}_\theta|_{500}$). It is instructive to first consider the role of $\overline{T}_\theta|_{500}$ on the natural decade-to-decade variations in cyclone number. In the control simulation the latitude of maximum $\overline{T}_\theta|_{500}$, denoted θ^* (estimated using cubic spline interpolation), is temporally correlated with the decadal number of sub-Antarctic (Antarctic) Ocean cyclones at a value of about 0.7 (−0.7). In other words, a poleward shift in maximum $\overline{T}_\theta|_{500}$ is associated with a decrease in sub-Antarctic Ocean cyclones and an increase in Antarctic Ocean cyclones, and vice versa. From these results we anticipate that the long-term compensation between sub-Antarctic and Antarctic Ocean cyclones seen in Fig. 2 is associated with a sustained poleward shift in $\overline{T}_\theta|_{500}$. Indeed, Fig. 3 shows this to be the case for both the NCEP–NCAR reanalysis (red dots) and the ensemble of climate change simulations (blue dots). Evidently then, a poleward shift in $\overline{T}_\theta|_{500}$ is at the heart of the observed and simulated cyclone number changes. The fact that these shifts are comparable to the grid spacing of the analysis grid does not imply that the response is not resolved. These small, but dynamically important, shifts are resolved as they are an order of magnitude smaller than the spatial scale of the thermal gradient itself. A similar situation, and explanation, prevails in Kushner et al. (2001) in the context of small horizontal (vertical) shifts in zonal wind (static stability).

What about changes in the mean depth of the cyclones? Figure 4 shows the mean depth distribution change (1980–99 minus 1960–79) for the NCEP–NCAR reanalysis (red dots). The black bars reflect the natural variability as estimated from the control simulation. Over the sub-Antarctic Ocean the NCEP–NCAR reanalysis shows number decreases in nearly all depth categories, with the number of shallow cyclones being reduced more than the number of deep cyclones—for an overall increase in mean depth. These results would appear to contradict those from a recent study suggesting an increase in SH ''bombs'' from 1979 to 1999 (Lin and Simmonds 2002). Our analysis restricted to the 1979–99 period (not shown) indeed shows a small increase in the number of deep cyclones. Over the sub-Antarctic Ocean the climate change simulations (blue bars) show a similar change in the mean depth distribution.

4. Conclusions and discussion

In association with a poleward shift in baroclinicity the number of high-latitude SH cyclones in the NCEP–NCAR reanalysis has changed significantly over recent decades. These changes are consistent with those arising in a GCM employing effective greenhouse gas and sulfate aerosol forcing changes. While published modeling studies of SH cyclones are very few (e.g., Lambert 1995; Sinclair and Watterson 1999) and limited to short equilibrium simulations with earlier generation GCMs, they appear to be in general agreement with the present results. As for the fidelity of the NCEP–NCAR reanalysis system we note that while the presence of fictitious trends cannot be discounted, the GCM results presented here (together with the corroborating observational studies reviewed in SK) point to these as being real physical changes operating in conjunction with a recognized shift in the SH tropospheric circulation (Thompson and Solomon 2002). Notwithstanding concerns with the NCEP–NCAR reanalysis in this data-sparse region, and with the completeness of the GCM, these results underscore the potential impact of human activity on far-removed geographical locations and phenomena.

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