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Atmospheric forcing validation for modeling the central Arctic

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[1] We compare daily data from the National Center for Atmospheric Research and National Centers for Environmental Prediction "Reanalysis 1" project with observational data obtained from the North Pole drifting stations in order to validate the atmospheric forcing data used in coupled ice-ocean models. This analysis is conducted to assess the role of errors associated with model forcing before performing model verifications against observed ocean variables. Our analysis shows an excellent agreement between observed and reanalysis sea level pressures and a relatively good correlation between observed and reanalysis surface winds. The observed temperature is in good agreement with reanalysis data only in winter. Specific air humidity and cloudiness are not reproduced well by reanalysis and are not recommended for model forcing. An example sensitivity study demonstrates that the equilibrium ice thickness obtained using NP forcing is two times thicker than using reanalysis forcing.

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1. Introduction

[2] For the global and regional ocean models dealing with the Arctic Ocean, correct atmospheric forcing is crucial to reproduce the variability of sea ice and ocean conditions. In particular, sea ice concentration is a critical parameter to accurately capture. Sea ice regulates rates of momentum and heat exchange between the atmosphere and ocean. Small errors in sea ice parameters stemming from errors in atmospheric forcing can translate into serious errors in ocean variables. This was clearly demonstrated by *Hunke and Holland* [2007] who compared three forcing data sets in global ice-ocean simulations and evaluated their potential use in Arctic model studies. Remarkably, in the 20-year model runs, relatively minor changes to the forcing data resulted in substantial discrepancies not only in the sea ice parameters, but also in the deep ocean layers (for example, the sense of rotation of the Atlantic water layer differed depending on atmospheric forcing variant). Analogous with the "sea ice-albedo feedback mechanism", this situation could be identified as "a sea ice-atmospheric forcing error feedback" reflecting how the small errors in the atmospheric forcing are enhanced in sea ice and ocean variables due to the presence of sea ice on the ocean surface. The major recommendations of *Hunke and Holland* [2007] (that is, the prescribed data set to use for model forcing) are valuable for modeling studies in general but are not specifically universal - they are largely relevant only for their particular model because other models can react differently to a particular forcing due to their individual internal tuning.

[3] Thus, a process of verification of model-derived atmospheric forcing data against observational data can be used to solve the problem, or at least more clearly delineate its extent. The major goal of this study therefore is to assess the possible errors in the arctic atmospheric forcing fields used by modelers. Knowing model errors due to forcing fields will allow a more accurate evaluation of the significance and range of errors associated with the internal model physics and its parameterizations. This study complements previous evaluations of the reanalysis data which have ignored the Arctic [e.g., *Smith et al.*, 2001; *Ladd and Bond*, 2002].

2. Data and Data Validation Approach

[4] Here we validate five parameters from the NCEP/NCAR Reanalysis 1 project (hereinafter referred to as R1 [*Kalnay et al.*, 1996; *Kistler et al.*, 2001]): sea level pressure (SLP), surface (2 m) air temperature (SAT), surface (10 m) winds (WIN), specific humidity (2 m) (SH), and total cloudiness (TCL). The temporal resolution of the extracted fields is daily and covers the period 1/1/1954–31/12/2006. The daily R1 data were compared to daily observations from the "North Pole" (NP) drifting stations for the same period (averaged based on 4- or 8-times daily observing regimes depending on the station sampling interval) after interpolation of R1 data onto NP daily locations. One to three stations per year (except 1992–2001 when the NP program was temporally interrupted) covered the central Arctic region during this period (Figure 1). For the period 1954–1991, NP data are available from the *Arctic Climatology Project* [2000] which is an updated version of the NP data set first released in 1996 [*National Snow and Ice Data Center (NSIDC)*, 1996]. The 2003–2006 data from NP-32, NP-33 and NP-34, which characterize modern arctic conditions, were obtained from the data archives held at the Arctic and Antarctic Research Institute (St. Petersburg). When data from all available NP stations are put together each parameter is represented by more than 100,000 observations. Some of these data have already been successfully used to reconstruct the air temperature fields over the Arctic Ocean for 1979–1993 [*Martin and Munoz*, 1997]. *Rigor et al.* [2000] extended the gridded fields to 1997. *Lindsay* [1998] utilized the NP data [*NSIDC*, 1996] to investigate the temporal variability of the energy balance over thick arctic

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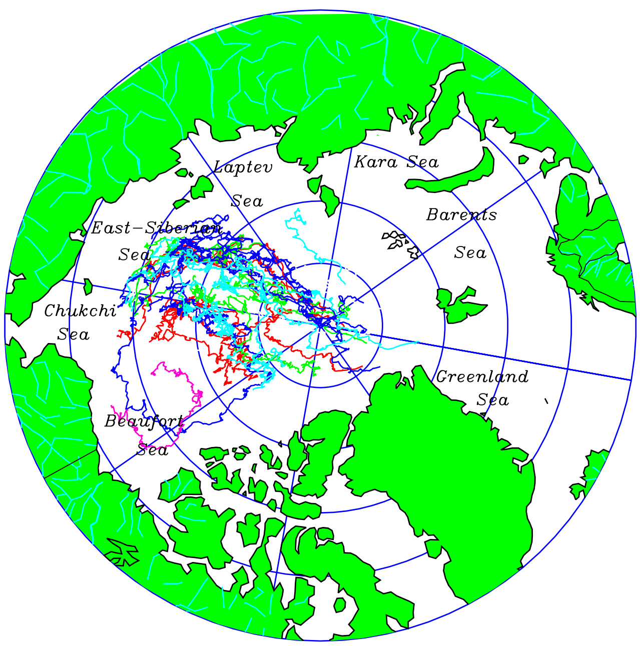

Figure 1. Areal coverage of the central Arctic by NP-2–NP-34 drifting stations, 1954–2006. NP drift trajectories are depicted by lines with different colors.

ice. *Walsh and Chapman* [1998] studied associations between cloudiness, radiative fluxes, and surface air temperature in the central Arctic using NP, R1 and ECMWF data.

[5] SLP, SAT, WIN, SH, and TCL were extracted from both NP and R1 data archives. Using time series of these parameters, analyses of their errors were conducted for both the entire period of observations and for three selected periods reflecting different observational and climate conditions. These periods are: (1) 1954–1977 - before satellite era and before launching of the International Arctic Buoy Program (IABP), [*Thorndike and Colony*, 1980]; (2) 1978–1991 - after 1978 buoys from the IAPB program and satellites started providing more spatially comprehensive observational data for assimilation procedures in R1; and (3) 2003–2006 — reflecting modern arctic climate conditions. Figure 2 shows seasonal variability of all parameters averaged for the entire period of observations and Table 1 summarizes error statistics.

3. Results and Discussions

3.1. Sea Level Pressure (SLP)

[6] SLP data from R1 are in good agreement with NP data (Figure 2, Table 1). The correlation between the NP and R1 SLP fields exceeds 0.99 in all three periods; the mean error does not exceed 1.5 hPa and is consistently negative, indicating that R1 systematically slightly underestimates SLP in all seasons (Figure 2, Table 1). This, to some degree, could be attributed to the errors associated with the R1 SAT (see section 3.2) which is higher than observed. Another feature apparent from the SLP for each period (not shown) is a negative SLP trend indicating that SLP in the central Arctic has been gradually decreasing from 1954 through 2006. A decreasing SLP trend in the central Arctic during 1978–1994 was described by *Walsh et al.* [1996]. Recently this trend was re-evaluated and confirmed for 1948–2006 by *Proshutinsky et al.* [2004] and by *Proshutinsky et al.* [2007, Figure 1] based on R1 data. Here now is presented further confirmation of this trend from the NP data analyses for the 1954–2006 period.

3.2. Surface (2 m) Air Temperature (SAT)

[7] Comparison between R1 and NP SAT data shows generally good agreement, although a significant seasonality in the quality of R1 SAT for the central Arctic is apparent (Figure 2, Table 1). In winter, the correlation between observed and reconstructed air temperature is relatively high and on average exceeds 0.80 with a mean error not exceeding 0.9°C (Table 1). The mean error is positive indicating that in winter the R1 SAT is persistently higher than observed.

[8] In spring, the correlations between NP and R1 data increase (seasonal warming) from their wintertime values and also exhibit an increasing trend over the study time frame (Table 1). The increasing competence of R1 SAT is probably attributable, at least in part, to the progressive inclusion of satellite data. The bias between NP and R1 SAT remains persistently positive but increases up to 5°C with a mean error of approximately 2.3°C.

[9] In summer, the R1 bias remains positive but decreases from spring values to lie in the range 1.1–1.3°C. Correlations between daily values drop off sharply to 0.53–0.64. Similar results for the summer period were obtained by *Rigor et al.* [2000] in their comparison of different datasets with the NP station data. In their case the largest bias and lowest correlations are found for the 1978–1991 period when the IABP program was active.

[10] In autumn, the R1 SAT bias is negative but the correlation between data sets increases (seasonal cooling). Note the trend towards increasing accuracy over time for autumn SAT (Table 1).

[11] An analysis of the temporal variability of R1 errors revealed no significant differences in the error statistics between the periods mentioned above, between the Western or Eastern Arctic, or between cyclonic and anticyclonic circulation regimes of the Arctic Ocean [*Proshutinsky and Johnson*, 1997]. The R1 SAT errors could be related to the parameterizations of surface albedo and also (and probably more likely) to the problems with cloudiness described below.

3.3. Total Cloudiness (TCL)

[12] The radiation budget of the arctic is strongly modulated by the presence of clouds, yet cloudiness represents one of the greatest uncertainties in model results. In the Arctic, most model estimates of TCL are too high in winter and too low in summer, with respect to observations. This makes model diagnostics and use of model results to project sea ice conditions very uncertain. The problems with Arctic cloudiness are well known and have been described in many papers [*Schweiger and Key*, 1992; *Curry et al.*, 1996; *Walsh et al.*, 1998; *Makshtas et al.*, 1999; *Schweiger et al.*, 1999; *Lindsay and Makshtas*, 2003; *Schweiger*, 2004] with different goals and objectives. In all cases, NP cloudiness data have been used as the observational basis against which model cloudiness is compared. TLC at NP stations was estimated visually. The examination of TCL undertaken

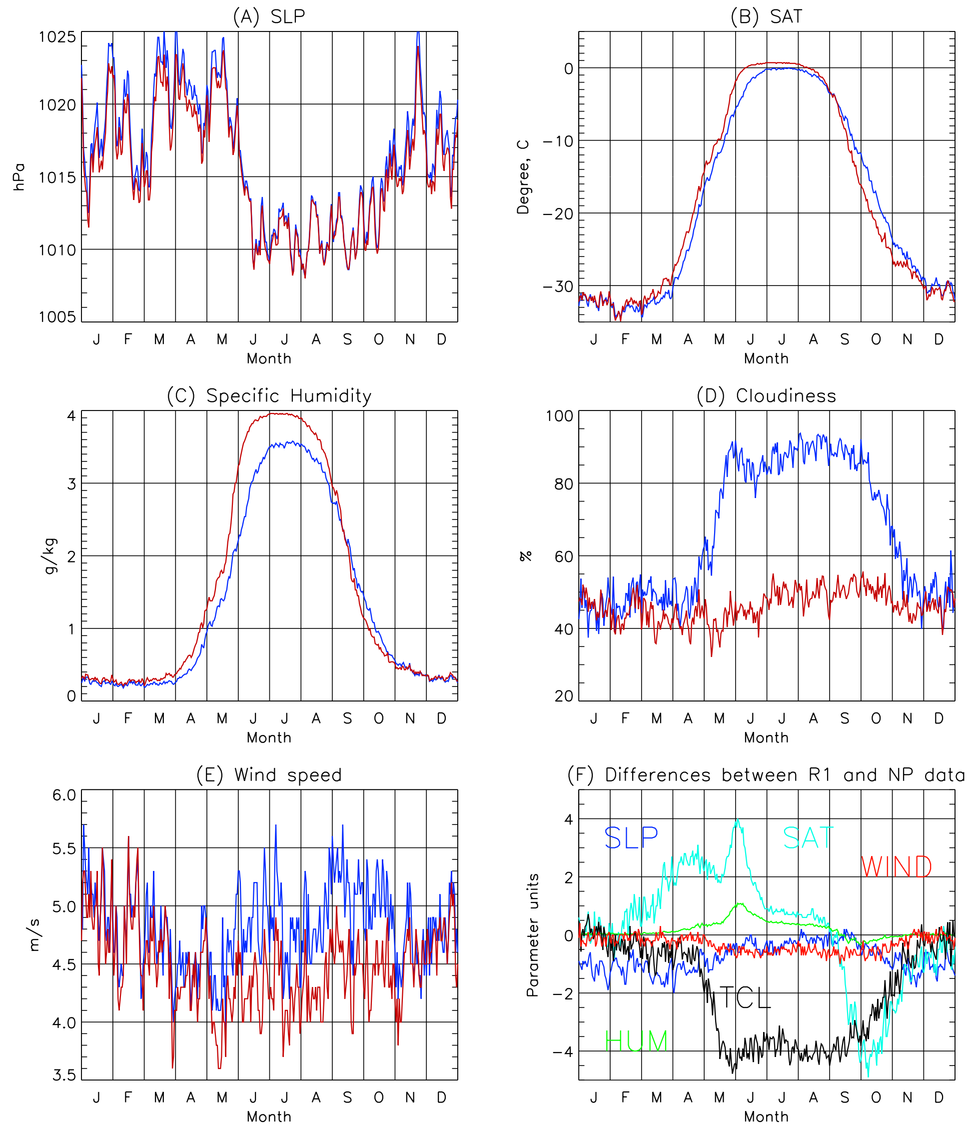

Figure 2. (a–f) 1954–2006 daily mean values for atmospheric variables extracted from R1 data and NP stations. NP data are shown in blue and R1 data are in red except for in Figure 2f which shows differences between the R1 and NP data. Note that cloudiness differences in Figure 2f are multiplied by 10^{-1}.

for the present effort shows striking differences between observations and R1 results and corroborates previous conclusions that models underestimate summer and overestimate winter TCL over the Arctic Ocean (Figure 2, Table 1). Most of the regional Arctic coupled ice-ocean models use monthly climatologic TCL data which do not include interannual variability and thus changes in cloud cover at interannual scales observed at the NP stations (order of 1 to 2 tenths units) do not influence sea ice conditions in the model results.

[13] *Schweiger et al.* [1999] analyzed cloud amounts provided by the TOVS Polar Pathfinder data set [*Francis and Schweiger*, 1999] and compared this dataset to surface observations of cloud amount from the NP drifting stations. The results show that TCL provided by the TOVS Polar Pathfinder data accurately represent the annual cycle and could be recommended for future testing as a model forcing field within the Arctic Ocean Model Intercomparison Project (AOMIP). However, it is unclear how well the interannual variability of TCL is represented in the TOVS data set.

3.4. Specific Humidity (SH)

[14] At NP stations, at air temperatures above −10°C, the relative humidity was determined using standard psychrometric tables based on psychrometer measurements (i.e. wet bulb and dry bulb temperatures). These results were compared with a hair hygrometer to correct the psychrometer reading at regular intervals. At air temperatures below −10°C, the humidity was measured by an instrument which was able to measure relative humidity values ranging from 30 to 100% with an error of approximately 10%. It is important to note that the accuracy of humidity observations at NP stations is low in cold air temperatures (<−10°C), which means summer values are the most accurate. In general, R1 humidity values compare

Table 1. Seasonal Error Statistics[a]

Period Parameter	1954–1977 me/std (cor)	1978–1991 me/std (cor)	2003–2006 me/std (cor)
SLP (winter)	−1.4/1.8 hPa (0.995)	−1.1/2.1 hPa (0.992)	−0.6/1.9 hPa (0.990)
SLP (spring)	−0.9/1.6 hPa (0.991)	−1.0/1.7 hPa (0.989)	−0.6/1.3 hPa (0.993)
SLP (summer)	−0.2/1.4 hPa (0.990)	−0.3/1.5 hPa (0.988)	−0.0/1.3 hPa (0.990)
SLP (autumn)	−0.8/1.5 hPa (0.994)	−0.6/1.9 hPa (0.991)	−0.3/1.4 hPa (0.990)
SAT (winter)	0.2/4.3°C (0.83)	0.5/4.3°C (0.81)	0.9/4.3°C (0.82)
SAT (spring)	2.5/3.6°C (0.92)	2.3/3.4°C (0.93)	2.0/2.3°C (0.97)
SAT (summer)	1.2/1.9°C (0.55)	1.1/1.3°C (0.53)	1.3/1.3°C (0.64)
SAT (autumn)	−2.6/4.5°C (0.90)	−1.8/4.2°C (0.92)	−1.7/3.8°C)0.92)
SH (winter)	0.03/0.15 g/kg (0.82)	0.05/0.16 g/kg (0.82)	0.04/0.19 g/kg (0.81)
SH (spring)	0.39/0.46 g/kg (0.90)	0.35/0.39 g/kg (0.92)	0.35/0.44 g/kg (0.95)
SH (summer)	0.48/0.45 g/kg (0.59)	0.50/0.43 g/kg (0.56)	0.51/0.36 g/kg (0.61)
SH (autumn)	−0.11/0.41 g/kg (0.89)	−0.04/0.38 g/kg (0.92)	−0.08/0.35 g/kg (0.91)
TCL (winter)	10/41% (0.42)	−11/39% (0.36)	−10/37% (0.49)
TCL (spring)	−21/43% (0.33)	−24/39% (0.35)	−34/40% (0.30)
TCL (summer)	−38/32% (0.30)	−40/31% (0.34)	−46/33% (0.20)
TCL (autumn)	−21/41% (0.35)	−26/34% (0.38)	−24/36% (0.40)
W (winter)	−10/19 m/s (0.75)	0.5/2.1 m/s (0.71)	−0.3/2.1 m/s (0.77)
W (spring)	0.2/1.7 m/s (0.73)	0.5/1.7 m/s (0.73)	0.0/1.8 m/s (0.76)
W (summer)	0.4/1.7 m/s (0.74)	0.8/1.7 m/s (0.73)	0.8/1.8 m/s (0.68)
W (autumn)	0.2/2.0 m/s (0.74)	0.9/2.1 m/s (0.71)	0.3/2.2 m/s (0.68)

[a]Mean error (me, a difference between R1 and NP data), standard deviation (std), and correlation coefficient (cor) between R1 and NP parameters. All estimates are based on daily data.

well with respect to annual form but there are some discrepancies: R1 SH reaches its summer peak several weeks earlier than NP SH, peaks at and maintains a greater value (~15% greater), and then undergoes a more rapid decrease into the autumn (Figure 2, Table 1). *Lindsay and Makshtas* [2003] showed that an overestimation of SH results in sea ice thinning because of an increased latent heat flux to the sea ice surface. On the other hand, it is necessary to mention that values for SH obtained from R1 data are "contaminated" by R1 SLP and SAT because lower than observed SLP in combination with larger than observed SAT influence the resulting values of R1 SH, namely towards higher SH which agrees with the errors.

3.5. Ten m Winds

[15] Surface wind parameters at NP stations are taken either directly, from observed winds at 10 m level, or by winds at other levels extrapolated to the 10 m level by applying a standard vertical wind profile correction. At NP stations before 1962, wind direction and speed were measured with a Wild wind vane, and later with different types of anemometers and anemorumbographs. Note that the NP observations of wind have a relatively low quality, caused by problems associated with: Different heights of wind sensor locations at different stations forcing the need to extrapolate wind to the standard 10 m level; The wind direction at NP is coded by two characters that represent only 8 major directions: N, NE, E, SE, S, SW, W, and NW; before 1962, wind direction was measured mostly visually and it seems that observers tended to "observe" only 4 basic directions (N, E, S, and W). In general, wind parameters of both data sets are in relatively good agreement. The best results were obtained for station NP-22, which drifted in the Beaufort Gyre region from 1973–1982.

3.6. Sensitivity Experiments

[16] A set of numerical experiments were run with a thermodynamic only sea ice model [*Makshtas et al.*, 1988] forced by the climatologic seasonal cycles of forcing parameters extracted from NP and R1 data sources (Figure 3). These runs demonstrated that the R1 forced equilibrium ice thickness stabilizes at values a factor of two less than NP forced model runs. More detailed sensitivity experiments consisted of re-running the model using NP forcing with select, single parameters replaced by the R1

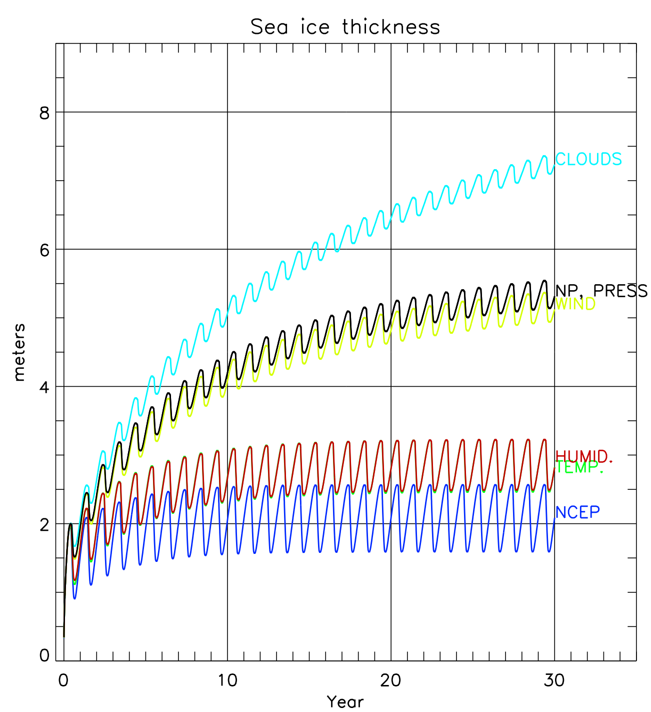

Figure 3. 30-year time series of simulated sea ice thickness. Lines depict thickness variability under R1 forcing only (NCEP), under NP forcing only (NP), under NP forcing using R1 wind (WIND), NP forcing using R1 SAT (TEMP.), NP forcing using R1 specific humidity (HUMID.), and NP forcing using R1 clouds (CLOUDS).

equivalent. These results revealed a range of sea-ice model sensitivities (Figure 3). When NP SLP is replaced with R1 SLP, no difference was noted - the resulting thickness curve matched that obtained using only NP forcing. R1 wind, being derived from SLP, is similarly accurate enough to match the NP results to a few percent. At the other end of the spectrum, when R1 TCL is introduced the largest errors occur. Artificially low TCL allows upwelling longwave emissions to remain high facilitating the continued, excessive growth of sea ice observed in the model run. When run with R1 SAT, even though the SAT discrepancy with NP SAT appears relatively small, it is critically situated around the freezing point and the impact on sea ice thickness is large. In summer, R1 SAT is consistently above freezing, unlike NP SAT, which is why it has such a large capacity to limit sea-ice thickness in the sea-ice model results. R1 SH also reduces ice thickness because an increased SH without an increase in TCL gives excess latent heat flux into the sea-ice which accelerates its decay. Note that these experiments reflect only thermal effects and do not show how, for example NP and R1 winds influence sea ice redistribution and thickness due to ridging.

4. Summary

[17] The NP SAT data are in good agreement with R1 SAT data only in winter. In autumn, the NCEP air temperature is lower than observed but in spring it is higher than observed at the NP stations. In summer, the R1 SAT is 1.2°C higher than NP SAT. Similarly, R1 SH data are in good agreement with NP SH only in winter. In other seasons, especially summer, the R1 SH is significantly higher than NP. Sensitivity experiments run on a thermodynamic sea-ice model indicate that both of these discrepancies can exert a strong influence on the surface heat balance and thus model simulated sea-ice thickness results. Comparing the NP and NCEP SLP data, it is clear that the observed and reconstructed SLP data are in good agreement in all periods. On the other hand, the NCEP SLP is usually a bit lower than observed. In general, R1 wind speed and direction are in relatively good agreement with the NP data. It is important to note, however, that NP wind observations have a relatively low quality (mostly direction), caused by a variety of factors, including various wind sensor heights at different stations. Arguably, the most significant discrepancy showed up with TCL, confirming that R1 TCL is not correct. Maximum errors occur in summer, while winter values were improved with the application of a 5-day running mean. It is suggested that these smoothed values be used to force models, at least in winter, instead of applying the climatologic TCL usually recommended for model forcing.

[18] This study has indicated that the use of R1 data to force sea ice models should be undertaken with great caution, noting the problems that are introduced by the discrepancies in summertime SAT, SH and TCL.

[19] A final point emerging from this study is that NP data were observed to confirm the general decreasing SLP trend over the period 1954–2006.

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