1.11 Relationship between fast ice and local meteorological conditions at Davis Station, East Antarctica: A case study.

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1 Introduction

Analyses[1] of data from several coastal stations off East Antarctica revealed considerable interannual variability in the fast-ice properties. Focussing on measurements obtained near Davis Station (77° 58'E, 68° 35'S) changes in fast-ice thickness, extent, volume, breakout date and length of ice season are investigated in relation to changes observed in the lower atmosphere. A major source for fast-ice variability is suspected to be due to the feedback between atmosphere and fast ice, similar to the feedback identified between atmosphere and pack ice (e.g., Simmonds, 1996). Changes and trends have been confirmed for properties of the polar atmosphere, e.g., changes in latitude and frequency of cyclone trajectories (Jones and Simmonds 1993), or changes in the coastal precipitation pattern (Budd et al. 1995). Here we view the variability in fast-ice properties in relation to such atmospheric changes.

2 Fast-ice variability

Time-series of measurements of fast-ice parameters are useful for the identification of the variability or trends in the polar ocean-ice-atmosphere system. The local bathymetry in the area of the Davis fast ice varies from about 5 to 33 m, with deeper ocean only underneath the outer fast ice. Hence we expect that after onset of freezing the supply of oceanic heat is small, and that the thermal energy budget of the fast ice is largely driven by atmospheric forcing. *In situ* measurements of the fast ice near Davis have been carried out intermittently since 1957, except for 1965 to 1969 when the station was not staffed. Sampling location, frequency and accuracy limit the data available to this study to 1957, 1958, 1979 to 1986, and 1992 to 1999. Here the focus is on the discussion of maximum ice thickness, breakout date, and duration of the fast-ice season.

2.1 Maximum ice thickness

The annual maximum ice thickness is a good measure of persistence and severity of a particular season. Observations at Davis show that the annual maximum ice thickness occurs well before the final ice breakout. Hence the annual maximum ice thickness obtained can be related to the thermal energy budget of the system. The date of occurrence of the maximum ice thickness is indicative of the seasonal evolution of the overall thermal energy balance of the ocean-ice-atmosphere system. Interannual variability in this date is likely to reflect changes in the atmospheric surface forcing, which includes the radiative forcing, although interannual changes in the oceanic heat content cannot be disregarded.

Using all available data, the long-term mean (standard error) annual maximum ice thickness was 1.652 (± 0.011) m. The overall maximum occurred in 1993 (Fig.1) when the ice thickness peaked at 1.980 m. The interannual minimum in the annual maximum ice thickness occurred in 1998 (1.100 m). Because in 1998 the fast ice at Davis experienced an unusually extensive midwinter breakout, which also removed the fast ice from the measuring site, the 1998 data are excluded from the following discussion of the long-term mean. The recalculated long-term mean (standard error) annual maximum ice thickness is then 1.684 (± 0.008) m; and the revised decadal means are: 1950s – 1.677 (± 0.090) m, 1980s – 1.691 (± 0.011) m, and 1990s – 1.678 (± 0.017) m, indicating no significant change over this time interval. The revised minimum occurred in 1996 (1.430 m). Most noticeable there has been an increase in the interannual variability in the 1990s relative to previous epochs ($\sigma_{1990s} = 3 * \sigma_{1980s}$).

At Davis maximum ice thickness usually occurred between early October and late November (not shown). There is a shift towards later occurrence of the maximum ice thickness, especially from the 1980s to the 1990s. This would suggest that the intensity and persistence of the thermal forcing have changed, possibly indicating milder winter air temperatures or colder spring air temperatures.

The exception of this shift towards later occurrence of maximum ice thickness was in 1998 when the maximum ice thickness occurred in mid July just prior to a major fast ice breakout, which included the measurement site. Although ice formation resumed immediately after the blowout, the remainder of the

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1998 ice-growth season was too short to compensate for this major advectional fast-ice loss. The 1998 midwinter breakout of the inner fast ice at Davis had been preconditioned by a series of cyclonic system passing overhead. The low-pressure system during the breakout event lasted for 3.5 days and was determined at 958 hPa. This case presents evidence of the influence of mean sea-level pressure variations on the date of ice breakout.

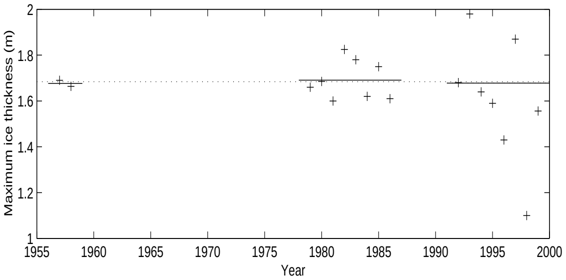

Figure 1: Time-series of the annual maximum fast-ice thickness (crosses). Also shown are decadal averages of the maximum thickness (solid lines) and the long-term average (dotted line) excluding the 1998 data.

The temporal variability in both maximum ice thickness and its occurrence suggest that the thickness evolution depends on a number of external forcing parameters. While the extensive midwinter breakout in 1998 can be directly linked to atmospheric cyclonic forcing (see also section 2.2), highlighting its importance on the ice-mass balance, the range of the interannual variations in maximum ice thickness and timing may be associated with changes in the thermal forcing, e.g., surface air temperature.

2.2 Annual fast-ice duration

The overall duration of individual fast-ice seasons is determined from the dates of fast-ice formation and breakout at 1 km distance from the coastline. Around Davis the ice formation generally occurs simultanously over a wide area (10s of km's). However, the timing of the ice breakout varies, mostly as a function of distance from the coast. Only the fast ice within Davis harbour, which covers about 4 km by 3 km and which is protected by coastal islands, usually shares the same breakout date.

A shift towards longer fast-ice seasons and later final breakout dates has been observed from the late 1950s to the last two decades (Fig. 2). In the late 1950s the final ice breakout occurred in mid December (mean: DoY 347), while in the 1980s and 1990s final breakout occurred mostly between mid December and February (mean: DoY 367). The duration of the fast-ice season has increased by about 8 %. This is from a mean of 273 days in late 1950s to a mean of 295 day in the 1980s and 1990s. For all years the onset of fast-ice formation took place in early to mid March, except for 1994 to 1996 when the formation of the fast ice took place in mid to late February. The delayed breakout of the fast ice could be seen to indicate a weakening of the spring cyclone density (expressed through the air pressure field), the latter generally being the precursor for the final outbreak of the Davis fast ice.

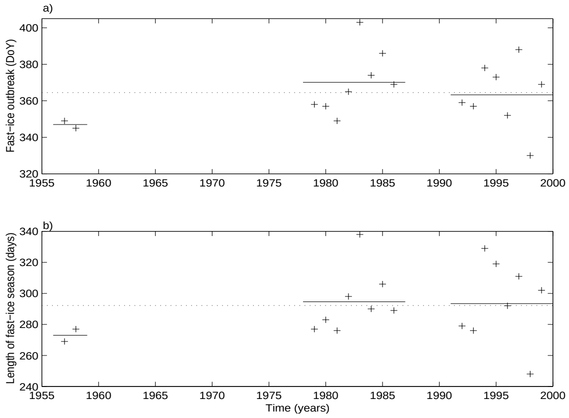

Figure 2: Time-series of the (a) date of the final fast-ice outbreak and (b) duration of fast-ice coverage at Davis. Solid lines represent decadal means.

Changes in the annual duration of fast-ice coverage are likely to be reflected in the local heat and moisture balance. Only during intervals of sufficient open water can large amounts of thermal energy and water vapour be transfered from the ocean into the atmosphere. The open-water evaporation mostly precipitates locally due to the low saturation water-vapour pressure. It is difficult to quantify the effect of this local-scale moisture and heat transfer on atmospheric properties. However, based on the changes in open-water duration, we suggest on average lower precipitation rates during the recent decade.

3 Atmospheric variability

Meteorological measurements at Davis were taken 13 m above sea level. These measurements included 3-hourly manual and automated surface observations as well as vertical profiles from radiosondes (twice daily). Here the analysis of 20 years (1980 - 1999) of surface air temperature, mean-sea level pressure, and 2 years (1998 - 1999) of solid precipitation data are presented.

3.1 Surface temperature

Based on 3-hourly observations the 20 year trend (1980 - 1999) of the annual mean (standard error) surface air temperature at Davis reveals a warming of $+0.016\ (\pm 0.002)^\circ\,\mathrm{C\,yr^{-1}}$. Based on the χ^2-test (Kreyszig 1988) this trend is significant at the 5 % level. Seasonally only the winter mean shows a significant trend ($+0.021^\circ\,\mathrm{C\,yr^{-1}}$), while the results of summer warming, and autumn and spring cooling do not pass the significance test. For the same location based on surface measurements Jacka and Budd (1998) derived a non-significant air temperature trend of $+0.005^\circ\,\mathrm{C\,yr^{-1}}$ (1949 - 1996) and Comiso (2000) gives a 20 year trend of $+0.012^\circ\,\mathrm{C\,yr^{-1}}$ (1979 - 1998). There is a good agreement between the latter and our study. The large discrepancy between results from Jacka and Budd (1998) and this study may arise from the difference in the temporal intervals (1949 - 1996 versus 1980 - 1999) or from the difference in the temporal resolution of the two data series (monthly versus 3-hourly) of the two time series. However, the discrepancy may also indicate that a long-term modulation ($\tau > 12$ - 15 years) may be superimposed on the variations in surface air temperature.

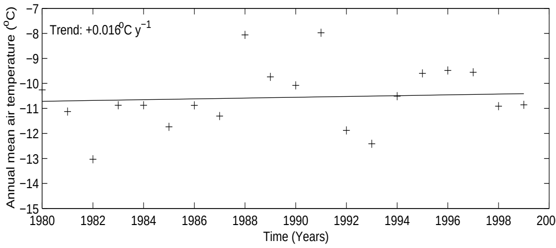

Figure 3: Time-series of the annual mean surface air temperature (crosses) and trend (dotted line) for data from 1980 - 1999.

The trend of increasing mean annual air temperatures is not clearly reflected by consistent net decrease of maximum ice thickness from the 1980s to the 1990s. The trend of a 20 year warming is seen to cause the shift towards later dates for the annual maximum ice thickness (see section 2.1). The relationship between maximum ice thickness and surface air temperature becomes clearer for comparisons on shorter (e.g., annual) time scales. For years with a high annual maximum ice thickness (e.g., 1982, 1993 or 1997) we find that the spring and to a lesser extent the winter surface air temperatures have been extremely low compared to other years. A correlation coefficient of -0.68 between annual mean air temperature and the annual maximum ice thickness (Fig. 4) supports the suggestion of a link between the two. On the other hand, in 1992, when despite cold winter and spring temperature only an average maximum ice thickness was reached, demonstrate that other mechanisms (e.g., oceanic heat flux) must play significant roles in the thermal balance of the fast ice.

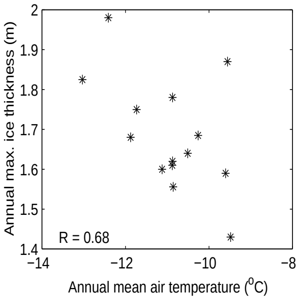

Figure 4: Scatterplot of the annual mean surface air temperature and the annual maximum ice thickness for 1980-1986, 1992-1997, and 1999.

3.2 Mean sea-level pressure

The measured surface air pressure has been converted to mean-sea level pressure. Detailed analysis of the pressure data (not presented here) from Davis show that lower values in air pressure were due to increased frequency or intensity of cyclones rather than to a general lowering of the air pressure itself.

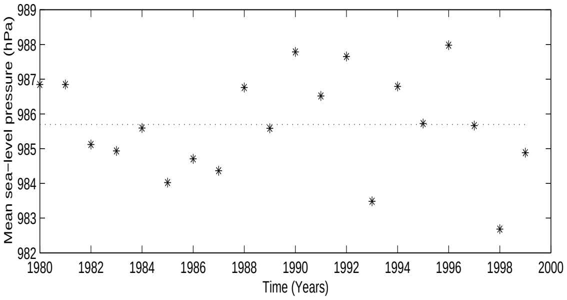

Figure 5: Time-series of the annual mean sea-level pressure (stars); the dotted line shows the long-term mean pressure.

The time-series of mean-sea level pressure does not contain a significant annual trend, instead the annual means appear to be distributed around the 20 year mean in a sinusoidal pattern with an approximated period of 17 years (Fig. 5). The physical reasoning for an atmospheric variability at such a period is not intuitive. However, longer-period atmospheric variability has been observed elsewhere (see Jones and Simmonds (1993) for summary). The seasonal analysis yields a significant trend for spring, for which an upward trend in mean-sea level pressure (+0.05 $\mathrm{hPa\,yr^{-1}}$; at 5 % significance level) was found over the 20 year interval. This is in agreement with delayed breakout dates of the fast ice (see section 2.2).

3.3 Precipitation

Frontal cyclonic systems are the major source for precipitation near the coast. At Davis the precipitation is generally small, as the moisture transport is limited by the saturation water vapour pressure, which is low for cold air. However, at times when

Davis was within the upstream region of strong cyclonic systems heavy precipitation preceeded or coincided with the arrival of a warm change. A further source of precipition is thought to originate, during intervals of open water (see section 2.2), from strong local evaporation, especially during times when the ocean-atmosphere temperature gradient is large. Examples for such local precipitation are given in 1998 and 1999 (the only two years for which data are currently available), when midwinter breakouts of the fast ice exposed extensive areas of the ocean, and substantial transfer of water vapour into the atmosphere was observed. The moisture exchange was generally active for about 2 - 5 days and was accompanied by a weak onshore breeze. The complete time-series of snow-gauge measurements from Davis is currently obtained, and will be used to study the proposed relationship between fast ice and atmosphere. This proposed link appears to be the strongest between the two media on local scale.

Having seen an effect of fast-ice removal on the evaporation rate and hence on local precipitation, it is also necessary to mention the effect of precipitation on the fast ice. During winter the main effect of the snow on the fast ice is the thermal insulation from the colder atmosphere, thereby effectively reducing the ice-growth rate. However, in late spring and summer the snow cover is shielding the ice from surface ablation due to solar insolation. This effectively prolongs the lifetime of the fast-ice cover at Davis. The interaction between precipitation and fast ice will be discussed once the full precipitation data are available.

4 Conclusion

The analysis of fast-ice and meteorological measurements from Davis station revealed interannual changes in both media. Atmospheric changes reflect strongly in the variability of fast-ice parameters, while on local scale there is only limited evidence (precipitation) of feedback from the fast ice on the atmosphere. The main finding of this study of interannual variability during the 1980s and 1990s in fast ice and atmosphere is that there appears to be little or no net change in the ice properties. This is in contrast with atmospheric properties, which show trends, such as an upward trend in air temperature and a sinusoidal variation in mean sea-level pressure. However, the magnitude of the interannual variability of several fast-ice properties has increased from the 1980s to the 1990s. We conclude that while the fast ice reacts to changed atmospheric forcing conditions, other forcing mechanism (e.g., oceanic-heat flux, tidal forcing) are likely to exert influence on the fast ice to compensate for atmospheric changes. To gain further understanding of the ice-atmosphere interactions it appears necessary to use modelling studies, which include the complete system, including the ocean component.

Acknowledgements

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