Holland, D.M., 2001, Explaining the Weddell Polynya – a Large Ocean Eddy Shed at Maud Rise. *Science*, **292**, 2697-2700.

Lemke, P., 1987: A coupled one-dimensional sea ice–ocean model. *J. Geophys. Res.*, **92**, 13164-13172.

Martinson, D.G., P.D. Killworth, and A.L. Gordon, 1981: A Convective Model for the Weddell Polynya. *J. Phys. Oceanogr.*, **11**, 466-487.

Martinson, D.G., 1990: Evolution of the Southern Ocean winter mixed layer and sea ice; open ocean deep water formation and ventilation. *J. Geophys. Res.*, **95**, 11641-11654.

Muench, R.D., J.H. Morison, L. Padman, D. Martinson, P. Schlosser, B. Huber, and R. Hohmann, 2001: Maud Rise revisited. *J. Geophys. Res.*, **106**, 2423-2440.

Olbers, D.J., V. Gouretski, G. Seiß, and J. Schröter, 1992: Hydrographic Atlas of the Southern Ocean. AWI, Bremerhaven, 82pp.

Schröder, M., and E. Fahrbach, 1999: On the structure and the transport of the eastern Weddell Gyre. *Deep Sea Res*, **46**, 501-527.

Timmermann, R., P. Lemke, and Ch. Kottmeier, 1999: Formation and maintenance of a polynya in the Weddell Sea. *J. Phys. Oceanogr.*, **29**, 1251-1264.

Timmermann, R., A. Beckmann, and H.H. Hellmer, 2001: Simulation of ice-ocean dynamics in the Weddell Sea. Part I: Model configuration and validation. *J. Geophys. Res.*, in press.

van den Broeke, M., 2000: On the interpretation of Antarctic temperature trends. *J. Climate*, **13**, 3885-3889.

Long-term Warming of Weddell Sea Warm Deep Water

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Warming of the deep water in the Weddell Sea has important implications for Antarctic Bottom Water (AABW) formation, melting of pack ice, and the regional ocean-atmosphere heat transfer. In order to evaluate temporal changes in the deep waters of the Weddell Sea, a historical data set encompassing CTD and bottle data from 1912 to 2000 was analyzed for both trends and variability in the Warm Deep Water (WDW) (Robertson et al., 2002). We focused on two regions with the highest data concentration (Figure 1a, page 19): an inflow region, near where the Circumpolar Deep Water (CDW) flows into the Weddell Sea, and an outflow region after where the WDW interacts with shelf waters to form Weddell Sea Deep Water, a precursor to AABW.

The WDW was warmer in both the inflow and outflow regions during the 1990's than in the 1970's (Figure 1b). Most of the coldest maximum potential temperatures occurred during 1973 through 1978, which surrounds the time of the Weddell Polynya (1974-1976). Since then, 1984 had the coldest q_{MAX} values for the inflow and outflow regions.

The post Weddell Polynya warming trend was 0.012 ±0.007 $^{o}C\ yr^{-1}$ for both regions (dashed lines in Figure 1b). Since the temperatures of the late 1980's matched the pre-1970 temperatures and the temperatures of the 1990's were higher than those of the 1980's (Figure 1b), the warming indicates not only a return to pre-Weddell Polynya temperatures but further subsequent warming. The increase in temperature was not compensated by a change in salinity, with the result that the WDW became less dense from the 1970's to the 1990's (Robertson et al., 2002)

The observed warming trend was comparable to the average warming of the surface of the global ocean since the 1950's, 0.31^{o}C or 0.006 $^{o}C\ yr^{-1}$ (Levitus et al., 2000) and the warming trend of ~0.01$^{o}C\ yr^{-1}$ for the Weddell Sea Bottom Water from 1989-1995 observed by Fahrbach et al. (1998) in the central Weddell Sea. Although there is no direct connection between the surface ice temperature and the WDW, the trend was also comparable to warming of the surface ice from 1970 to 1998 in the Weddell Sea, ~0.01-0.02$^{o}C\ yr^{-1}$, observed in satellite data by Comiso (2000).

The cause of the warming trend is hypothesized to be modification of the inflow waters with warmer or a larger quantity of Circumpolar Deep Water flowing into the Weddell Sea. Either of these changes could be linked to movement of the Weddell Front. The short record and gaps in the data precluded determination of a robust (lag) correlation between either the Southern Annular Mode (Antarctic Oscillation) (Hall and Visbeck, 2001) or the location of the Antarctic Circumpolar Front and the changes at the inflow region.

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References:

Comiso, J.C., 2000: Variability and trends in Antarctic surface temperatures from in situ and satellite infared measurements. *J. Climate*, **13**, 1674-1696.

Fahrbach, E., R. Meyer, G. Rohardt, M. Schröder, and R.A. Woodgate, 1998: Gradual warming of the Weddell Sea

Deep and Bottom Water. *Filchner-Ronne Ice Shelf Program*, Report No. **12**, Alfred-Wegener-Institut, Bremerhaven, Germany, 24-34.

Hall, A., and M. Visbeck, 2001: Ocean and sea ice response to the southern hemisphere annular mode: esults from a coupled climate model. *CLIVAR Exchanges*, this issue.

Levitus, S., J.I. Antonov, T.B. Boyer, C. Stephens, 2000, Warming of the World Ocean. *Science*, **287**, 2225-2229.

Robertson, R., M. Visbeck, A.L. Gordon, E. Fahrbach, 2002: Long-term Temperature Trends in the Deep Waters of the Weddell Sea. *Deep Sea Res.*, in revision.

Southern Ocean ALACE Float Temperatures are Warmer than Historic Temperatures

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As part of the World Ocean Circulation Experiment (WOCE) in the 1990s, some 300 Autonomous Lagrangian Circulation Explorer (ALACE) floats were deployed south of 30°S. The basic measurements from ALACE floats include mid-depth temperatures and velocities, averaged over 10 to 25 day time intervals (Davis et al., 1992). Around the globe, ALACE velocity data have been used to examine mean and varying flow fields in a variety of regions e.g. Davis et al. (1996), Davis (1998). Since 1990, ALACE floats have collected nearly 13,000 Southern Ocean observations. This is equivalent to roughly two-thirds the total number of mid-depth temperature observations collected by ships in the Southern Ocean since the 1930s, and it thus represents a significant increase to the global database. Some of the more recently deployed floats also recorded vertical temperature profiles, but these have not been included in the present analysis.

This note compares objectively mapped temperature fields at 900 m derived from 1990s ALACE observations with Gouretski et al.'s (1998) objectively mapped temperature fields from shipboard data collected primarily between 1950 and 1990 (although Gouretski et al included 1990s WOCE data when it was available.) Figure 1a (page 20) shows the atlas temperatures at 900 m depth, and Figure 1b shows objectively mapped ALACE temperatures at 900 m depth. In both cases, data were mapped using the algorithm described by Bretherton et al. (1976), assuming a Gaussian covariance function with an isotropic decorrelation scale of 500 km. ALACE floats drifted at depths between 700 and 1100 m depth, and historic vertical temperature gradients were used to extrapolate the ALACE measurements to 900 m. Floats that were entrained into the Antarctic Circumpolar Current (ACC) tended to disperse themselves more uniformly around the Southern Ocean, so geographic coverage in Figure 1b is better within the ACC than it is to the north or south of the current.

ALACE data are on average 0.16°C warmer than atlas data. This apparent warm bias in ALACE data exceeds instrumental errors (<0.02°C, but these should be unbiased), statistical errors (<0.01°C), and formal mapping errors (estimated to be about 0.1°C). Figure 1c shows the temperature difference between objectively mapped ALACE and hydrography. (High error bar regions have been eliminated from this comparison.) Both data sets are noisy, and ice edge effects may bias the temperature difference at the southern end of the domain, since ALACE is unable to return measurements in ice-covered regions. Nonetheless, careful examination of the data suggests that the atlas/ALACE temperature difference is indicative of a longterm warming trend concentrated in the southern portion of the Southern Ocean. (Gille, 2001a) provides a detailed discussion of the point by point differences, and two other manuscripts examine mapped mean flow (Gille, 2001b) and eddy heat fluxes (Gille, 2001c).

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Bretherton, F.P., R.E. Davis, and C.B. Fandry, 1976: A technique for objective analysis and design of oceanographic experiments applied to MODE-73. *Deep Sea Res.*, **23**, 559-582.

Davis, R.E., 1998: Preliminary results from directly measuring middepth circulation in the tropical and South Pacific. *J. Geophys. Res.*, **103**, 24,619-24,639.

Davis, R.E., D.C. Webb, L.A. Regier, and J.Dufour, 1992: The Autonomous Lagrangian Circulation Explorer (ALACE). *J. Atmos. Ocean. Tech.*, **9**, 264-285.

Davis, R.E., P.D. Killworth, and J.R. Blundell, 1996: Comparison of Autonomous Lagrangian Circulation Explorer and fine resolution Antarctic model results in the South Atlantic. *J. Geophys. Res.*, **101**, 855-884.

Gille, S.T., 2001a: Warming of the Southern Ocean since the 1950s. *Science*, submitted.

Gille, S.T., 2001b: Float Observations of the Southern Ocean: Part 1, Estimating Mean Fields, Bottom Velocities, and Topographic Steering. *J. Phys. Oceanogr.*, submitted.

Gille, S.T., 2001c: Float Observations of the Southern Ocean: Part 2, Eddy Fluxes. *J. Phys. Oceanogr.*, submitted.

Gouretski, V.V., and K. Jancke, 1998: A new climatology for the World Ocean, Tech. Rep. WHP SAC Tech. Rep. No. 3, WOCE Report No. 162/98, Southampton, UK.

From R. Robertson et al.: Long-term Warming of Weddell Sea Warm Deep Water, page 21:

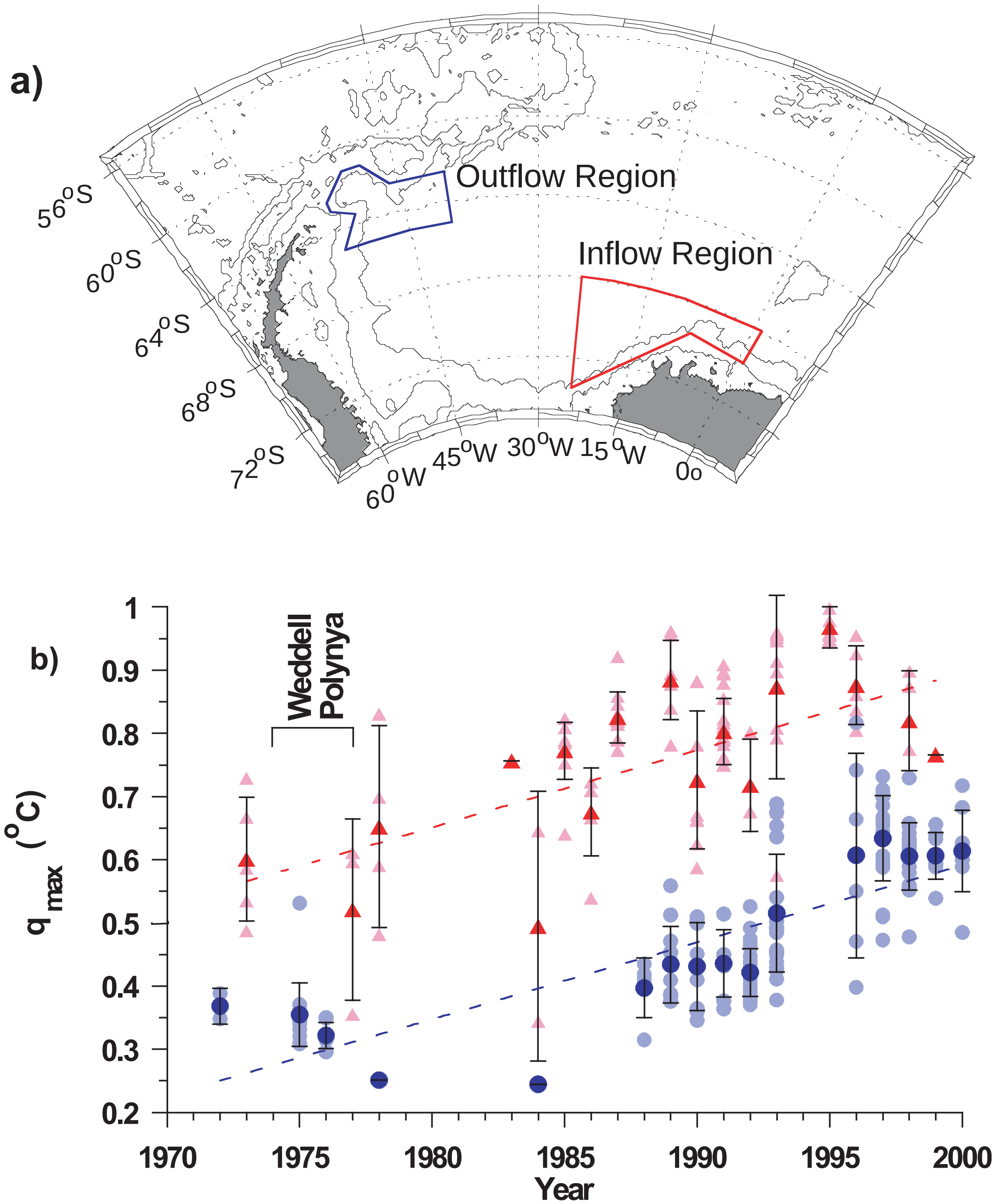

Figure 1. a) The bathymetry for the Weddell Sea with contours at 500 and 3000 m. The inflow and outflow regions are indicated by red and blue boxes, respectively. b) Annual average potential temperature profiles were calculated for three depth ranges representing the core of the WDW (bottom depths of 3000 to 3500 m, 3500 to 4000 m, and 4000 to 4500 m) for the inflow and outflow regions. The maximum potential temperature, q_{MAX}, determined for each of these average profiles is shown for the inflow region (red triangles) and the outflow region (blue dots). The pink triangles and light blue dots are the values for the individual profiles in the inflow and outflow regions, respectively. The error bars represent one standard deviation of the values. The red and blue dashed lines are fitted trends for the inflow and outflow regions, respectively. For a complete explanation of the technique, see Robertson et al. (2002).