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# Atmospheric net transport of water vapor and latent heat across 60°S

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**Abstract.** The mean annual moisture flux across 60°S is estimated using results of numerical analyses produced by the U. S. National Centers for Environmental Prediction and the European Centre for Medium-Range Weather Forecasts for the 7-year period 1985-1991. The atmospheric data indicate a net poleward transport of 17.06 kg $m^{-1}$ $s^{-1}$ or 10.74 Tt $yr^{-1}$. The mean annual moisture transport divergence for the area poleward of 60°S is estimated using a combination of surface and near-surface data (precipitation and evaporation for the Southern Ocean, net surface accumulation and seaward drifting snow transport for the Antarctic ice sheet). The mass exchange rates at the ice sheet–atmosphere and ocean-atmosphere interfaces are integrated strictly for the area between 60°S and 70°S and are combined with the results of a preceding surface data estimate of transport divergence for the area poleward of 70°S. The surface data are a combination of diverse sets representative of various multiyear periods distributed through 1941-1990 and indicate a poleward transport of 18.60 kg $m^{-1}$ $s^{-1}$ or 11.79 Tt $yr^{-1}$ across 60°S. The estimates based on atmospheric and surface data show remarkable agreement (the difference is well within the error estimates) and indicate net atmospheric transports of water vapor and latent heat poleward across 60°S of 17.8 kg $m^{-1}$ $s^{-1}$ and 50 MJ $m^{-1}$ $s^{-1}$, respectively.

## Introduction

An understanding of the energy and moisture budgets in the area poleward of 60°S (Figure 1) is important to atmospheric, glaciological, and oceanographic studies. Improved estimates of mass and energy transfer rates in the polar regions eventually become inputs to dynamic models such as general circulation models and enhance the potential use of such models in assessments of global change [e.g., *Trenberth*, 1992a]. The paucity of in situ data available at these latitudes, however, severely limits model evaluation and thus brings into question the validity of dynamic models for southern hemisphere study. Previously, the atmospheric net transport of water vapor (and latent heat) had been estimated using upper air data from stations distributed in two zones, with mean latitudes of approximately 46°S and 71°S. Some estimates have included comparisons with estimates of surface precipitation and evaporation as well as drifting snow transport (references to these appear in works by *Giovinetto et al.* [1992] and *Yamazaki* [1992, 1994]). The recent availability of long-duration numerical analyses that incorporate large amounts of satellite observations offers an alternative method for computing moisture transport that is more promising than previous work and bears comparison to new surface measurement estimates.

In this study we present two estimates of net vapor transport following different approaches (Figure 2). One is a moisture flux estimate using numerical analyses from operational weather centers. The other is a composite estimate of transport divergence in which terms obtained using surface and near-surface data for the area between 60°S and 70°S are combined with a previous estimate of transport across 70°S [*Giovinetto et al.*, 1992]. It should be noted that all four authors have contributed to similar preceding studies for 70°S, but this study is their first for 60°S in which the moisture flux estimate is compared to an estimate of transport divergence for the whole area. Rates of surface precipitation over the ocean area and of net surface accumulation (surface mass balance) for the ice sheet area correspond to climatic means available in the literature; the rate of evaporation for the ocean area is estimated using climatic means of sea ice distribution and sporadic site-specific determinations of latent heat flux; drifting snow transport across the ice terminus lying north of 70°S is estimated using surface wind and snow transport models derived from a combination of climatic and synoptic data [e.g., *Bromwich*, 1990; *Parish and Bromwich*, 1991; *Wendler*, 1991; *Wendler et al.*, 1993].

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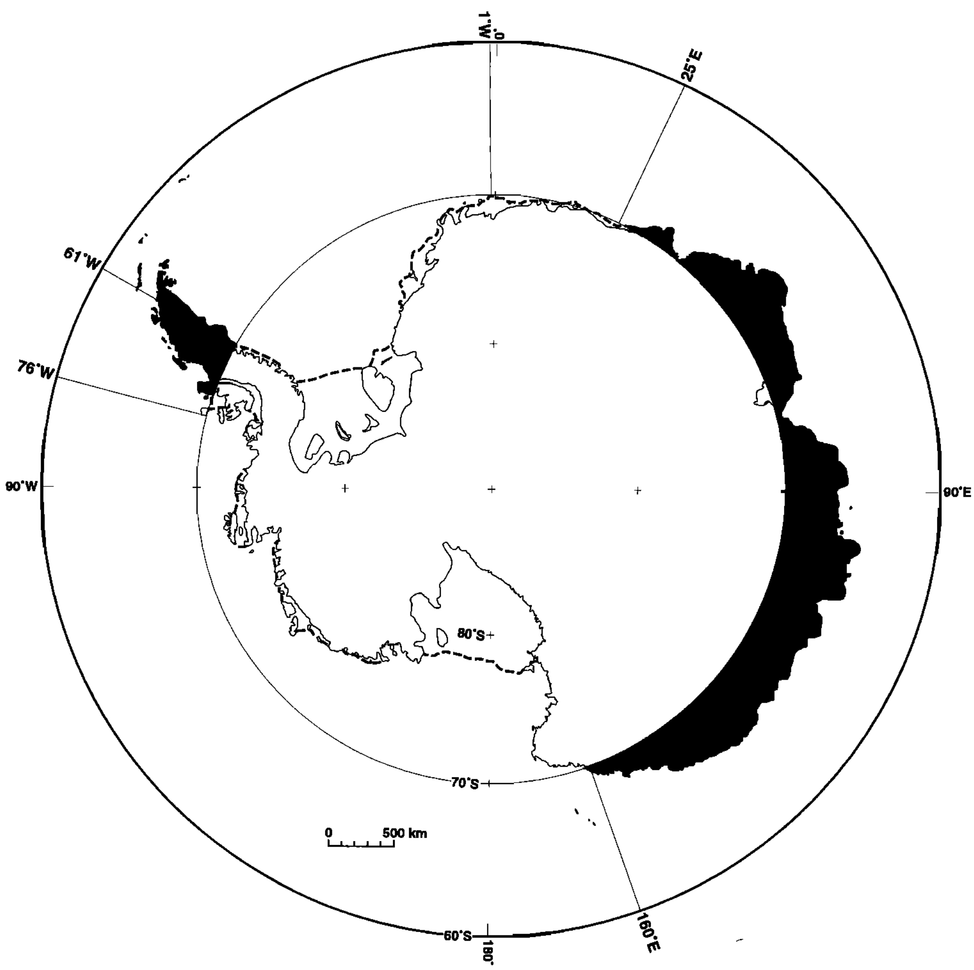


**Figure 1.** Antarctic and Southern Ocean areas and sectors discussed in the text that lie between and within the 60th and 70th parallels.

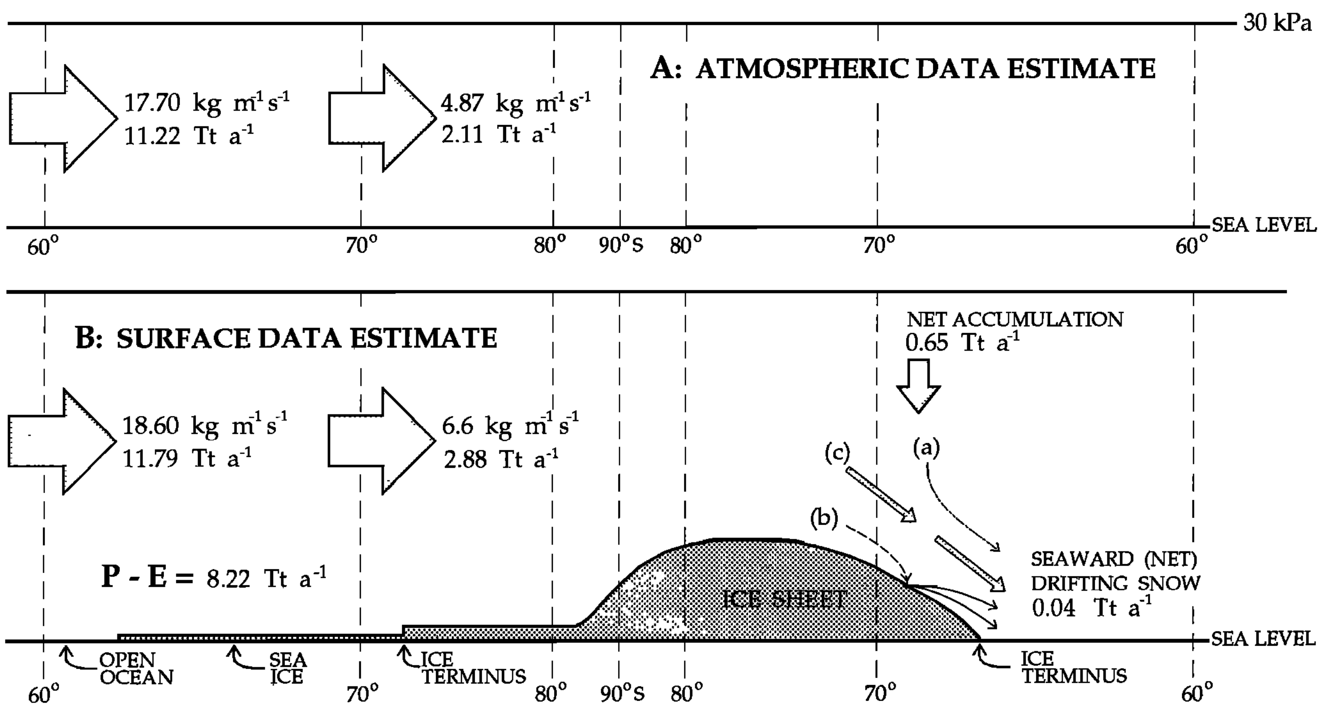


**Figure 2.** Schematic cross section of Antarctica and the Southern Ocean illustrating the disposition of terms derived from (a) atmospheric and (b) surface data discussed in the text. Latitude scale is proportional to area.

**Table 1.** Net Moisture Flux

| Analysis | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | Mean | Standard Deviation |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | *60° Latitude* | | | | |
| NCEP* | -17.44 | -17.31 | -16.50 | -17.93 | -18.56 | -18.39 | -17.51 | -17.66 | 0.70 |
| NCEP† | -17.19 | -17.13 | -16.19 | -17.56 | -18.35 | -18.15 | -17.33 | -17.41 | 0.72 |
| ECMWF† | -17.34 | -17.41 | -15.73 | -16.13 | -17.56 | -15.54 | -16.29 | -16.57 | 0.85 |
| | | | | | *70° Latitude* | | | | |
| NCEP* | -4.38 | -4.50 | -4.08 | -5.32 | -5.55 | -4.41 | -5.39 | -4.80 | 0.59 |
| NCEP† | -4.20 | -4.33 | -3.89 | -5.10 | -5.28 | -4.23 | -5.14 | -4.59 | 0.56 |
| ECMWF† | -4.59 | -4.90 | -3.86 | -4.66 | -4.71 | -4.17 | -4.95 | -4.55 | 0.40 |

Values are in kilograms per meter per second, negative southward. NCEP is National Centres for Environmental Prediction, and ECMWF is European Centre for Medium-Range Weather Forecasts.

*These values are after *Yamazaki* [1992, 1994]; flux estimates for 1985 and 1991 were added for this study.

†These values are after *Bromwich et al.* [1995].

## Estimates

### Atmospheric Data Estimate

Global atmospheric numerical analyses are routinely produced by operational weather forecasting centers and represent the most comprehensive assimilation of meteorological data available [*Trenberth*, 1992b]. The analyses are produced by a four-dimensional data assimilation system that uses a "first guess" derived from the previous 6-hour numerical forecast as the base for integrating the observations into the analysis. The observations are assimilated using a multivariate three-dimensional evaluation of deviations of observations from the forecast field. This technique allows consistent use to be made of observations with different error characteristics and takes into account their spatial distribution [*Lorenc*, 1981; *European Centre for Medium-Range Weather Forecasts* (*ECMWF*), 1992]. An assessment of the numerical analyses around and over the Antarctic continent has been made by *Bromwich et al.* [1995] and *Cullather et al.* [1997] using available rawinsonde, automatic weather station (AWS), ship, and synthesized long-term observations. Analyses obtained from the ECMWF were found to compare closely with AWS and ship observations over a 10-year period and to generally offer a reasonable

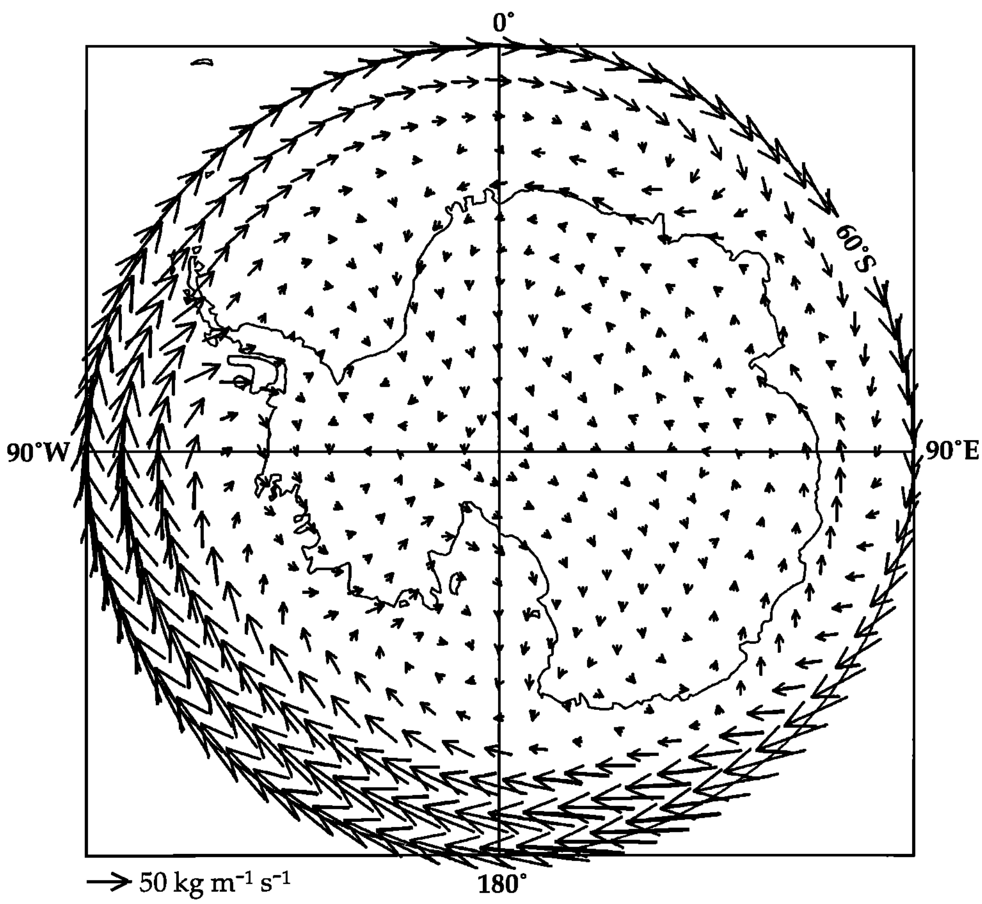


**Figure 3.** Six-year (1986-1991) mean moisture flux.

**Table 2.** Comparison of Mean Flux Values for 60°S and 70°S and Precipitation Minus Evaporation for 60°-70°S

| | Mean Flux Values, kg m$^{-1}$ s$^{-1}$ 60°S | 70°S | P-E, kg m$^{-2}$ yr$^{-1}$ 60°S-70°S |
|---|---|---|---|
| *Atmospheric Data* | | | |
| *Starr et al.* [1969] | -6.1 | +0.73 | 221 |
| *Peixoto and Oort* [1983] | -10.0 | -2.7 | 245 |
| *Howarth* [1983] and *Howarth and Rayner* [1986] | -6.2 | -3.7 | 133 |
| *Masuda* [1990] | --- | -5.26 | --- |
| This work, from Table 1, | | | |
| NCEP | -17.66 | -4.80 | 484 |
| NCEP | -17.41 | -4.59 | 481 |
| ECMWF | -16.57 | -4.55 | 453 |
| Mean | -17.06 | -4.62 | 468 |
| *Surface Data* | | | |
| *Sellers* [1965] | -8.1 | -1.3 | 244 |
| *Baumgartner and Reichel* [1975] | -13.0 | -5.2 | 320 |
| *Korzoun et al.* [1977, 1978] | -21.0 | -6.1 | 578 |
| This work, from Table 3 | -18.6 | -6.6† | 471 |

†Value is from *Giovinetto et al.* [1992]

depiction of the broad-scale atmospheric circulation. Analyses produced by the U.S. National Centers for Environmental Prediction (NCEP) show significant improvement over the same period, particularly during the period 1985-1990. A comparison of atmospheric moisture transport values by *Bromwich et al.* [1995] for the continent and a comparison to derived values for Macquarie Island (54.5°S, 159°E) indicate that the large errors found in NCEP values are largely confined to the continental interior. Particularly important for the present study, the monthly averaged meridional transports obtained using NCEP and ECMWF data agreed well with those obtained from the upper air observations along the Antarctic coast.

Three other studies have employed numerical analyses to study atmospheric moisture fluxes near Antarctica. *Masuda* [1990] estimated moisture and energy transports across 70°S using ECMWF data for 1979. *Yamazaki* [1992, 1994] calculated the mean accumulation rate (precipitation minus evaporation) for the area poleward of 70°S and for Antarctica from NCEP data for the 5-year period 1986-1990 and showed good agreement for a sector near Syowa station between the results from numerical analyses and rawinsonde and surface accumulation measurements. A similar study was made by *Budd et al.* [1995] using the Australian Bureau of Meteorology Global Atmospheric Assimilation and Prediction Scheme (GASP) for the 3-year period 1989-1992; the derived accumulation values were close to time-averaged glaciological observations. The results obtained by these three studies and by *Bromwich et al.* [1995] demonstrate the reliability of numerical analyses for moisture budget studies in high southern latitudes.

**Table 3.** Estimates of Transport Divergence Poleward of 60°S

| | Transport Divergence kg m$^{-2}$ yr$^{-1}$ | Tt yr$^{-1}$ |
|---|---|---|
| Ocean area 60°S-70°S, 16.953 x 10$^6$ km$^2$ | | |
| Precipitation | 770 | |
| Evaporation | 285 | |
| Net | 485 | 8.22 |
| Antarctica, area 60°-70°S | | |
| Sector 25°E-160°E, 1.784 x 10$^6$ km$^2$ | | |
| Net surface accumulation | 307 | 0.55 |
| Net drifting snow | | 0.04 |
| Sector 61°W-76°W, 0.174 x 10$^6$ km$^2$ | | |
| Net surface accumulation | (600) | 0.10 |
| Antarctica and ocean, area poleward of 70°S | | |
| Divergence on 15.51 x 10$^6$ km$^2$ | | 2.88* |
| Divergence, area poleward of 60°S, 34.42 x 10$^6$ km$^2$ | | 11.79 |

*Value is from *Giovinetto et al.* [1992].

The moisture flux estimate in this study is based on data from NCEP and ECMWF, which include relative humidity, wind speed and direction, temperature, and geopotential height at six standard levels between 100 and 30 kPa with a horizontal resolution of 2.5°. The data are produced twice daily and cover the 7-year period 1985-1991.

The computational techniques by which the transport estimate (negative southward) is integrated vertically and over time have been described in preceding studies [*Yamazaki*, 1992, 1994; *Bromwich et al.*, 1995]. The ECMWF data set included near-surface wind and moisture data. Surface values for NCEP are computed using

$$C_{sfc} = C_1 + \frac{(C_2 - C_1)(P_{sfc} - P_1)}{(P_2 - P_1)}, \quad P_{sfc} < 100 \text{ kPa} \qquad (1)$$

or

$$C_{sfc} = C_{100} + \frac{(C_{85} - C_{100})(P_{sfc} - P_{100})}{(P_{85} - P_{100})}, \quad P_{sfc} > 100 \text{ kPa} \qquad (2)$$

where $C$ is the variable of interest and $P$ is pressure. Subscripts 1 and 2 correspond to the level just below the surface and the level above, respectively, and 85 and 100 denote levels in kilopascals.

The mixing ratio of water vapor $q$ is calculated at each level

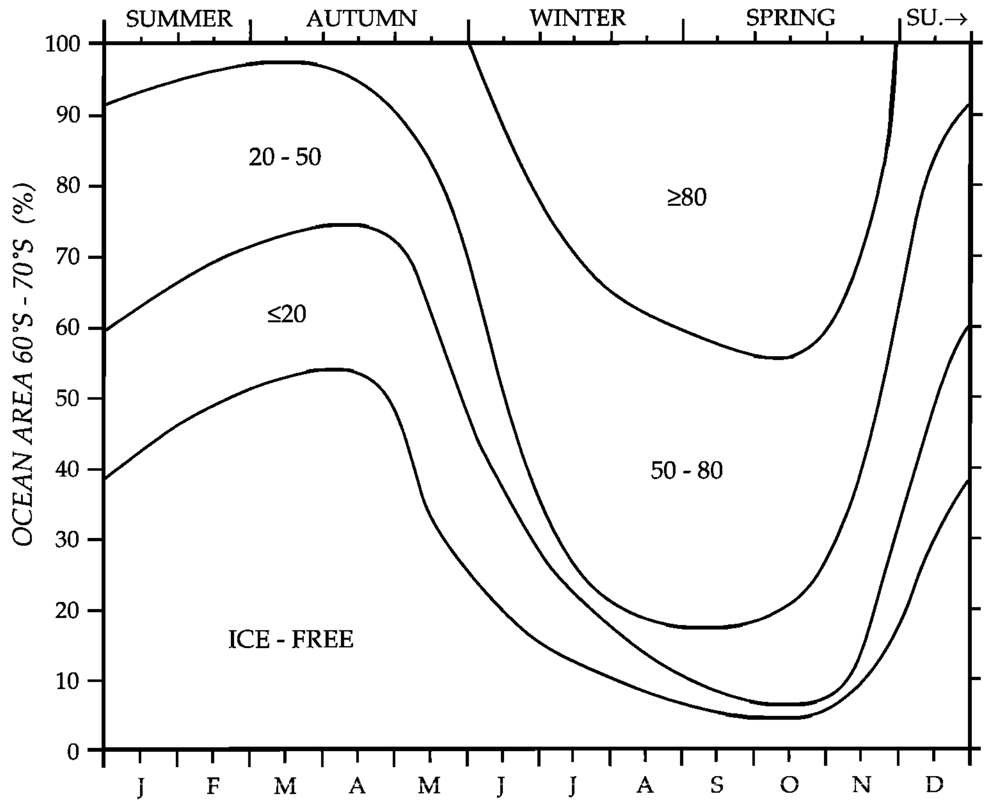


**Figure 4.** Composite annual distribution of mean sea ice concentration in the ocean area between 60°S and 70°S based on an analysis of semimonthly charts for the period 1973-1982. The seasonal labels correspond to the sea ice and latent heat flux distributions listed in Tables 4 and 5.

from relative humidity and temperature data using the Tetens formula. The total moisture flux vector is defined as

$$Q = \int_{P_t}^{P_s} q\mathbf{v} \frac{dp}{g} \qquad (3)$$

where **v** is the horizontal wind vector, $g$ is the acceleration of gravity, $P_s$ is surface pressure, and $P_t$ is the pressure at the effective top. No moisture data exist above 30 kPa.

The results from two NCEP analyses and one ECMWF analysis completed for this study are listed in Table 1. The differences between any two 7-year mean values at either 60°S or 70°S are smaller than the standard deviation for each series. The difference between the 7-year mean of the NCEP analyses for 60°S (-17.54 kg $m^{-1}$ $s^{-1}$) and the ECMWF analysis (-16.57 kg $m^{-1}$ $s^{-1}$) is approximately 5%. The difference between the 7-year mean of the NCEP analyses for 70°S (-4.70 kg $m^{-1}$ $s^{-1}$) and the ECMWF analysis (-4.55 kg $m^{-1}$ $s^{-1}$) is approximately 3%. From these means of the NCEP and ECMWF analyses, the net moisture flux across 60°S is estimated to be (-) 17.06 kg $m^{-1}$ $s^{-1}$ or (-) 10.74 Tt $yr^{-1}$. Values obtained from the ECMWF are the lowest at both 60°S and 70°S, but for practical purposes it may be stated that the results from all three analyses are approximately the same. The grid-value results were integrated to show the areal distribution of the moisture flux (Figure 3). Overall, the poleward flux across 60°S is large in the eastern Indian Ocean and western and central Pacific Ocean sectors (from 90°E eastward to 90°W), particularly in the 90°E-180° quadrant. Closer to the continent, at latitudes of 65°S and 70°S, poleward flux is largest in sectors centered at longitudes of approximately 40°E, 135°E, 150°W, and 70°W; these sectors lie to the east of the mean position of low-pressure areas in winter [cf. *Schwerdtfeger*, 1984; *Bromwich*, 1988].

The results of the numerical analyses presented in this paper indicate flux values for 60°S and 70°S that are greater than those reported almost in all previous analyses from atmospheric observations (Table 2). *Bromwich et al.* [1995] show that the latitude of maximum zonally averaged precipitation minus evaporation (P-E) in the southern hemisphere occurs farther south in the ECMWF and NCEP analyses than in previous studies, in part due to the impact of the Antarctic coastal topography on cyclonic activity. In addition, satellite observations are a critical source of information for the Southern Ocean, and the incorporation of these data into the numerical analyses likely produces results which are superior to those derived solely from the sparse rawinsonde network [*Starr et al.*, 1969; *Peixoto and Oort*, 1983]. The result shown for *Masuda* [1990] was obtained from the first year of ECMWF analyses during the First Global Atmospheric Research Program Global Experiment (FGGE). The value for average moisture flux at 70°S for 1 year (1979) is larger than this study's results shown in Table 2 but is within the range of values given for individual years in Table 1. The older version of Australian Bureau of Meteorology analyses utilized by *Howarth* [1983] and *Howarth and Rayner* [1986] has previously been found to underestimate substantially the eddy activity, with maxima at station locations [*van Loon*,

**Table 4.** Combined Area and Time-Weighted Indexes Used in the Estimate of Latent Heat of Evaporation in the Ocean Area Between 60°S and 70°S

| Nominal Sea Ice Concentration | | Ice-Free Ocean and Open Water | | Actual Area of Sea Ice | Weighted Index for Ice-Free Ocean, Open Water, and Sea Ice Used in the Estimate of Latent Heat | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Range | Weighted Index | Actual Area | Weighted Index | Weighted Index | Summer 7-2 | Autumn 3-5 | Winter 6-8 | Spring 9-11 | Annual 1-2 |
| 0, water | 26.5 | 100 | 26.5 | 0.0 | 20.5 | 20.9 | 11.3 | 9.0 | 61.7 |
| <20 | 14.6 | 90 | 13.1 | 1.5 | 0.6 | 0.5 | 0.3 | 0.1 | 1.5 |
| 20-50 | 18.8 | 65 | 12.2 | 6.6 | 2.5 | 1.8 | 0.9 | 1.4 | 6.6 |
| 50-80 | 24.6 | 35 | 8.5 | 16.1 | 1.4 | 1.8 | 6.5 | 6.4 | 16.1 |
| >80 | 15.6 | 10 | 1.5 | 14.1 | — | — | 6.0 | 8.1 | 14.1 |
| | 100.1 | | 61.8 | 38.3 | 25.0 | 25.0 | 25.0 | 25.0 | 100.0 |

All values are in percent.

1980; *Bromwich et al.*, 1995]. The derived long-term P-E for these older analyses, shown in Table 2, agrees more closely with the smaller values from the rawinsonde-based studies. Results presented in Table 2 highlight the importance of satellite data and comprehensive assimilation in data-sparse regions.

## Surface Data Estimate

The surface data used to estimate particular terms are first integrated specifically for the zone between 60°S and 70°S. Most of the data were collected during 1956-1990 and are representative of 1- to 35-year periods distributed between approximately 1941 and 1990. The overall estimate is the summation of the four terms described herein.

1. The difference between precipitation and evaporation in the ocean area (16.953 x$10^6$ km$^2$), which is estimated using the mean precipitation of 562 kg m$^{-2}$ yr$^{-1}$ obtained by *Baumgartner and Reichel* [1975] from a compilation by the German Weather Service and which is the most complete to date. There are more recent data such as those available through the NCEP/NCAR Reanalysis CD-ROM [*Kalnay et al.*, 1996] and which, in the polar and subpolar regions, rely on microwave remote sensing to obtain values over oceanic areas. We have examined the Global Precipitation Climatology Project (GPCP) data set which is available in the CD-ROM, but approximately 87% of the grid points between 60°S and 70°S have been labeled missing. Moreover, the proportion of missing data increases to 94% during the winter months, when a larger part of the precipitation is likely to occur. The estimate of *Baumgartner and Reichel* [1975] for the area between 60°S and 70°S is basically an interpolation between albeit scant ship data north of 60°S and the estimate of net accumulation at the surface (i.e., precipitation minus sublimation and drifting snow losses) on the ice sheet by *Giovinetto* [1964]. In the preceding study for the area south of 70°S [*Giovinetto et al.*, 1992] we found that the isohyet pattern for the Southern Ocean area poleward of 70°S drawn by *Baumgartner and Reichel* [1975], which was based on extrapolation from accumulation rates shown on the ice sheet in the compilation of *Giovinetto* [1964], showed an overestimate by 37%. The isohyet pattern for the ocean area poleward of 70°S drawn by *Giovinetto et al.* [1992] was based on extrapolation from accumulation rates shown on the ice sheet in the compilation of *Giovinetto and Bentley* [1985]. The total number of data sites as well as the reliability in the determination of the accumulation rate at particular sites increased significantly in the two decades that lapsed between the compilations. The number of data sites for Antarctica increased from approximately 350 in the early 1960s to 1500 in the early 1980s, and the estimate of mean accumulation for the coastal zone increased from approximately 600 to 750 kg m$^{-2}$ yr$^{-1}$ [*Giovinetto and Bull*, 1987]. The difference between the rates for the ocean area poleward of 70°S (388 kg m$^{-2}$ yr$^{-1}$ [*Baumgartner and Reichel*, 1975] and 531 kg m$^{-2}$ yr$^{-1}$ [*Giovinetto et al.*, 1992], respectively) is an increase of 37%, suggesting that the estimate of precipitation for 60°S-70°S selected for this study should be increased proportionally, i.e., by 200 to 770 kg m$^{-2}$ yr$^{-1}$ (Table 3).

To the adjusted precipitation mean of 770 kg m$^{-2}$ yr$^{-1}$ we subtract our estimate of evaporation based on seasonal latent heat flux estimates found in the literature. We used the estimates of *Zillman* [1972], *Andreas et al.* [1979], and *Brown* [1990] for ice-free ocean and open water within the pack and of *Allison* [1972], *Maykut* [1978], and *Weller* [1980] for sea ice. Their estimates were interpolated and extrapolated on the basis of latitude as well as sea ice thickness [*Washington et al.*, 1976; *Häkkinen*, 1990] and factored by area/time indexes obtained from an analysis of the semimonthly sea ice concentration distributions compiled by the *Naval Oceanography Command Detachment* [1985].

In this work we follow the procedures described in a preceding study [*Giovinetto et al.*, 1992] to estimate the mean annual evaporation rate for the ice-free ocean and open water area within the pack (62%; see Figure 4 and Table 4). We use the weighted mean latent heat flux (26 W m$^{-2}$, Table 5) and a latent heat of vaporization of 2.5 MJ kg$^{-1}$ for water with a surface temperature of approximately 273 K; these factors result in a mean open water evaporation of 328 kg m$^{-2}$ yr$^{-1}$. We also estimate the mean annual evaporation rate for the ocean area covered by ice (38%) using the weighted mean latent heat flux (19 W m$^{-2}$) and a latent heat of vaporization of 2.8 MJ kg$^{-1}$ (increased to account for sublimation since the snow/ice surface temperature is between 268 and 258 K for approximately 8 months of the year [cf. *Comiso*, 1994]). These factors result in a mean evaporation for ice-covered and open water areas of 214 kg m$^{-2}$ yr$^{-1}$.

A combined mean evaporation rate for ice-free ocean, open water within the pack, and sea ice of 285 kg m$^{-2}$ yr$^{-1}$, and the precipitation estimate mentioned above (770 kg m$^{-2}$ yr$^{-1}$)

**Table 5.** Estimate of Latent Heat Flux in the Ocean Area Between 60°S and 70°S

| Nominal Sea Ice Concentration | Summer 12-2 | Autumn 3-5 | Winter 6-8 | Spring 9-11 | Weighted Annual Mean |
|---|---|---|---|---|---|
| 0, water | 17 | 25 | 52 | 19 | 26 |
| <20 | 16 | 23 | 47 | 17 | 25 |
| 20-50 | 14 | 21 | 42 | 15 | 20 |
| 50-80 | 11 | 16 | 32 | 12 | 20 |
| >80 | 9 | 14 | 28 | 10 | 18 |
| Weighted mean, ice | 13 | 19 | 31 | 11 | 19 |
| Weighted mean, area | 16 | 24 | 41 | 14 | 24 |

Heat flux values in watts per square meter.

indicate a difference between precipitation and evaporation of 485 kg $m^{-2}$ $yr^{-1}$ or 8.22 Tt $yr^{-1}$.

2. The difference between gross accumulation and gross ablation in the area of Antarctica that lies north of 70°S (1.958 x $10^6$ $km^2$), which is estimated separately for the two sectors. First, for the area of the ice sheet in East Antarctica lying north of 70°S between 25°E and 160°E the estimate is 1.784 x $10^6$ $km^2$. The integration of the rate as shown by the isopleth pattern would result in a mean of 337 kg $m^{-2}$ $yr^{-1}$ or 601 Gt $yr^{-1}$ However, small areas where there is excessive snow deflation or even net ablation (negative accumulation) cannot be shown on relatively small scale maps. Estimates of the extent of those areas and of the rates of deflation and ablation indicate that the integration of the rate for the sector 25°E-160°E should be reduced by 53 Gt $yr^{-1}$ [*Giovinetto and Bentley*, 1985], which results in a smaller mean accumulation of 548 Gt $yr^{-1}$ or 307 kg $m^{-2}$ $yr^{-1}$.

Second, for the area that lies north of 70°S in the sector 61°W - 76°W the estimate is 0.174 x $10^6$ $km^2$ (mainly Graham Land including adjacent ice shelves and islands connected by ice). Some accumulation maps, e.g., as compiled by E.S. Korotkevich and V.N. Petrov (described by *Korzoun et al.* [1977]) indicate that the rate decreases from 800 kg $m^{-2}$ $yr^{-1}$ in the west coast to 400 kg $m^{-2}$ $yr^{-1}$ in the east coast, suggesting that a first approximation to the estimate of accumulation in the area may be made using a midrange value of 600 kg $m^{-2}$ $yr^{-1}$ or 104 Gt $yr^{-1}$. This estimate is coherent with others made for the overall region of the Antarctic peninsula [e.g., *Jacobs et al.*, 1992]. The summation of the bulk estimates for the two sectors indicates a total accumulation of approximately 0.65 Tt $yr^{-1}$.

3. Net drifting snow transport seaward across the ice terminus (grounded ice or ice shelf) , which in the sector 25°E - 160°E needs to be assessed in the particular context of this study (Figure 2b). First, drifting snow blowing seaward across the ice terminus is treated as an extra contribution to precipitation on the ocean area; it should be noted that drifting snow mass is not a part of estimates of either net accumulation on the ice sheet or of precipitation on the ocean area. Second, drifting snow blowing seaward across the ice terminus is reduced by an amount equal to drifting snow that enters the sector of reference, blowing northward across 70°S; this is because its contribution to divergence has been included in a previous estimate of transport divergence for the area poleward of 70°S [*Giovinetto et al.*, 1992] that will be added in toto (Table 3).

In the context of this study, drifting snow reaching the sea in the sector 25°E-160°E has three main sources: (1) water vapor advected southward across the ice terminus which after condensation and precipitation in the area north of 70°S reaches the sea blowing northward across the terminus; (2) surface snow from preceding deposition events which is deflated principally by impact of snow grains already in motion; and (3) drifting snow blown northward across 70°S. The snow mass from the first two sources does not contribute

**Table 6.** Meridional Drifting Snow Transport for the Sector Between 25°E and 160°E

| Sector, °E | Northward Across 70°S*† | | Northward Across the Ice Terminus* | | | |
|---|---|---|---|---|---|---|
| | Budd et al.‡ | Lister§ | Budd et al.‡ | Lister§ | Kobayashi 1ø | Kobayashi 2ø |
| 25-30 | 0.07 | 0.06 | 0.6 | 2.6 | 2.1 | 0.3 |
| 30-40 | 0.61 | 1.10 | 0.3 | 1.5 | 1.2 | 0.2 |
| 40-50 | 0.98 | 1.50 | 0.2 | 1.0 | 0.8 | 0.1 |
| 50-60 | 2.00 | 2.20 | 3.3 | 18.0 | 14.3 | 2.3 |
| 60-70 | 2.80 | 4.10 | 2.5 | 9.1 | 7.4 | 1.2 |
| 70-80 | 0.10 | 0.02 | 0.3 | 0.5 | 0.5 | 0.1 |
| 80-90 | 3.90 | 14.00 | 0.4 | 1.2 | 1.0 | 0.2 |
| 90-100 | 8.70 | 65.00 | 2.4 | 15.5 | 12.1 | 1.9 |
| 100-110 | 4.90 | 28.00 | 5.6 | 51.9 | 39.7 | 6.3 |
| 110-120 | 3.00 | 8.90 | 2.2 | 10.0 | 8.0 | 1.3 |
| 120-130 | 3.80 | 17.00 | 2.3 | 14.8 | 11.6 | 1.9 |
| 130-140 | 1.90 | 4.00 | 3.5 | 23.6 | 18.5 | 2.9 |
| 140-150 | 8.80 | 59.00 | 10.5 | 118.3 | 89.4 | 14.3 |
| 150-160 | 0.87 | 0.93 | 3.7 | 20.5 | 16.2 | 2.6 |
| Totals | 42.43 | 205.81 | 37.8 | 288.6 | 222.7 | 35.5 |

Values are in gigatons per year. The range for values across 70°S and the ice terminus are 124.12 and 129.1 (i.e. Kobayashi 1 and 2), respectively. The adopted ranges for values across 70°S and the ice terminus are 124.12 and 163.2, respectively.

*Wind data from the model of *Parish and Bromwich* [1991].

†Values are from *Giovinetto et al.* [1992].

‡Model is described by *Radok* [1970].

§Model is described by *Loewe* [1970].

øMaximum and minimum transports were obtained from a model decribed by *Kobayashi* [1978].

to net accumulation and therefore needs to be added as a part of the moisture transport divergence. The snow mass from the third source has already been accounted for in the net atmospheric water vapor advected southward across 70°S.

The surface wind and snow transport models used in the previous estimate of drifting snow across 70°S [*Giovinetto et al.*, 1992] are used here without modification (Table 6). The wind data produced by the wind model of *Parish and Bromwich* [1991] are combined with snow transport models of W.F. Budd et al. (discussed by *Radok*, [1970]), H. Lister (discussed by *Loewe*, [1970]), and *Kobayashi* [1978]. Using these models we obtain a range between 37.8 and 288.6 Gt $yr^{-1}$. The midrange value of these estimates (163.2 Gt $yr^{-1}$) is larger than the transport across 70°S (a range between 42.4 and 205.8 Gt $yr^{-1}$, i.e., a midrange value of 124.1 Gt $yr^{-1}$). The difference between the two transport estimates in the sector of reference indicates that the net contribution to the overall estimate of transport divergence is approximately 0.04 Tt $yr^{-1}$.

Drifting snow transport seaward across the ice terminus in the sector from 1°W (eastward) to 25°E, where the ice terminus extends approximately along the 70°S parallel, has been included in the estimate of transport across 70°S [*Giovinetto et al.*, 1992]. This transport should be added to the estimate of precipitation in the ocean, but it is relatively small (2 Gt $yr^{-1}$) and is ignored. The transport corresponding to the sector 61°W-76°W is negligible also relative to the overall estimate because the slopes are short and the snow fetch areas are small.

4. Divergence in the area poleward of 70°S, which has been estimated on the basis of surface data to be 2.88 Tt $yr^{-1}$ [*Giovinetto et al.*, 1992].

The summation of the terms 1-4 listed above is 11.79 Tt $yr^{-1}$ (Table 3), a divergence that indicates a net water vapor transport across 60°S of (-) 18.60 kg $m^{-1}$ $s^{-1}$. This estimate is larger than those of *Sellers* [1965] and *Baumgartner and Reichel* [1975] but smaller than that of *Korzoun et al.* [1977, 1978] (Table 2).

## Discussion of Results

Conspicuous agreement exists among estimates of net transport of water vapor across 60°S using separate approaches. The difference between the estimates based on atmospheric numerical analyses and on surface data is 1.54 kg $m^{-1}$ $s^{-1}$ or 9% of the midrange value of the estimates. The agreement found here indicates a good approximation to the poleward moisture transport is attainable despite the paucity of available in situ data.

The agreement between the NCEP and ECMWF numerical analyses for 60°S is in large part due to the assimilation of the same satellite data. However, the values at both 60°S and 70°S are obtained from differing assimilation schemes, and thus the agreement indicates that the computed transport does not suffer from a significant dependence on the assimilation methods employed. In the following sections we concentrate the discussion on mean precipitation and evaporation estimates in the ocean area between 60°S and 70°S.

1. The estimate of precipitation of *Baumgartner and Reichel* [1975] (562 kg $m^{-2}$ $yr^{-1}$) selected as the basis for our estimate is larger than the estimate of *Jaeger* [1976] (discussed by *Peixoto and Oort* [1992]) (320 kg $m^{-2}$ $yr^{-1}$). Their estimates converge at other latitudes (at 80°S and 36°S with values of approximately 300 and 950 kg $m^{-2}$ $yr^{-1}$, respectively); however, the estimates show the largest difference at 55°S, where Baumgartner and Reichel list a value of 1001 kg $m^{-2}$ $yr^{-1}$, and Jaeger shows a value of approximately 360 kg $m^{-2}$ $yr^{-1}$. Our estimate of 770 kg $m^{-2}$ $yr^{-1}$ for the 60°S-70°S zone is close to and slightly larger than a linear interpolation between the estimate of *Giovinetto et al.* [1992] for the area poleward of 70°S (specifically, 531 kg $m^{-2}$ $yr^{-1}$ at a mean latitude of 73°S) and the estimate of *Baumgartner and Reichel* [1975] at a latitude of 55°S. We believe that large rather than low precipitation values appear to be consistent with the maxima of frequency of cyclones and of fronts at a mean latitude of 65°S [e.g., *Schwerdtfeger*, 1984] and of cloud cover at mean latitude of 60°S [e.g., *Berlyand and Strokina*, 1980], although the presence of sea ice in winter may induce stability and thus reduce precipitation [e.g., *Zillman*, 1972; *Andreas and Makshtas*, 1985].

2. The mean rate of evaporation estimated in this study (285 kg $m^{-2}$ $yr^{-1}$) is close to and of intermediate value between those of *Baumgartner and Reichel* [1975] (244 kg $m^{-2}$ $yr^{-1}$) and of *Peixoto and Oort* [1992] (approximately 340 kg $m^{-2}$ $yr^{-1}$), the latter derived using 1963-1973 surface data and a bulk transfer model. This indicates that our estimate of evaporation is consistent with other estimates.

3. The net precipitation (P-E) estimate of 485 kg $m^{-2}$ $yr^{-1}$ is very close to values derived from the numerical analyses. The P-E estimate for 60°S-70°S is 453 kg $m^{-2}$ $yr^{-1}$ for ECMWF and 481 kg $m^{-2}$ $yr^{-1}$ for NCEP.

## Conclusions

Estimates of atmospheric net water vapor southward across 60°S based on two separate numerical analysis data sets are in close agreement. The averaged transport is 16.99 kg $m^{-1}$ $s^{-1}$. The estimate based on surface data (18.60 kg $m^{-1}$ $s^{-1}$) appears to be reliable because the estimates of precipitation and evaporation on the ocean area are consistent with some of the rates and meteorological phenomena reported in the literature. The coincidence of the analyses and surface data estimates belies the large probable error in each, which we assess to be no less than 10% for the atmospheric data analyses and 20% for the surface data estimate. Nevertheless, the small difference between them is rare in studies of this type and is a form of substantiation. Accurate estimates of the surface moisture budget for the area south of 60°S and of moisture transport across 60°S are necessary for an understanding of the moisture and energy budgets over the Southern Ocean as well as for model validation and initialization; yet it would be difficult to conceive of a more exact means of estimation than the methods provided here, given the current data constraints. Overall, this study indicates an atmospheric net transport southward across 60°S of approximately 17.80 kg $m^{-1}$ $s^{-1}$ and a corresponding atmospheric net latent heat transport of approximately 50 MJ $m^{-1}$ $s^{-1}$.

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