The Arctic Energy Budget
The global heat engine [courtesy Kevin Trenberth, NCAR]. Differential solar heating between low and high latitudes gives rise to a circulation of the atmosphere and ocean that transports heat poleward. As a result of these transports, poleward of about 38 deg. in both hemispheres, longwave radiation emission to space exceeds shortwave (solar) radiation gain. Without this transport, the polar regions would be colder than observed.
A closer look – averages of the annual mean net radiation budget at the top of the atmosphere based on ERBE data [from Trenberth and Caron, 2001, by permission of AMS].
The global pattern of the annual mean net radiation budget at the top of the atmosphere based on ERBE data [from Trenberth et al., 2001, by permission of Springer-Verlag].
Zonal averages from the ERBE period of the total annual northward energy transport (RT) required by the net radiation budget at the top of the atmosphere, and the contributions from atmospheric transport (AT) and oceanic transport (OT). Units are petawatts (PW) [from Trenberth and Caron, 2001, by permission of AMS]. Atmospheric transport dominates.
The zonal mean annual cycle of northward atmospheric energy transport, averaged for 1979-1998 (PW). Negative values in the Southern Hemisphere mean transport to the south (towards the South Pole) [from Trenberth and Stepaniak, 2003, by permission of AMS].
Atmospheric energy transports

The poleward transport of atmospheric energy occurs in several forms (sensible heat, latent heat, kinetic energy, potential energy). Let’s focus on the sensible and latent heat transports. Much (not all) of this transport in middle and high latitudes is termed eddy transport, in that it is associated with atmospheric disturbances (eddies). The meridional (north/south) component of the wind (v) and the temperature (t) at a given location, time and level in the atmosphere can be expressed as:

\[ v' = v - <v> \]
\[ t' = t - <t> \]

Where \(<v>\) and \(<t>\) are time means (e.g., long-term annual averages; the angle brackets denote means), \(v\) and \(t\) are instantaneous values, and \(v'\) and \(t'\) are departures from the means (anomalies). The mean eddy temperature flux is:

\[ E_{\text{flux}} = <v't'> \]

Multiply the temperature flux (m s\(^{-1}\) K) by the specific heat of air at constant volume (J kg\(^{-1}\) K\(^{-1}\)) and you get the eddy heat flux (J kg\(^{-1}\) m s\(^{-1}\)). One can extend this, using temperatures and winds at a series of levels in the atmosphere and for a series of latitudes and longitudes to get (for example) the total eddy sensible heat flux across latitude circles in units of J s\(^{-1}\) (which is Watts, the units in the previous slide).

Key: Winds with an anomalous southerly component (positive \(v'\)) tend to be associated with positive temperature anomalies (positive \(t'\)). Winds with an anomalous northerly component (negative \(v'\)) tend to be associated with negative temperature anomalies (negative \(t'\)).
Atmospheric energy transport

Hence, when winds have an anomalous southerly component, we have $v'$ positive, $t'$ positive, hence $v't'$ is positive, so the heat flux is positive (poleward)

When winds have an anomalous northerly component, we have $v'$ negative, $t'$ negative, hence $v't'$ is also positive, so the heat flux is positive (poleward)

Phrased differently: Winds from the south tend to transport warm air poleward, while winds from the north tend to transport cold air equatorward, resulting in a net poleward heat transport.

This is what travelling extratropical cyclones do!

Once can similarly compute the eddy latent heat transports using data on humidity, winds and the latent heat of vaporization.

Extratropical cyclones tend to transport relatively moist air poleward (air with a relatively high latent heat content) and relatively dry air equatorward (air with a relatively low latent heat content).

http://cimms.ou.edu/~doswell/Conference_papers/WAF86/Diagnosis.html
The atmospheric energy budget is

$$\frac{\partial A_E}{\partial t} = -\nabla \cdot \mathbf{F}_A + R_{\text{top}} + F_{\text{sfc}}$$

where the time change (tendency) of atmospheric energy storage $A_E$ in the column represents the sum of the convergence of atmospheric energy transport ($ - \nabla \cdot \mathbf{F}_A$), the net radiation at the top of the atmosphere ($R_{\text{top}}$, positive downward) and the net heat flux at the earth’s surface ($F_{\text{sfc}}$, positive upward).

The net surface flux is

$$F_{\text{sfc}} = R_{\text{sfc}} + Q_H + Q_E$$

where $R_{\text{sfc}}$ is the net radiation at the surface, and $Q_H$ and $Q_E$ are the turbulent sensible and latent heat fluxes (all three terms are positive upward). If the sum is negative, there is a net heat flux from the atmospheric column into the subsurface column. If the sum is positive, the opposite holds.

The energy budget of the ocean column is

$$\frac{\partial O_E}{\partial t} = \frac{\partial}{\partial t} (L_i + S_o + S_i) = -\nabla \cdot \mathbf{F}_o + \nabla \cdot \mathbf{F}_i - F_{\text{sfc}}$$

which states that the tendency in energy storage of the ocean $\frac{\partial O_E}{\partial t}$, can be broken down into changes in latent heat storage as floating sea ice and any overlying snow cover ($L_i$), changes in sensible heat storage of the ocean water ($S_o$) and changes in sensible heat storage as sea ice ($S_i$). The tendency in oceanic energy storage is in turn equal to the sum of the net surface heat flux, the horizontal convergence of the oceanic sensible heat flux ($\mathbf{F}_o$) and the horizontal divergence of the latent heat flux as sea ice ($\mathbf{F}_i$). The combination of the latter two is the oceanic equivalent of the atmospheric transport in the first equation.
Change in Atmospheric Energy Storage

TOA Radiation Budget

Net Surface Flux

Basic Energy Budget of the Polar Cap (North of 70 deg.)

Atmospheric Transport

Ocean Heat Transport

Sea Ice Export

Sea Ice

Sea Ice

Land

Change in Ocean/Land Heat Storage
Monthly time series of vertically integrated sensible and latent heat storage for the polar cap from the ERA-40 reanalysis (over the period 1979-2001) and from the NCEP/NCAR reanalysis (over the period 1979-2005). Note the strong annual cycle. The atmosphere gains energy through spring and summer then loses energy from autumn through winter [from Serreze et al., 2007].

Monthly change in atmospheric energy:

January -2 W m\(^{-2}\)  
April +25 W m\(^{-2}\)  
July +1 W m\(^{-2}\)  
November -11 W m\(^{-2}\)  

Annual: 0 W m\(^{-2}\) (steady state)
The mean annual cycle of 300 hPa geopotential height for the region 70-90°N. Results are based on NCEP/NCAR reanalysis data over the period 1970-1999. Reflecting the seasonality in atmospheric heat storage, there is a summer maximum and a winter minimum.

The mean annual cycle of precipitable water averaged for the region 70-90°N. Results are based on NCEP/NCAR reanalysis data over the period 1979-2000. Again, reflecting the seasonality in atmospheric heat storage, there is a summer maximum and a winter minimum.
Annual cycle of the vertically-integrated flow of (a) total atmospheric energy and (b) latent heat energy across 70 deg. N by longitude. Results are based on ERA-40 data for the period 1979-2001. Poleward (equatorward) flows are shown in red (blue). While the average flux is poleward (there is a horizontal atmospheric energy flux convergence into the polar cap), there are strong variations in the flow (both magnitude and direction) by longitude [from Serreze et al., 2007].

Monthly total energy flux convergence:

January  108 W m\(^{-2}\)  
April     92 W m\(^{-2}\)  
July      94 W m\(^{-2}\)  
November 105 W m\(^{-2}\)

Annual 100 W m\(^{-2}\)
i.e., there is a modest annual cycle
Annual Atmospheric Energy Fluxes Across 70 deg. N

Total Energy

Latent Heat Energy
Seasonal cycle of top of atmosphere radiation budget components for the polar cap from ERA-40 data. Components are the net shortwave radiation ($SW_{\text{top}}$) net longwave radiation ($LW_{\text{top}}$) and net total radiation ($R_{\text{top}}$).

Values of $R_{\text{top}}$

- January: -175 W m$^{-2}$
- April: -88 W m$^{-2}$
- July: +11 W m$^{-2}$
- November: -184 M m$^{-2}$

Annual: -110 W m$^{-2}$
Seasonal ice growth and melt

Ice growth (autumn through winter) represents an ocean heat loss (one is going from liquid to solid, which is a lower latent heat state). Ice melt (spring through summer, solid to liquid) represents an ocean heat gain.
Arctic Ocean Sensible Heat Content

Jan 3.65633
Feb 2.95006
Mar 3.01168
Apr 2.92278
May 3.49785
Jun 4.90397
Jul 6.20166
Aug 7.25292
Sep 7.33829
Oct 7.01069
Nov 6.52471
Dec 3.66975

Months

The ocean gains sensible heat through spring and summer and loses sensible heat from autumn through winter.

Courtesy M. Steele
The mean net surface flux from ERA-40 (1979-2001) extending to 60 deg. N for January, April, July and October. The 70 deg. N circle is indicated in bold. Note the strong seasonality, with downward fluxes in July (summer) and upward fluxes in January (winter), associated with heat gain and loss, respectively, in the subsurface column [from Serreze et al., 2007]. Seasonality over land is small compared to the ocean.
The annual mean net surface flux from ERA-40 (1979-2001) extending to 60 deg. N. The 70 deg. N circle is indicated in bold. The 0 \( W \ m^{-2} \) contour is shown as dashed lines. The positive (upward) net surface flux over the ocean compensates for ocean heat flux convergence and ice export. In steady state, the net flux over land should be close to zero. That it is downward points to a departure from steady state (warming of the subsurface columns) or problems with the data [from Serreze et al., 2007].
The mean annual sea ice drift in the Arctic, based on data from the IABP, the North Pole program and other sources with overlay of sea level pressure from NCEP/NCAR [ice drift field courtesy of I. Rigor, Polar Science Center, University of Washington, Seattle, WA, sea level pressure field by the authors]. Sea ice export from the Arctic Ocean is largely via Fram Strait, between Greenland and Svalbard, and counts as a small ocean heat gain.

Annual ocean heat gain from ice export is about 3 W m$^{-2}$
Ocean heat flux convergence is mostly represented by Atlantic inflow via the West Spitzbergen and Barents Sea branches (warm waters of Atlantic origin, red arrows). The annual value is small at about 3 W m^{-2}.

Figure 4: Map showing
a) Scheme of exchanges between the North Atlantic and the Arctic Ocean
b) Areas of field work for ASOF - clustered proposals

- Green: Arctic ice and freshwater output
- Blue: Arctic deep outflow and overflow
- Red: Atlantic inflow

Courtesy R. Dickson
Summary for an Arctic Ocean Domain
(see slides that follow)

from Serreze et al., 2006
Annual Energy Budget of the Arctic Ocean

Change Atmospheric Energy Storage
0 W m\(^{-2}\)

TOA Radiation Budget
-115 W m\(^{-2}\)

Atmospheric Transport
+84 W m\(^{-2}\)

Net Surface Flux
+11 W m\(^{-2}\)

Sea Ice Export
3 W m\(^{-2}\)

Change in Ocean Heat Storage
-5 W m\(^{-2}\)

Ocean Heat Transport 3 W m\(^{-2}\)

NUMBERS DON’T BALANCE!!
(welcome to real-world data!!)
January Energy Budget of the Arctic Ocean

Atmospheric Transport
+81 W m\(^{-2}\)

TOA Radiation Budget
-178 W m\(^{-2}\)

Change Atmospheric Energy Storage
-4 W m\(^{-2}\)

Sea Ice Export
3 W m\(^{-2}\)

Net Surface Flux
+58 W m\(^{-2}\)

Change in Ocean Heat Storage
-52 W m\(^{-2}\)

Ocean Heat Transport 3 W m\(^{-2}\)

NUMBERS DON’T BALANCE!!
July Energy Budget of the Arctic Ocean

Atmospheric Transport
+91 W m\(^{-2}\)

TOA Radiation Budget
+ 10 W m\(^{-2}\)

Change Atmospheric Energy Storage
+2 W m\(^{-2}\)

Sea Ice Export
2 W m\(^{-2}\)

Net Surface Flux
-100 W m\(^{-2}\)

Change in Ocean Heat Storage
+105 W m\(^{-2}\)

Ocean Heat Transport
3 W m\(^{-2}\)

NUMBERS DON’T BALANCE!!