The Atmospheric Circulation
“Weather” occurs mostly in the troposphere, but there are links between weather in the troposphere and the circulation of the stratosphere.
The atmospheric circulation of the Arctic is part of the global heat engine discussed earlier. Differential solar heating between low and high latitudes gives rise to a circulation of the atmosphere and ocean that transports heat poleward. In the middle and high latitudes, much of the atmospheric transport is eddy transport, accomplished by traveling cyclones and anticyclones. Without atmospheric energy transports, the polar regions would be colder than observed [figure courtesy K. Trenberth, NCAR].
Eddies in the atmosphere: cyclones and anticyclones

Typical pattern of 500 hPa height (left) and sea level pressure (right) for the Northern Hemisphere (January 1, 2009). Note the atmospheric waves at 500 hPa and their relationship to the low and high pressure cells (cyclones and anticyclones) at the surface. To reiterate, the effect of these eddies (atmospheric disturbances extending from the surface through the troposphere) is to transport atmospheric energy poleward to balance the differential solar heating of the earth’s surface.
Traveling cyclones and anticyclones

From here (screen shot above):
http://www.weatheroffice.gc.ca/model_forecast/global_e.html

Click on “anim” for either the 00z run of the 12z run

This starts an animation from a numerical weather prediction model (Canadian Climate Center) that shows traveling eddies. You loop through the forecasts through 144 hours (six days). Look especially at the upper right-hand panel, showing sea level pressure (SLP) and the 1000-500 hPa thickness. Keep looking to get a feel for how the eddies behave.
Rossby wave equation

\[ c = U - \beta L^2 \]

The basic Rossby equation, named after Carl Gustav Rossby

- U is zonal wind speed, c is wave speed, L is wavelength
- The zonal wind U is faster than the wave speed, so air moves through waves

\[ \beta = \frac{\Delta f}{\Delta \phi} \]

\(\beta\), the change in the Coriolis parameter \(f\) with latitude \(\Phi\), is the restoring force

- For wavelengths of waves associated with midlatitude cyclones (shortwaves):

\[ U > \beta L^2 \]

- So shortwaves propagate eastward relative to the surface
- As wavelength increases, for the same U it propagates eastward more slowly
- Hence longwaves (planetary waves) move slowly or are nearly stationary
- Shortwaves move through and are guided by the longwaves
- Lows and highs at the surface are the surface expression of shortwaves

Vertical structure of cyclones and anticyclones

The low (cyclone) at the surface is located to the east of the shortwave trough at higher levels. It is necessary to place the surface low under an area of mass divergence aloft, evacuating air. In turn, this is compensated by convergence near the surface, with rising motion in between (fostering cloud formation and precipitation). If the upper level divergence exceeds the lower level convergence, surface pressure falls. Similarly, the anticyclone at the surface is located to the east of the ridge in the shortwave at higher levels, necessary to place the surface high under an area of mass convergence. There is compensating divergence at low levels, with sinking motion in between, fostering clear skies and fine weather.

http://apollo.lsc.vsc.edu/classes/met130/notes/chapter12/vert_struct_tilted2.html
**Temperature (thickness) advection**

**Temperature advection** is the primary process that cyclones and anticyclones intensify. The temperature advection amplifies the shortwave, making the upper-level patterns of divergence and convergence stronger.

Initially (a), streamlines and isotherms parallel each other (the atmosphere is barotropic). In (b), the shortwave has caused the streamlines to cross the isotherms west and east of the trough (the atmosphere there is now baroclinic). In the baroclinic region west (east) of the trough, cold (warm) advection is occurring. Along with amplifying the wave, cold-air advection west of the trough will produce sinking motion as the cold air descends to the surface behind the cold front, while warm-air advection east of the trough will produce rising motion near the center of the low. In (c) the temperature advection is cut off and the cyclone occludes.

http://apollo.lsc.vsc.edu/classes/met130/notes/chapter12/cold_warm_air_advection.html
Fields of mean 500 hPa height for the four mid-season months over the period 1970-1999, based on NCEP/NCAR data [by the authors]. Compared to daily 500 hPa height fields (e.g., two slides ago) the long-term average pattern at 500 hPa looks much smoother. This is because the traveling shortwaves get averaged out, leaving the standing longwave pattern. The standing longwave pattern at 500 hPa is more pronounced in winter than in summer. Recall that the shortwaves move through the longwaves, with the longwaves in turn acting to steer the shortwaves.
Mean sea level pressure (hPa) for the four mid-season months over the period 1970-1999, based on NCEP/NCAR data [by the authors]. The prominent features of autumn and winter are the mean Icelandic and Aleutian lows in the northern north Pacific and northern north Atlantic, respectively, and the Siberian High over northern Eurasia. The summer pattern is flatter. The mean July field shows weak low pressure over the central Arctic Ocean. Mean lows reflect the presence of many cyclones in the region.
Cyclone frequency (cyclone centers per month) for winter, spring, summer and autumn over the period 1970-1999, based on NCEP/NCAR data [by the authors]. Throughout the year, cyclone activity is maximized in the northern North Atlantic, especially near the Icelandic Low. Summer also sees frequent cyclone activity over northern Eurasia and the central Arctic Ocean.
Cyclogenesis counts for winter, spring, summer and autumn over the period 1970-1999, based on NCEP/NCAR data [by the authors]. For most of the year, cyclogenesis is most common in the northern North Atlantic. In summer, it is most frequent over northeastern Eurasia and northern Alaska.
Fields of mean 30 hPa height for the four mid-season months over the period 1970-1999, based on NCEP/NCAR data [by the authors]. The mean fields are much smoother than at 500 hPa; only the very longest of planetary waves propagate into the stratosphere. Note also the sharp contrast between the cyclonic (counterclockwise) circulation in January and October and the very symmetric (anticyclonic) circulation centered over the pole in July. This is because in summer, solar radiation receipts (daily totals) are highest at the pole, and stratospheric ozone absorbs strongly in the UV part of the solar spectrum.
Vertical wave propagation (Charney and Drazin, 1961)

For stationary Rossby waves, phase speed \( c=0 \), a wave WILL propagate in the vertical if the mean zonal wind \( U \) satisfies:

\[
0 < U < \beta \left[ \left( k^2 + l^2 \right) + \frac{f_0^2}{4 N^2 H^2} \right]^{-1} \equiv U_c
\]

where \( k \) and \( l \) are zonal and meridional wave numbers (inverse wavelengths)

Implications of wave propagation criterion:

• If the mean wind is easterly \( (U < 0) \), stationary waves cannot propagate
• Likewise, if mean winds are westerly but too strong, there is no propagation.

• Longer waves (small \( k \)) propagate vertically through a wider range of \( U \), i.e., through stronger \( U \). In July, stratospheric winds are easterly, so there is no vertical propagation, explaining the very symmetric anticyclonic flow in the stratosphere.
Mean column ozone totals (Dobson units) versus latitude for 1984-1993 [from Bojkov and Fiolotov, 1995, by permission of AGU]. The atmospheric circulation transports ozone polewards. The “ozone hole” is largely a problem of the Southern Hemisphere (because of the colder conditions) but “mini ozone holes” have been observed in the Arctic.
Sudden stratospheric warmings

The change of 10 hPa temperatures (°C) associated with a sudden stratospheric warming event that occurred during late December 1984 through early January 1985. The plots give mean temperatures for the prewarming (17-21 December), warming (December 27-31) and postwarming (January 6-10) phases as identified by Kodera and Chiba [1995]. Results are based on the NCEP/NCAR reanalysis [by the authors]. Sudden stratospheric warmings are fairly common in winter and can be linked to anomalous upward propagation of planetary waves, setting in motion a chain of events resulting in breakdown of the stratospheric vortex. Changes in the circulation of the stratosphere can affect the circulation of the troposphere and surface.
Winter: A Focus on the Icelandic Low region
Icelandic Low region

- Synoptically active and complex
- Lots of cyclogenesis/deepening
- Key area of transport of atmospheric energy into the Arctic
  - sensible heat
  - latent heat
  - geopotential
- Modulation of Arctic freshwater budget
  - precipitation
  - sea ice flux
- Northern node of North Atlantic Oscillation (NAO)

Lots of cyclogenesis and deepening
The Icelandic and Aleutian lows are found ahead of the eastern North American and east Asian troughs and in regions with strong horizontal temperature gradients that favor cyclogenesis and cyclone deepening [from Tsukernik et al., 2006].
Greenland has a big impact on cyclone activity in the Icelandic Low region

- Steering
- Bifurcation/splitting
- Leeside cyclogenesis
- Cold air source

http://earthobservatory.nasa.gov/IOTD/view.php?id=5118
CASE 22: “Classic Deepener”
SLP, 500 hPa height (solid) and 1000-500 hPa thickness (dashed) for Region 2 (62N, 37W) at time -18h

System moves in from the Southwest
CASE 22: “Classic Deepener”
SLP, 500 hPa height (solid) and 1000-500 hPa thickness (dashed) for Region 2 (62N, 37W) at time -6h

System moves into Icelandic Low region
CASE 22: “Classic Deepener”

SLP, 500 hPa height (solid) and 1000-500 hPa thickness (dashed) for Region 2 (62N, 37W) at time 0h
CASE 44: “Bifurcator”
SLP, 500 hPa height (solid) and 1000-500 hPa thickness (dashed) for Region 0 (62N, 37W) at time -24h

System moves in from the Southwest
CASE 44: “Bifurcator”
SLP, 500 hPa height (solid) and 1000-500 hPa thickness (dashed) for Region 0 (62N, 37W) at time -12h

Starts to distort at tip of Greenland
CASE 44: “Bifurcator”
SLP, 500 hPa height (solid) and 1000-500 hPa thickness (dashed) for Region 0 (62N, 37W) at time -6h
CASE 44: “Bifurcator”
SLP, 500 hPa height (solid) and 1000-500 hPa thickness (dashed) for Region 0 (62N, 37W) at time 0h

Now there are two low pressure centers
CASE 69: “Leeside Cyclone”
SLP, 500 hPa height (solid) and 1000-500 hPa thickness (dashed) for Region 0 (62N, 37W) at time -18h

System moves in from the West
CASE 69: “Leeside Cyclone”
SLP, 500 hPa height (solid) and 1000-500 hPa thickness (dashed) for Region 0 (62N, 37W) at time -6h

It approaches Greenland
CASE 69: “Leeside Cyclone”
SLP, 500 hPa height (solid) and 1000-500 hPa thickness (dashed) for Region 0 (62N, 37W) at time 0h

- Parent low dissipates
- New system forms in lee of Greenland
CASE 69: “Leeside Cyclone”

SLP, 500 hPa height (solid) and 1000-500 hPa thickness (dashed) for Region 0 (62N, 37W) at time +6h

The new low deepens and migrates to the east.
Modes of variability

Key modes of atmospheric and oceanic variability affecting the Arctic are:

North Atlantic Oscillation (NAO)
Northern Annular Mode (NAM) or Arctic Oscillation (AO)
Arctic Dipole Anomaly (DA) -- later
Pacific Decadal Oscillation (PDO) -- later

“Leading modes of variability” or “teleconnections”
⇒ mapping of spatial patterns of correlated anomalies
The first EOF of winter (December-March) SLP for the North Atlantic sector over the period 1899-1977 based on Trenberth and Paolino [1980] [from Dickson et al., 2000, by permission of AMS]. The variance pattern captures the NAO – covariability in the strengths of the Icelandic Low and Azores High.
The NAO in a decidedly positive mode

Courtesy James Overland, NOAA/PMEL
Anomalies in sea level pressure (left) associated with the positive mode of the NAO and (right) correlation between the NAO index and surface air temperature anomalies. Note how the anomaly patterns shift with the seasons.

http://www.cpc.ncep.noaa.gov/data/teledoc/nao.shtml
The Northern Annular Mode (NAM) or Arctic Oscillation (AO): The big brother of the NAO

Normalized leading EOF of winter (December-March) sea level pressure anomalies over the Northern Hemisphere (20-90°N). The pattern (accounting for 23.5% of the variance in Northern Hemisphere sea level pressure) is displayed in term of amplitude (hPa) obtained by regressing the hemispheric sea level pressure anomalies upon the leading principal component time series. The contour interval is 0.5 hPa and the zero contour has been excluded. The data cover the period 1899-2001 [from Hurrell et al., 2003, by permission of AGU]. Think of the NAO as the North Atlantic part of the NAM.
Normalized indices of the winter (December-March) NAO, based on the difference in normalized sea level pressure between Lisbon, Portugal and Stykkisholmur/Reykjavik, Island, PC1 of Atlantic sector sea level pressure (20-70°N, 90°W-40°E), and PC1 of Northern Hemisphere sea level pressure (20-90°N). The latter time series is also known as the Arctic Oscillation or Northern Annular Mode. The heavy solid lines represent the indices smoothed to remove fluctuations with periods less than four years [from Hurrell et al., 2003, by permission of AGU]. Major point – the time series all look similar.
Figure 11.12: Changes in surface temperature (x10°C) corresponding to a unit deviation of the NAO index, computed over the winters (December-March) of 1900-2002. Regions of insufficient data are not contoured. The NAO index is based on PC1 of the sea level pressure field for the Atlantic sector [from Hurrell et al., 2003, by permission of AGU]. The phase of the NAO (or NAM) has widespread effect on temperature.
NAM contribution to winter temperature changes, 1970s through early 2000s -- increasingly positive NAM

(from Dave Thompson, Colorado State University)
Arctic Oscillation (NAM) time series, 1920-2011

Note extreme negative values for the past two winters

http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/month_ao_index.shtml
Sea level pressure and surface temperature anomalies for winter 2009-2010, corresponding to an extreme negative phase of the NAM.
Summer: The cyclone maximum over the central Arctic Ocean and the Arctic frontal zone
Annual cycle of cyclone center counts over central Arctic ocean. There is about a factor of two difference between winter and summer with a sharp rise between May and June [from Serreze et al., 2008].
A classic summer storm over the central Arctic Ocean

Xiangdong Zhang, IARC
Where do systems contributing to the summer cyclone maximum come from? Where do they die?

**Cyclogenesis:** Eurasia and within cyclone max. region

**Cyclolysis:** within cyclone max. region and surrounding area

Once cyclones migrate into or form within the central Arctic Ocean region, they are largely destined to die there. This contributes to the high counts of cyclone centers [adapted from Serreze et al., 2008].
When there are lots of cyclones....

**500 hPa Height: Strong Composite**

**SLP: Strong Composite**

Strong, symmetric vortex

Well-developed surface low
When there are few cyclones....

- 500 hPa Height: Weak Composite
- SLP: Weak Composite

Weak vortex

Surface anticyclone
Composite differences:

- Negative 500 hPa anomalies over pole, positive over midlatitudes
- Oscillation of mass seen in SLP

Similar to summer NAM pattern (Ogi et al., 2004)
The Summer Arctic Frontal Zone

Arises from differential heating between the snow-free land and cold Arctic Ocean and topographic “trapping” of cold Arctic Ocean air. Best expressed over eastern Siberia and Alaska. Development corresponds to removal of seasonal snow cover. Regions where the frontal zone is well expressed (northeast Eurasia, northern Alaska, in red) are also areas of frequent cyclogenesis. Some of the lows generated over Eurasia move into the central Arctic Ocean.

Based on Serreze et al. [2001]
Zonal mean winds, equator to pole
60 to 270 deg. E

January: One jet

Consistent with the effects of differential heating between the land and ocean, the summer Arctic frontal zone is expressed aloft as a separate high latitude wind maximum.
Polar lows
Intense maritime mesoscale cyclones (100-500 km) largely limited to winter

Can rapidly intensify, with winds to hurricane force

They are short-lived (3-36 hrs)

Can be viewed as hybrid systems, having features both baroclinic and convective in nature

Growth has been explained via in terms of two related processes:

CI3K: Convective Instability of the Second Kind (same process that allows hurricanes to grow), see animation:


WISHE: Wind induced surface heat exchange
NOAA-9 image for 27 February, 1987 of a Polar Low off the coast of northern Norway. Note the spiral cloud signature and central eye in this example [by permission of the NERC Satellite Receiving Station, University of Dundee, http://www.sat.dundee.ac.uk/].
NOAA-12 image for 19 January, 1998 of a Polar Low. Norway is on the right side of the image, with Iceland to the left side. Note the comma-shaped cloud band in this example. [by permission of the NERC Satellite Receiving Station, University of Dundee, http://www.sat.dundee.ac.uk/].