Meteorology, Weather, & Climate

- **Meteorology** is the study of *phenomena of the atmosphere* – includes the dynamics, physics, and chemistry of the atmosphere. (from the Greek *meteōros* – ‘lofty’)
- More commonly thought of as restricted to the dynamics and thermodynamics of the atmosphere as it affects human life.

- **Weather**
  - The state of the atmosphere; mainly with respect to its effects upon human activities. Short term variability of the atmosphere (time scales of minutes to months). Popularly thought of in terms of: *temperature, wind, humidity, precipitation, cloudiness, brightness, and visibility.*
  - A category of individual/combined atmospheric phenomena which describe the conditions at the time of an observation.
- **Climate**
  - Long term statistical description of the atmospheric conditions, averaged over a specified period of time - usually decades.

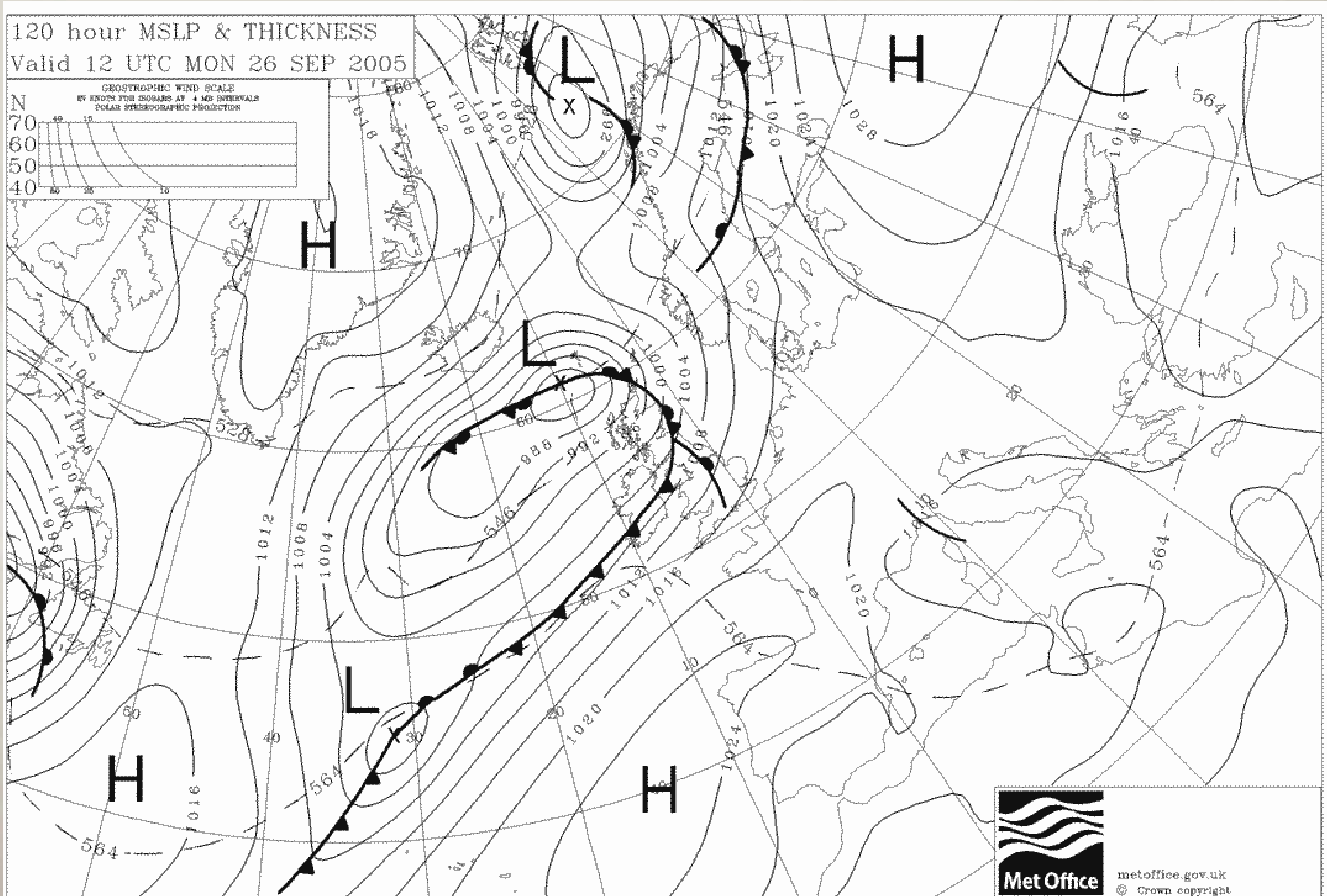
Why study meteorology?

- Warning of severe weather
- Agriculture
  - Timing of planting, harvesting, etc to avoid bad weather, hazards to livestock
- Transport & services
  - Shipping, aviation, road gritting, flood warnings,…
- Commerce
  - Should a supermarket order BBQs and icecream, or umbrellas?

What do we want to know?

- Temperature
- Wind speed
- Wind direction
- Clouds
  - Type, extent, altitude
- Precipitation?
  - Type, amount, location
- Visibility
  - Fog, haze
- Humidity

- Trends in all of these
- Timing of significant changes
- Occurrence of extreme events


120 hour MSLP & THICKNESS
Valid 12 UTC MON 26 SEP 2005
GEOSTROPHIC WIND SCALE
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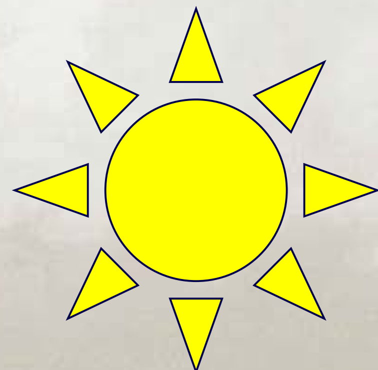
Methods of Forecasting

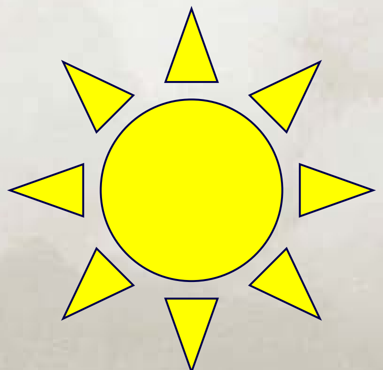
- Persistence Method:
  - Tomorrow will be much the same as today

Today's Weather



Clear skies, 19°C, low winds

Tomorrow's Forecast



Clear skies, 19°C, low winds

Works well when conditions change only slowly. Also surprisingly effective for general forecasts of periods >10 days, for which most other – more advanced – methods lose all their skill. Several weeks of hot sunny weather often followed by several more.

Statistical methods

Simple statistics: climatology

- Given a long record of past weather on every day of the year, forecast most frequently observed weather for day of interest.

    Works well, provided the general conditions are similar to the ‘usual’ or most common conditions for the time of year. Requires long records – many years – to provide reasonable statistics

Analog method

- Given a long record of the sequence of weather conditions, look for a past sequence that resembles the last few days to weeks, and forecast whatever followed it.

    Difficult to use effectively because of difficulty in finding a close match between current and past conditions. Again, requires records going back many years.

Physical Processes

- Thermal – atmospheric dynamics are ultimately driven by temperature gradients arising from uneven solar heating
- Pressure gradient forces – immediate cause of horizontal motions
- Moisture – effect of water vapour content on air density, and release of latent heat has a major impact on convection

Numerical Weather Prediction

- Physical processes are reduced to a (simplified) set of equations that describe changes of physical quantities in time & space. These are **initialized** with latest observations and **stepped** forward in time to produce a forecast.
- Requires:
  - an extensive set of simultaneous measurements over a wide area (*synoptic* observations) to initialize it
  - Fast, powerful computer
  - Adequate representation of the physical processes

Summary

- Meteorology is important to a wide variety of activities
- A huge array of meteorological information is freely available
- With a basic understanding of the physical processes involved YOU can make timely and accurate forecasts

Met. Resources Online

http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/home.rxml
- Basic meteorology course

http://www.metoffice.com/education/index.html
- Guides to interpretation of charts and imagery, and access to some current data

http://www.weather.org.uk/
- A wide variety of current meteorological data, analysis and forecast charts, etc. Links to lots of other sites.

http://www.wetterzentrale.de/topkarten/fsfaxsem.html
- Analysis and forecast charts for Europe from a variety of agencies and models (including UK Met Office)

http://grads.iges.org/pix/euro.fcst.html
- Analysis & forecast charts for Europe issued by National Centers for Environmental Prediction.

http://amsglossary.allenpress.com/glossary
- 'Glossary of Meteorology' from the American Meteorological Society

Introduction to Weather Forecasting

How are we able to predict anything?

- As mentioned previously, observations are the key to unlocking what the future may bring
- Numerous methods for predicting the future
- Numerous challenges with predicting a very “chaotic” system

Two primary approaches

- “Human” approach
  - Predict the weather off of what has happened in the past and the intuition/knowledge of the forecaster
- Computer approach
  - Use of computational resources to solve very complex mathematical/statistical equations to produce a guidance product for forecasters

"Human" approach – Persistence Method

- The persistence method is self-explanatory – it is a persistent forecast
  - The basic idea is that what is happening today will happen tomorrow. Thus, if the high temperature today was 54 degrees F with sunny skies, a forecaster will simply say it will be 54 degrees F tomorrow afternoon with sunny skies.
  - This method works well when the atmosphere is not rapidly changing and conditions are relatively tranquil.
  - Falls apart when the atmospheric patterns are changing.
  - Also works surprisingly well at longer time scales. For example, it has been dry in the Northeast in the late Winter and a forecaster may predict continued dry conditions in the Spring.

“Human” approach - Climatology

- Climatology can be thought of as what “typically” occurs in the atmosphere at a time and place
  - Example: The climatological maximum temperature on January 7th in State College is 34 degrees F. This is computed by taking each year’s maximum temperature on that day and finding the average – it’s that simple.
  - Another example: The average frequency of measurable precipitation on January 7th is XX% at city X.

"Human" approach - Climatology

- There are a number of ways to calculate climatologies
  - Use the historical period for a given weather station (long-term averages/statistics)
  - Use the most recent 30-year period for averages (most commonly used)
  - Use the most recent 10-year period
  - Can also compute highest/lowest record values, as well
- How is this useful to forecasters?
  - It provides a very basic starting point for making a forecast by asking, "What typically occurs at this time of year?" or "What are the record highest/lowest values at this time?"
  - It also is, on average, a better forecast at long ranges
    - In other words, just using what typically happens can be better than other forms of guidance when looking 20 to 30 days in the future

Example of Climatological Output

Almanac for STATE COLLEGE, PA
January 7, 2016

Daily Data	Observed	Normal	Record Highest	Record Lowest
Max Temperature	37	34	62 in 1930	9 in 1912
Min Temperature	11	20	52 in 1998	-9 in 2014
Avg Temperature	24.0	27.2	56.0 in 1998	6.0 in 1988
Precipitation	0.00	0.08	0.98 in 1915	0.00 in 2016
Snowfall	0.0	0.4	13.0 in 2002	0.0 in 2016
Snow Depth	0	-	13 in 1970	0 in 2016
HDD (base 65)	41	38	59 in 1988	9 in 1998
CDD (base 65)	0	0	0 in 2016	0 in 2016
Month-to-Date Summary	**Observed**	**Normal**	**Record Highest**	**Record Lowest**
Avg Max Temperature	32.9	34.3	52.3 in 2007	16.7 in 1918
Avg Min Temperature	18.1	20.6	38.1 in 1950	0.7 in 1904
Avg Temperature	25.5	27.5	44.0 in 1950	8.9 in 1918
Total Precipitation	0.04	0.57	3.00 in 2005	0.00 in 1983
Total Snowfall	T	2.5	24.5 in 1914	0.0 in 2007
Max Snow Depth	T	-	13 in 1970	0 in 2007
Total HDD (base 65)	275	263	390 in 1918	144 in 1950
Total CDD (base 65)	0	0	0 in 2016	0 in 2016
Year-to-Date Summary	**Observed**	**Normal**	**Record Highest**	**Record Lowest**
Avg Max Temperature	32.9	34.3	52.3 in 2007	16.7 in 1918
Avg Min Temperature	18.1	20.6	38.1 in 1950	0.7 in 1904
Avg Temperature	25.5	27.5	44.0 in 1950	8.9 in 1918
Total Precipitation	0.04	0.57	3.00 in 2005	0.00 in 1983
Total Snowfall (since July 1)	T	12.9	52.6 in 1996	T in 2016
Max Snow Depth (since July 1)	T	-	17 in 1969	0 in 1932
Total HDD (since July 1)	2032	2552	3494 in 1918	1740 in 1974
Total CDD (since Jan 1)	0	0	0 in 2016	0 in 2016

Compare to another year ▼

Period of Record:

- Max Temperature : 1893-02-01 to 2016-01-07
- Min Temperature : 1893-02-01 to 2016-01-07
- Precipitation : 1893-02-01 to 2016-01-07
- Snowfall : 1893-02-01 to 2016-01-07
- Snow Depth : 1899-01-15 to 2016-01-07

“Human” approach - Analogs

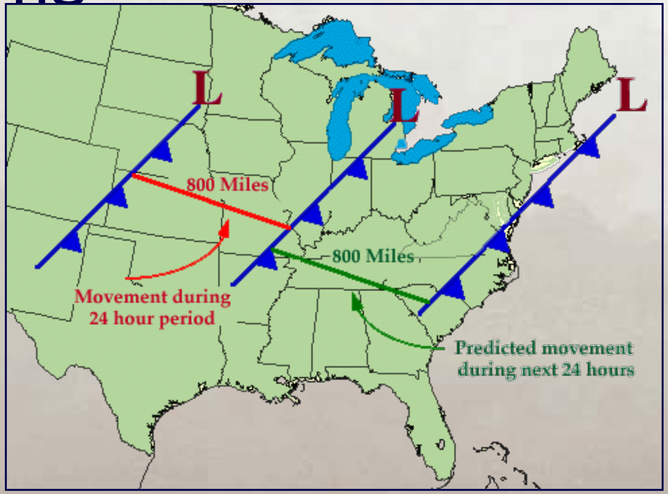
- Analogs go a step further than climatology
- Takes into account what typically happens at a given time when the atmosphere looks a specific way
  - Can be thought of as “regime-specific”
  - Using our climatology example, this would mean that the average maximum temperature is 34 degrees F on January 7th in State College over the past 30 years. But, when winds are out of the south, the average maximum temperature during those years was 38 degrees F.

"Human" approach - Analogs

- How is this method useful to forecasters?
  - It, again, provides a useful starting point based off of conditions that we can observe and measure (i.e. using the past to try to predict the future)
  - Can provide additional insights to the forecaster
    - From our example, the analogous years tell the forecaster that winds out of the south provide warmer maximum temperatures to State College – this can be very useful information that the forecaster may not have otherwise known
  - Can be useful at longer time scales (beyond 7-10 days) as well as seasonal forecasts (i.e. in years where the summer is dry, the fall is cold)

"Human" Approach – "NowCasting"

- Use current observational data to provide insight in near-term conditions
  - Examples: Estimating the speed of a line of thunderstorms



Computer Approach – The World of Numerical Weather Prediction (NWP)

- In the 21st century, the use of computers to produce forecasts has become universal – the most commonly used approach for forecasting today
- Basic idea:
  - Atmospheric scientists use their understanding of the physical processes that drive the weather and use mathematical equations to describe and predict how these processes evolve

Numerical Weather Prediction: Governing Equations (Primitive Equations)

$$\underbrace{\frac{du}{dt}}_{\text{TOT}} = \underbrace{\frac{\partial u}{\partial t}}_{\text{LOC}} + \underbrace{u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}}_{\text{ADV}} + \underbrace{\omega\frac{\partial u}{\partial p}}_{\text{VER}} = -\underbrace{\frac{\partial \phi}{\partial x}}_{\text{PGF}} + \underbrace{f\,v}_{\text{COR}}$$

$$\underbrace{\frac{dv}{dt}}_{\text{TOT}} = \underbrace{\frac{\partial v}{\partial t}}_{\text{LOC}} + \underbrace{u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}}_{\text{ADV}} + \underbrace{\omega\frac{\partial v}{\partial p}}_{\text{VER}} = -\underbrace{\frac{\partial \phi}{\partial y}}_{\text{PGF}} - \underbrace{f\,u}_{\text{COR}}$$

$$\frac{dw}{dt} = -\alpha\frac{\partial p}{\partial z} - g$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = -\frac{\partial \omega}{\partial p}$$

$$\underbrace{\partial T/\partial t}_{\text{LOC}} = \underbrace{-\mathbf{V}\bullet\nabla_p T}_{\text{ADV}} + \underbrace{(p/R)\,\omega\,\sigma}_{\text{ADB}} + \underbrace{\dot{Q}/C_p}_{\text{DIAB}}$$

Numerical Weather Prediction: Computers the Key

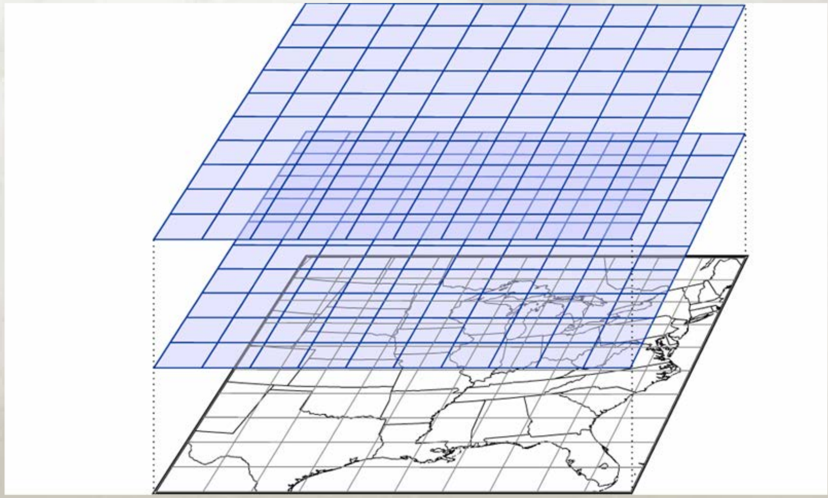
- These equations are not easily solved (in fact, nearly impossible without approximations) by human beings
- They must be solved by computers!
  – Computers allow for these equations to be solved in a *timely fashion* (i.e. 6-hour, 12-hour, etc. forecasts can be made before the events actually happen
  – Computers can assimilate data without the risk of human error (assuming there are no programming errors)

Numerical Weather Prediction: History

- All started in post-WW(world war)I central Europe
  - Lewis Fry Richardson made the first 6-hour forecast for two points in Europe using the set of equations and current weather observations – took 6 weeks to produce
  - Process modified/tweaked to improve results – first computer forecast was made in 1950 – called a computer model
    - Used numerous approximations and a simplified set of equations to complete – 24-hour forecast took 24 hours (forecast barely kept up with the weather)
    - US military made improvements over time through the ‘50’s and 60’s and the rest is history..

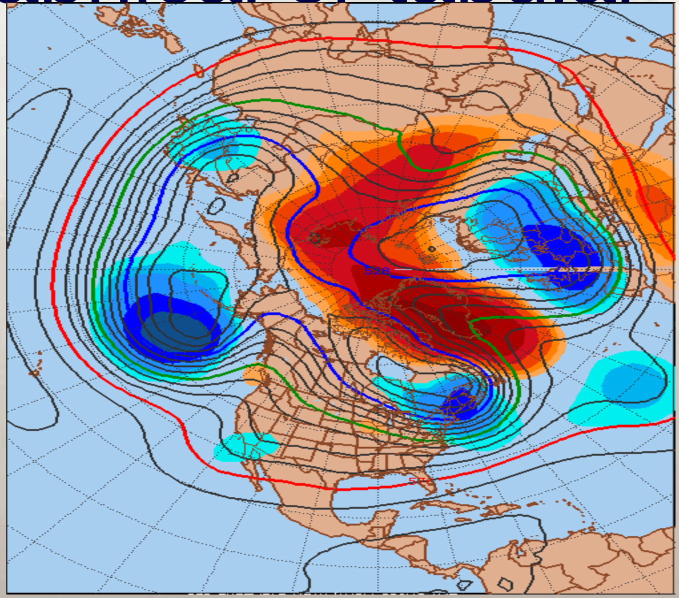
Numerical Weather Prediction: Basics

- Equations are solved at individual point locations aligned in a grid structure
- These **equations are imperfect** and are **highly sensitive to the accuracy of the observations** that are used to plug into the equations (this is known as initialization)



Numerical Weather Prediction: Output

- Equations are computed for each grid point in the model and displayed using graphical or tabular output



GFS MOS (MAV)

KUNV GFS MOS GUIDANCE 1/07/2016 1200 UTC

DT /JAN			7/JAN		8							/JAN	9							/JAN	10
HR	18	21	00	03	06	09	12	15	18	21	00	03	06	09	12	15	18	21	00	06	12
N/X							21				39				34				45		41
TMP	40	42	35	30	28	24	22	30	37	39	38	38	37	37	37	39	42	43	43	44	44
DPT	12	10	10	12	15	15	15	19	21	23	25	29	31	31	31	33	35	36	36	35	38
CLD	FW	CL	CL	CL	CL	CL	FW	BK	OV	OV	OV	OV	OV	OV	OV	OV	OV	OV	OV	OV	OV
WDR	21	18	00	00	00	00	00	00	14	15	13	18	20	15	36	08	15	19	11	09	07
WSP	02	01	00	00	00	00	00	00	02	02	02	03	03	02	03	02	03	03	02	04	03
P06			0		0		1		7		42		81		54		21		17	78	80
P12							2				42				81				30		96
Q06			0		0		0		0		1		2		1		0		0	5	5
Q12							0				1				2				0		6
T06			0/ 4		0/ 0		0/ 6		0/ 0		0/ 0		0/ 0		0/ 0		0/ 0		0/ 0		4/ 3
T12					0/ 4				0/ 6				1/ 0				1/ 0			1/ 0	
POZ	10	9	10	14	13	14	12	18	12	9	10	13	8	1	1	1	0	0	0	1	2
POS	31	19	27	23	24	8	27	21	26	4	7	20	5	4	4	4	0	0	0	1	0
TYP	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
SNW							0								0						0
CIG	8	8	8	8	8	8	8	8	8	6	4	3	3	4	4	4	4	4	4	3	3
VIS	7	7	7	7	7	7	7	7	7	7	5	3	7	6	5	5	7	7	7	5	4
OBV	N	N	N	N	N	N	N	N	N	N	BR	BR	BR	BR	BR	BR	N	N	N	BR	BR

Forecasting - Summary

- Techniques to forecast the weather can be broken down to two approaches:
  - Human-derived products (climatology, analogs, nowcasting, etc.)
  - Computer-derived products (numerical models)
- Computers have revolutionized how weather forecasters predict the weather
- Computer models, while imperfect, have continuously improved over time due to painstaking attention to detail and tweaking