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Supplement of

Observation of a tidal effect on the Polar Jet Stream

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Supplementary Information

These notes provide further details on the methodology used.

1. Code snippet to calculate tractional tide components for a given Julian date

The software that calculates tractional tidal components is written in IDL and uses the JPL ephemeris. The output is given by acceleration (force/mass) parallel to the earth's surface. In the case shown below the time step is one day starting 1st Jan 1950.

```
jstart=2433283.0D
for i=0,25999 do begin
    JPLEPHINTERP, pinfo, pdata, jstart, xearth, yearth, zearth,/EARTH
    JPLEPHINTERP, pinfo, pdata, jstart, xmoon, ymoon,  $
   zmoon,OBJECTNAME='MOON'
    JPLEPHINTERP, pinfo, pdata, jstart, xsun, ysun, zsun,OBJECTNAME='SUN'
   earth[0] = xearth*1000.
   earth[1] = yearth*1000.
   earth[2] = zearth*1000.
   moon[0] = xmoon*1000.
    moon[1] = ymoon*1000.
    moon[2] = zmoon*1000.
    sun[0] = xsun*1000.
    sun[1] = ysun*1000.
    sun[2] = zsun*1000.
    se = sun - earth
    me = moon-earth
    scal1 = sqrt(se[0]^2 + se[1]^2 + se[2]^2)
    scal2 = sqrt(me[0]^2 + me[1]^2 + me[2]^2)
    fcos = (me[0]*se[0]+me[1]*se[1]+me[2]*se[2])/(scal1*scal2)
    stide = 2.0*G*sunmass*rearth/scal1^3
    mtide = 2.0*G*moonmass*rearth/scal2^3
    if (fcos GT 0) then begin
      res = mtide/scal2*me + stide/scal1*se
    endif else begin
```

```
       res = mtide/scal2*me - stide/scal1*se
     endelse
     tide[i] = sqrt(res[0]^2 + res[1]^2 + res[2]^2)
     if (i gt 0) then wiggly[i] = 10.0*(tide[i] - tide[i-1])
     if (i gt 1) then d2[i]=(wiggly[i]-wiggly[i-1])
     angle = asin(res(2)/tide[i])
;  polang is lat of jet stream  75 or 50 or 45
MOONPOS, jstart, ra, dec, dis, geolong, geolat, /RADIAN
      polang = 1.047 - abs(dec)
      polang2 = 0.7854 - abs(dec)
      polang3 = 0.5236 -abs(dec)

        ftides[i]=stide
        ftidem[i]=mtide

        factor = rearth^2 + scal2^2 -2.0*rearth*scal2*cos(polang)
        sphi = rearth*sin(polang)/sqrt(factor)
        cphi = (scal2-rearth*cos(polang))/sqrt(factor)
        FX = G*moonmass*(cphi/factor -1/scal2^2)
        FY = -G*moonmass*sphi/factor

        ftract[i] = FX*sin(polang)+FY*cos(polang)

        factor = rearth^2 + scal2^2 -2.0*rearth*scal2*cos(polang2)
        sphi = rearth*sin(polang2)/sqrt(factor)
        cphi = (scal2-rearth*cos(polang2))/sqrt(factor)
        FX = G*moonmass*(cphi/factor -1/scal2^2)
        FY = -G*moonmass*sphi/factor

        ftract2[i] = FX*sin(polang2)+FY*cos(polang2)

        factor = rearth^2 + scal2^2 -2.0*rearth*scal2*cos(polang3)
        sphi = rearth*sin(polang3)/sqrt(factor)
```

```
        cphi = (scal2-rearth*cos(polang3))/sqrt(factor)
        FX = G*moonmass*(cphi/factor -1/scal2^2)
        FY = -G*moonmass*sphi/factor

        ftract3[i] = FX*sin(polang3)+FY*cos(polang3)

        pdate = (jstart -2451911)*86400.0
        printf,6,pdate,ftract[i],ftract2[i],ftract3[i]

    fdat[i]=jstart
     jstart=jstart+1.0
endfor
```

2. A Resultant Tractional Tidal field calculated for 30 Jan 2006

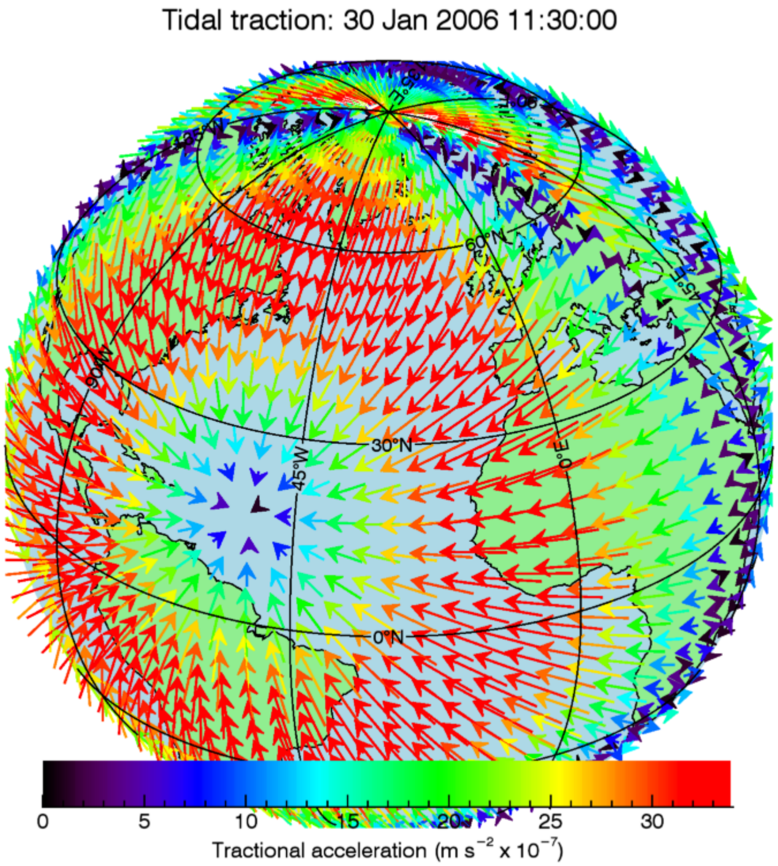


Figure 1 The field of calculated tractional forces on 30 Jan 2006.

Full simulations of tidal variations showing evolution of tractional forces during the lunar cycle can be seen at

2005/6 : Winter 2005/6 with rotating earth

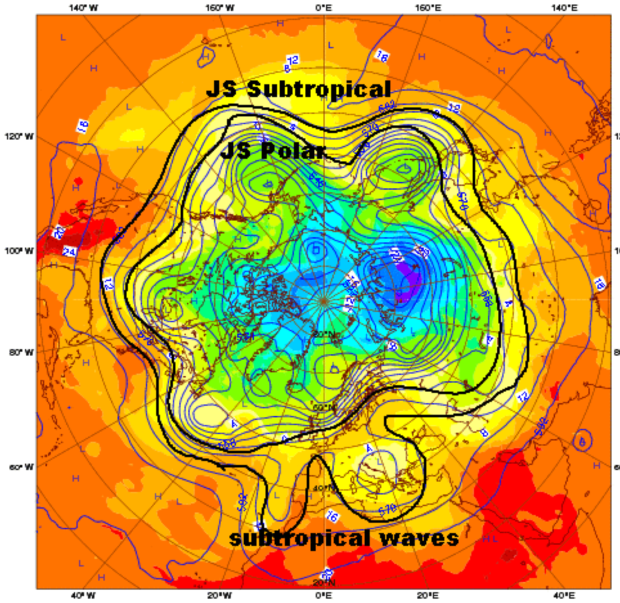
2014/15 Daily updates with stationary earth

2014 Aug/Sep 'Supermoon' with rotating earth

3. Tidal influences on tropospheric flow

Both net lunar tides (nearside and far-side) sweep round the world every 12 hours or so. They act over very large areas and their strength varies on a monthly basis. Around the equinoxes both tidal components become equal and then diverge as the seasons change. For northern Polar Regions the effect is to exert a varying southerly directed horizontal force acting on the Jet Stream whose strength more than doubles during maximum tides. The apparent tides flow from west to east exerting a Coriolis torque to the Jet stream flow. Therefore maxima in this increasing disturbance may be sufficient to distort and magnify Rosby waves in the Jet Stream. A possible example of exactly this effect can be seen in the next two figures which show ECMWF reanalysis data [2] at Jet Stream height overlaid with near surface temperatures comparing minima and subsequent maxima in tides. The example is taken from October 2014.

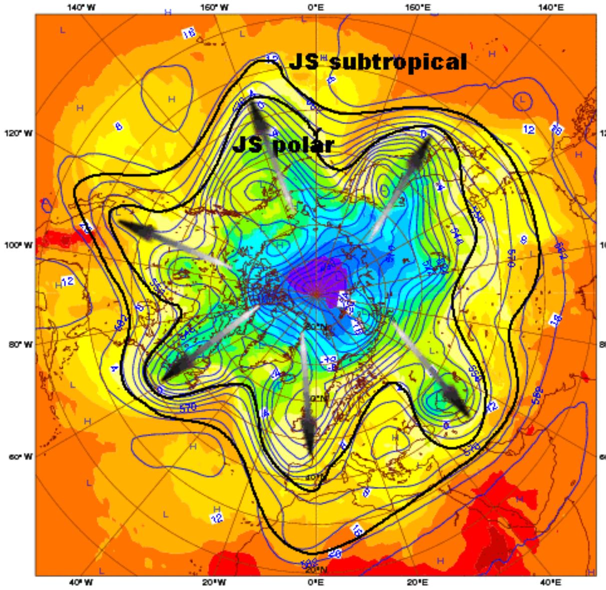
Wednesday 29 October 2014 00UTC ©ECMWF Analysis t+000 VT: Wednesday 29 October 2014 00UTC
850 hPa Temperature / 500 hPa Geopotential



min Tides

Polare Vortex
little disturbed
and in contraction

Thursday 30 October 2014 00UTC ©ECMWF Forecast t+120 VT: Tuesday 4 November 2014 00UTC
850 hPa Temperature / 500 hPa Geopotential



max Tides
Polar Vortex
very disturbed
and expanding

Colder air move
at low latitudes
generating
strong
Rossby Waves
evolving to
cut-off

Figure 2: Comparison of Polar vertex in October

3. UK Winter Storms 2013/14

During winter the Jet Stream strengthens as large temperature gradients develop. A strong poleward decrease in temperature causes ‘baroclinic instability’. Conditions are now critical for the formation of big storms. These are technically called ‘baroclinic waves’ and are composed of cold fronts as polar air moves south under warm tropical air, and warm fronts when simultaneously warm tropical air rises north over cold polar air, driven by Coriolis forces. Each front causes a rapid change in temperature on the ground. These storms are then accelerated by the release of gravitational potential energy as dense cold air falls downwards thereby feeding kinetic energy to the storm and causing strong winds. When conditions are right for baroclinic instability **any small external disturbance** will be amplified and trigger the formation of a storm. The storms last winter are evidence that **strong spring tides** are indeed one important trigger of such storms.

Tides provide an asymmetric disturbance that acts over vast northern latitudes. The changing tractional tidal force acting on the atmosphere varies rapidly as the earth rotates. Two examples cases are described the first of which is the storm surge on Dec 5th 2013.

On the 3rd December a low depression system had already just passed north of the UK and appeared to be weakening. However for some reason it stalled and then strengthened on the 4th and 5th December while it descended south along the east coast of the UK. The associated storm surge caused extensive coastal flooding. This storm was very similar to the devastating 1953 storm which killed 300 people in the UK and over a thousand in the Netherlands. This experience led to the strengthening of coastal defenses and the eventual construction of the Thames barrage. This 1953 storm also coincided with a high spring tide and extensive storm surge.

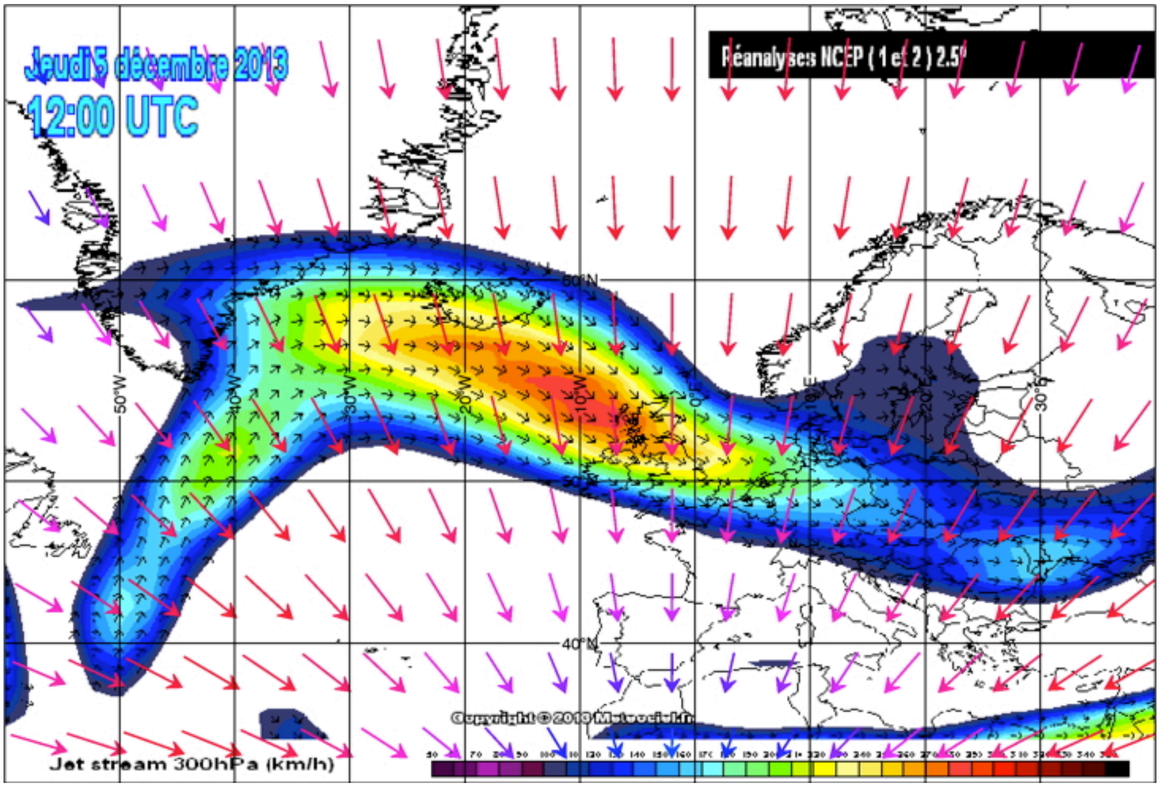
By midday on 4th December a depression had just passed over the UK and stalled to the North East of Scotland. The Jet Stream lay further south looping over the UK. The tides were increasing rapidly and strong tractional tidal forces were concentrated over northern polar latitudes tending to drag air south. These tidal forces are always changing as the earth rotates but during this period the moon's position was over the southern hemisphere causing asymmetric tides over the UK with one major tide effecting polar air masses every 24 hours. The net effect was to drag air down in a Southeasterly direction.

One day later on the 5th December the depression had now deepened and turned downwards towards Scotland bringing very strong winds to the north east coast. Tides still remained very high but now the Jet stream shows a southerly kink pulling to the east of the UK with very strong velocities. arrows show the focusing effect of the tidal forces acting directly on the Jet Stream. The storm is now well underway and moving down the North Sea.

The Jet Stream remained strong for the next 24 hours and lay further south than is normal during the winter period. At the same time very cold polar air was drawn down over the east coast of the US.

By 6th December there was a strong easterly flow of the Jet Stream driving the storm down the North Sea. This was then exacerbated by high maritime tides in the North Sea to create a storm surge similar to that in 1953. However this time there was far better warning, flood protection and preparation, but still hundreds were evacuated from their homes. By midday on the 6th December the storm center had moved off further to the east of the UK still leaving strong north easterly winds.

Is there any evidence that it was these same strong tides that actually **caused** the storms. The evidence is based on the weather plots below shown below which track both the development of the storm and changes in the Jet Stream over a 3 day period beginning on the 4th December. All these charts are taken from meteociel.fr(1). These charts have been overlaid with arrows resulting from calculations of the tractional vector tidal forces at the times shown. For comparison a deep red arrows correspond to a tidal acceleration of about $0.3*10^{-6}$ g.



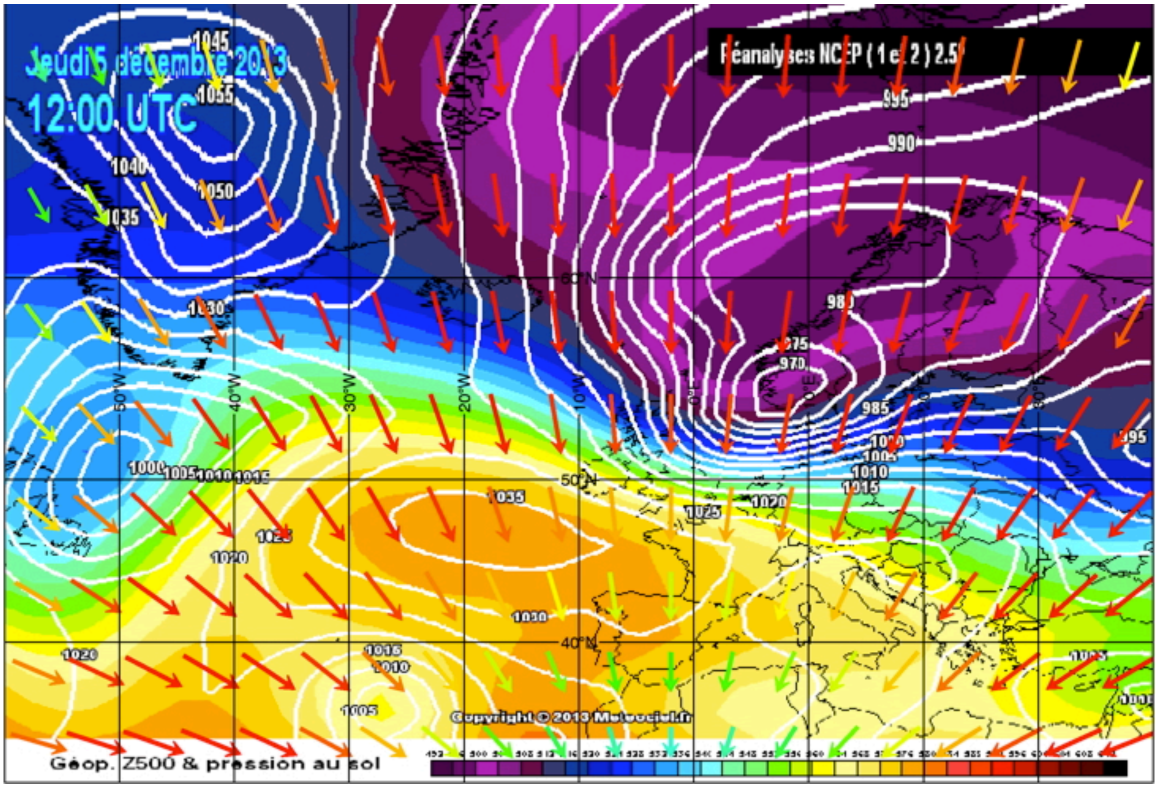


Figure 3: Weather chart from Metecel.fr overlaid with instantaneous tractional tidal vectors

The second example is the storms in early January again in coincidence with a strong spring tide. The fiercest storms to hit the UK last winter were two successive depressions between January 3rd and January 6th. The first storm brought flooding to Dorset, Aberystwyth and Northern Ireland. The second storm seems to have spawned off the first and produced the highest winds and rainfall. The coastline from Cornwall to Ireland was hit on January 6th by 8m waves and a storm surge.

The first storm swept through on the 3rd January, after doubling in size as the Jet Stream dipped downwards on the 2nd January. This was a period of exceptional tides. The second storm seems to have been triggered by a strong kink in the Jet Stream dragging warm air up from the gulf in the north west Atlantic. By the 4th January this second intense storm is forming fast off over Newfoundland. The tidal forces are very strong and the Jet Stream starts to kink. The previous low pressure system seems to be consumed by the next as it grows fast.

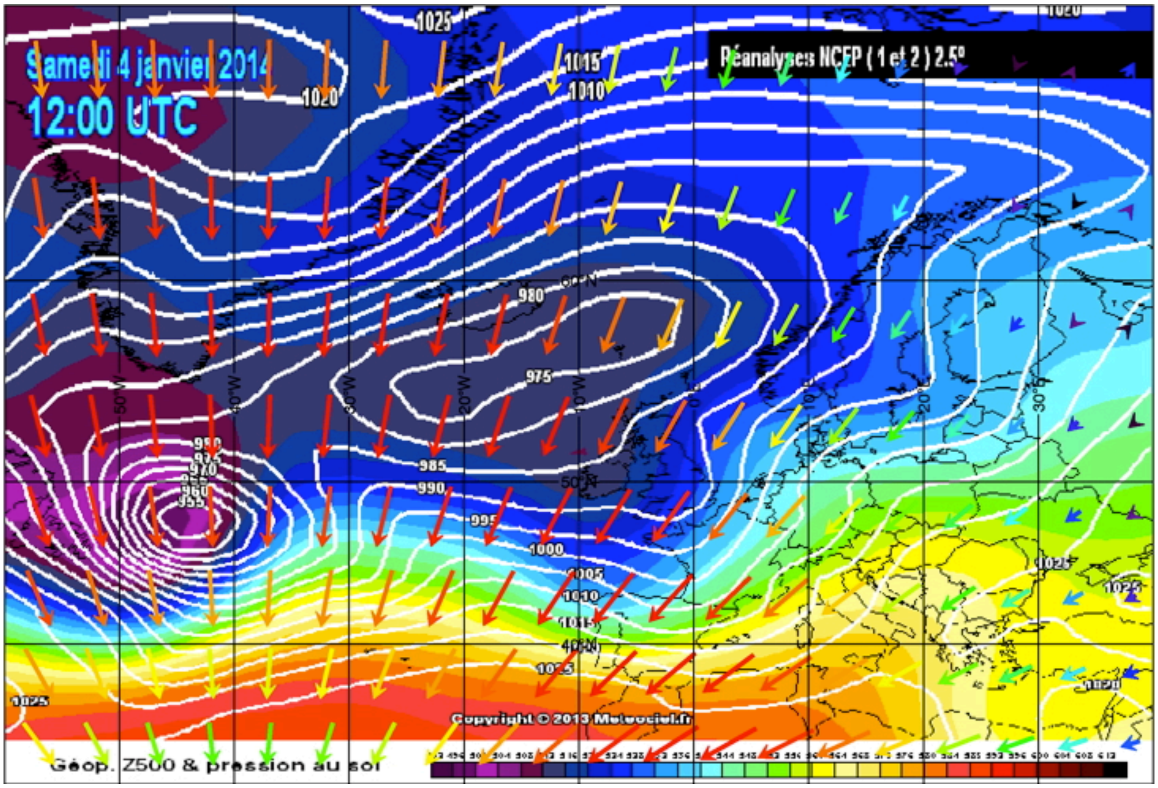


Figure 4: By 4th January this second intense storm is strengthening.. A strong wave of tractional tides sweeps from west to east. The new storm was triggered by a kink in the Jet Stream dragging warm air up in the northeast Atlantic. The previous low pressure system gets subsumed by the new storm.

The Jet stream position defines the boundary between tropical air and polar air. Storms form on the northern side of the Jet Stream at the eastern edge of the Atlantic. The path of these storms is determined by the kinks (Rossby waves) in the Jet Stream. As the earth rotates, an ever changing gravitational field of tractional forces sweep across the Atlantic ocean from east to west about every 12 hours. The effect is similar to that of a bar magnet sweeping across a sheet of paper covered in iron filings.

The southward rotational tidal force acting on the Jet Stream amounts to about 10 metric tons per km resulting in a Coriolis torque due to the earth's rotation. This gravitational torque varies strongly both in strength and in latitude during the lunar month and with seasonal changes to the lunar declination.

The net forces may be small but they act over vast distances and trigger instabilities in the unstable interface along the polar front. This then distorts the Jet Stream causing kinks which change the path of mid latitude storms.

They also can seed winter storms by disturbing baroclinic instability at maximum tidal forces. Therefore for lunar tides to effect mid latitude weather we need the following conditions.

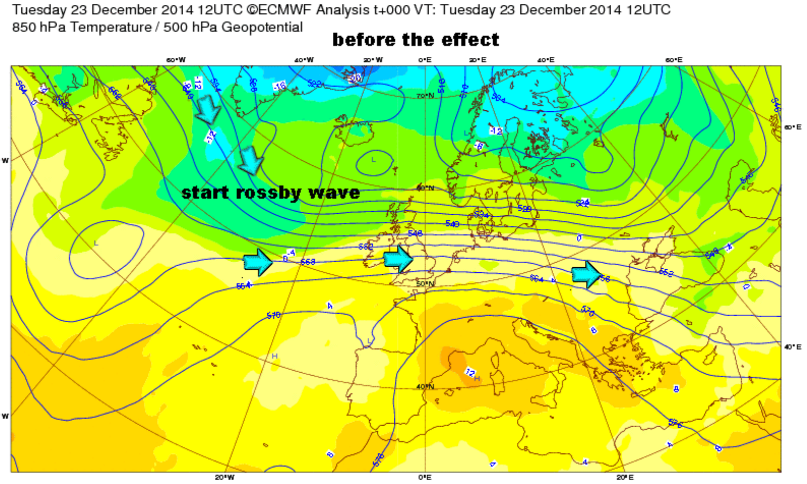
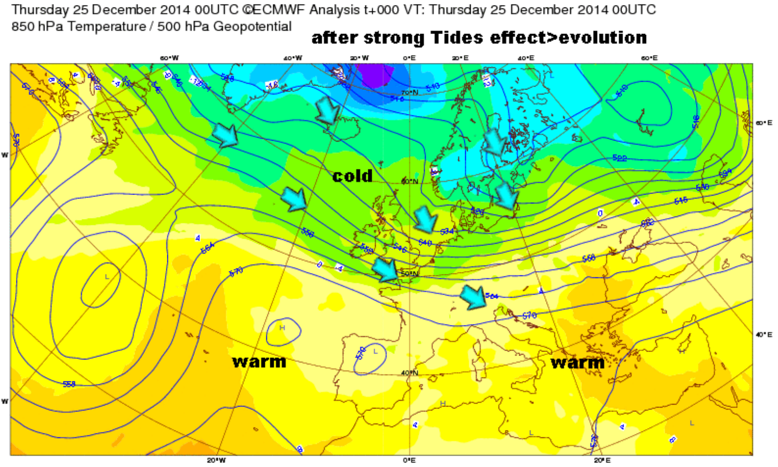
A sharp horizontal temperature gradient leads to a strong Jet Stream and Baroclinic instability.

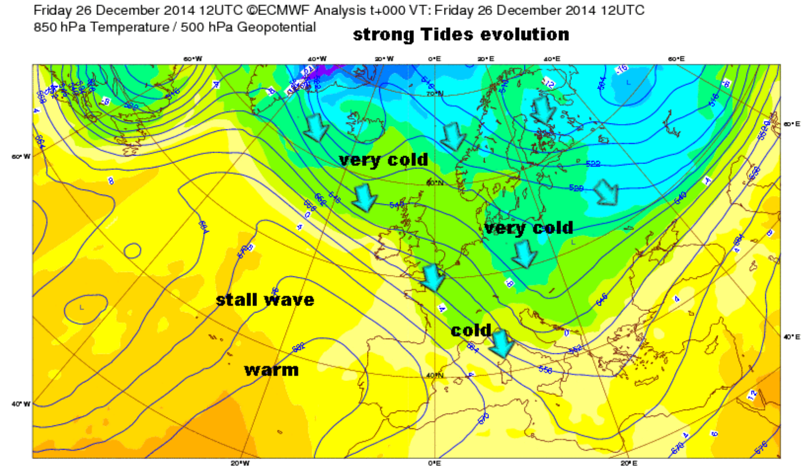
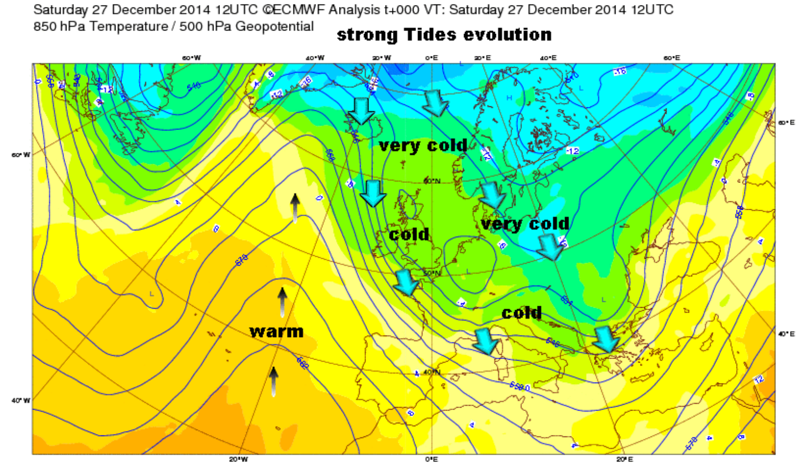
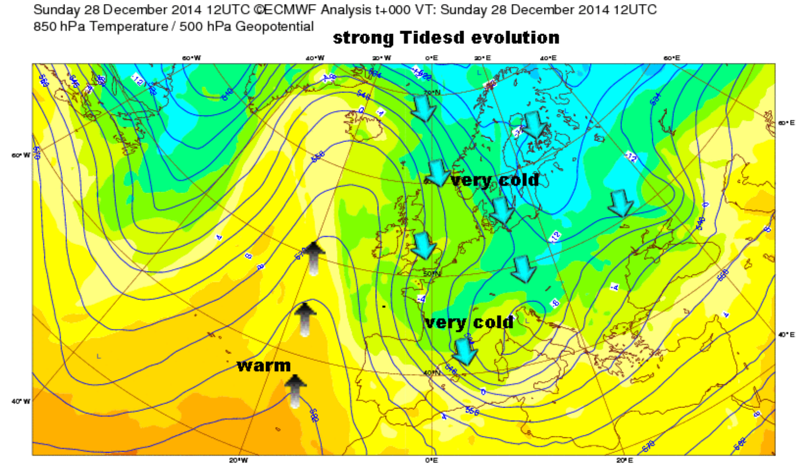
Increasing spring tides with strong tractional forces at high latitudes can trigger anti-cyclonic flow leading to cold/warm fronts and storms moving eastwards.

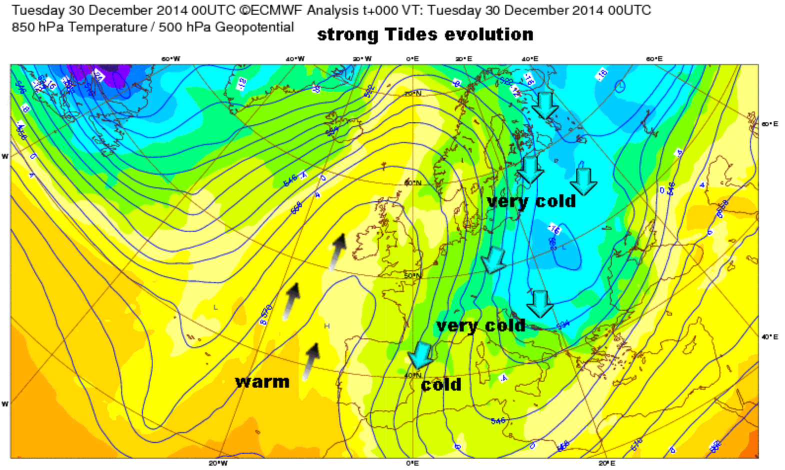
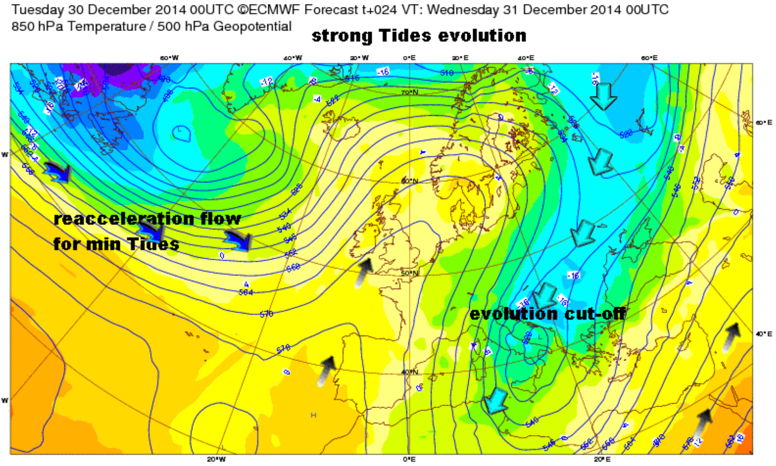
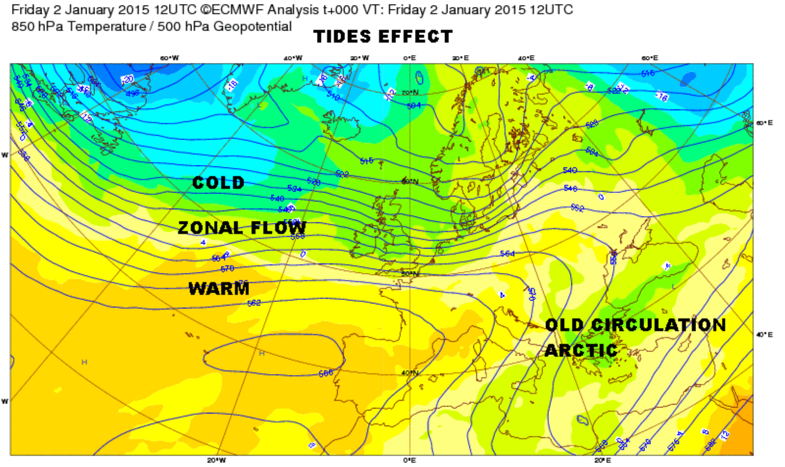
These storms are guided across the Atlantic by the current position of the Jet Stream which itself can be distorted by the same changing tidal torques. If these proposed tidal effects are valid then one would expect longer term changes in weather patterns as the lunar orbit changes

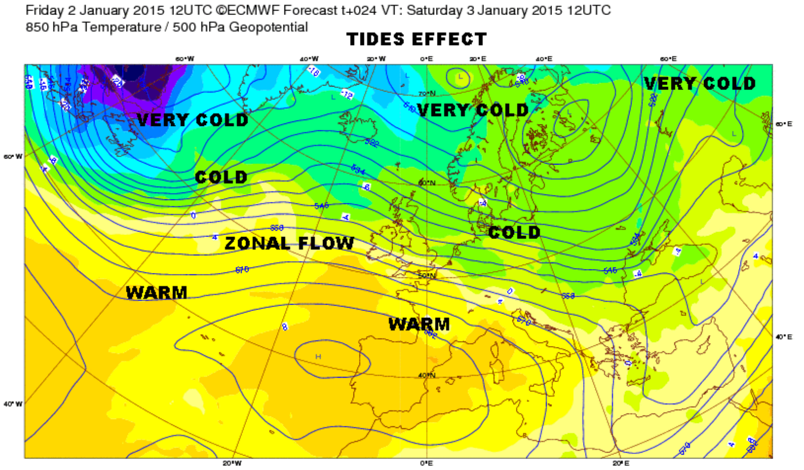
4. The lunar cycle from December 23rd 2014 to Jan 10th 2015

In this section we look in detail at variations in the Jet Stream tropospheric flow through one full tidal cycle. The spring tide on 23rd December was due to a new moon, which generates the largest tidal forces during northern winters. The secondary maximum is due to a full moon half a cycle later. The development of the Jet Stream flow over northern Europe is inferred from ECMWF forecast charts archived during this period

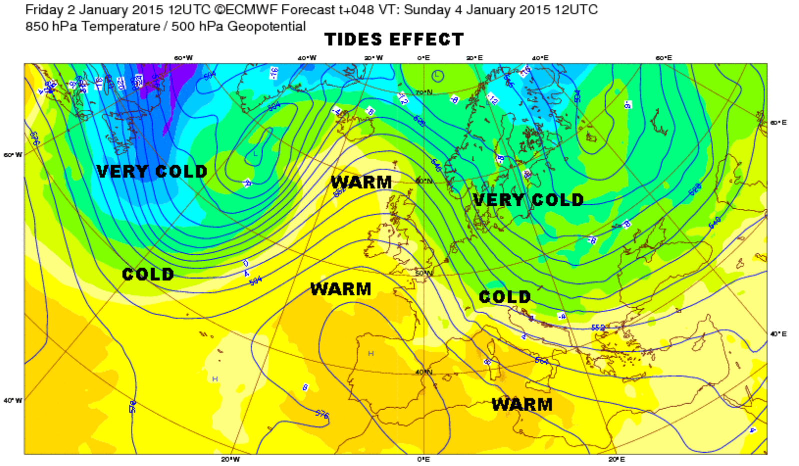
23rd Dec Maximum of spring tides in winter – New moon.	
25th Dec Tidal force moves south in latitude	

26th Dec Continues evolution	 Friday 26 December 2014 12UTC ©ECMWF Analysis t+000 VT: Friday 26 December 2014 12UTC 850 hPa Temperature / 500 hPa Geopotential **strong Tides evolution**
27th Dec Tidal force reduction	 Saturday 27 December 2014 12UTC ©ECMWF Analysis t+000 VT: Saturday 27 December 2014 12UTC 850 hPa Temperature / 500 hPa Geopotential **strong Tides evolution**
28 Dec Tractional force moves further south	 Sunday 28 December 2014 12UTC ©ECMWF Analysis t+000 VT: Sunday 28 December 2014 12UTC 850 hPa Temperature / 500 hPa Geopotential **strong Tidesd evolution**

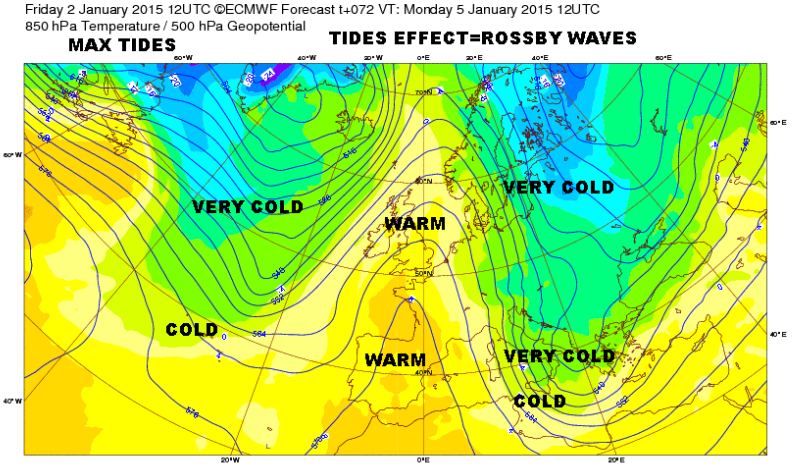
30 Dec Minimum Tide and minimum latitude.	 Tuesday 30 December 2014 00UTC ©ECMWF Analysis t+000 VT: Tuesday 30 December 2014 00UTC 850 hPa Temperature / 500 hPa Geopotential **strong Tides evolution**
31 Dec Increasing tides	 Tuesday 30 December 2014 00UTC ©ECMWF Forecast t+024 VT: Wednesday 31 December 2014 00UTC 850 hPa Temperature / 500 hPa Geopotential **strong Tides evolution**
2 Jan Increasing Tide moving north	 Friday 2 January 2015 12UTC ©ECMWF Analysis t+000 VT: Friday 2 January 2015 12UTC 850 hPa Temperature / 500 hPa Geopotential **TIDES EFFECT**

<table>
<tr>
<td>3 Jan
Tractional force moves north and increases</td>
<td>


Friday 2 January 2015 12UTC ©ECMWF Forecast t+024 VT: Saturday 3 January 2015 12UTC
850 hPa Temperature / 500 hPa Geopotential

</td>
</tr>
<tr>
<td>4 Jan
Rapidly increasing tide</td>
<td>


Friday 2 January 2015 12UTC ©ECMWF Forecast t+048 VT: Sunday 4 January 2015 12UTC
850 hPa Temperature / 500 hPa Geopotential

</td>
</tr>
<tr>
<td>5 Jan
Tidal maximum Full Moon.</td>
<td>


Friday 2 January 2015 12UTC ©ECMWF Forecast t+072 VT: Monday 5 January 2015 12UTC
850 hPa Temperature / 500 hPa Geopotential

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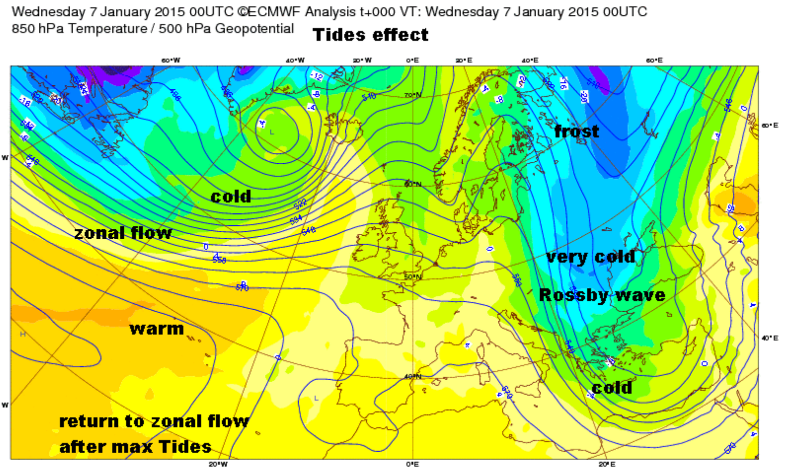
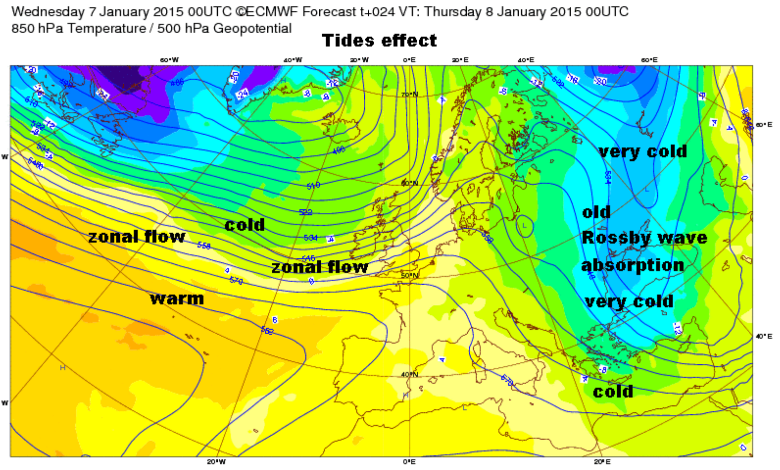
<table>
<tr>
<td>7 Jan
Cycle restarts</td>
<td>


</td>
</tr>
<tr>
<td>8 Jan
Reducing tide moving south.</td>
<td>


</td>
</tr>
</table>

The strongest changes in Rosby waves follow the tidal maxima as rapidly changing tidal tractional forces move southwards following a maximum spring tide. This effect is strongest following the new moon after the tidal bulge has reached its highest latitude.

5. Winter 2015 and the solar eclipse

In this section we look at the results for the latest winter 2015. Figure 14 shows the comparison of the AO with tidal forces. Again there is an evident anti-correlation, but what is particularly striking is the solar eclipse on March 20th. This coincided with the moon at perihelion (super-moon) and generated a very strong tide because the moon and sun were perfectly aligned. Figure 15 also compares to other recent March total eclipse which occurred in 1969 and 1970. 1970 was also close to a lunar standstill. The reduction in AO is striking at the time of the eclipse changing in magnitude by 6 units.

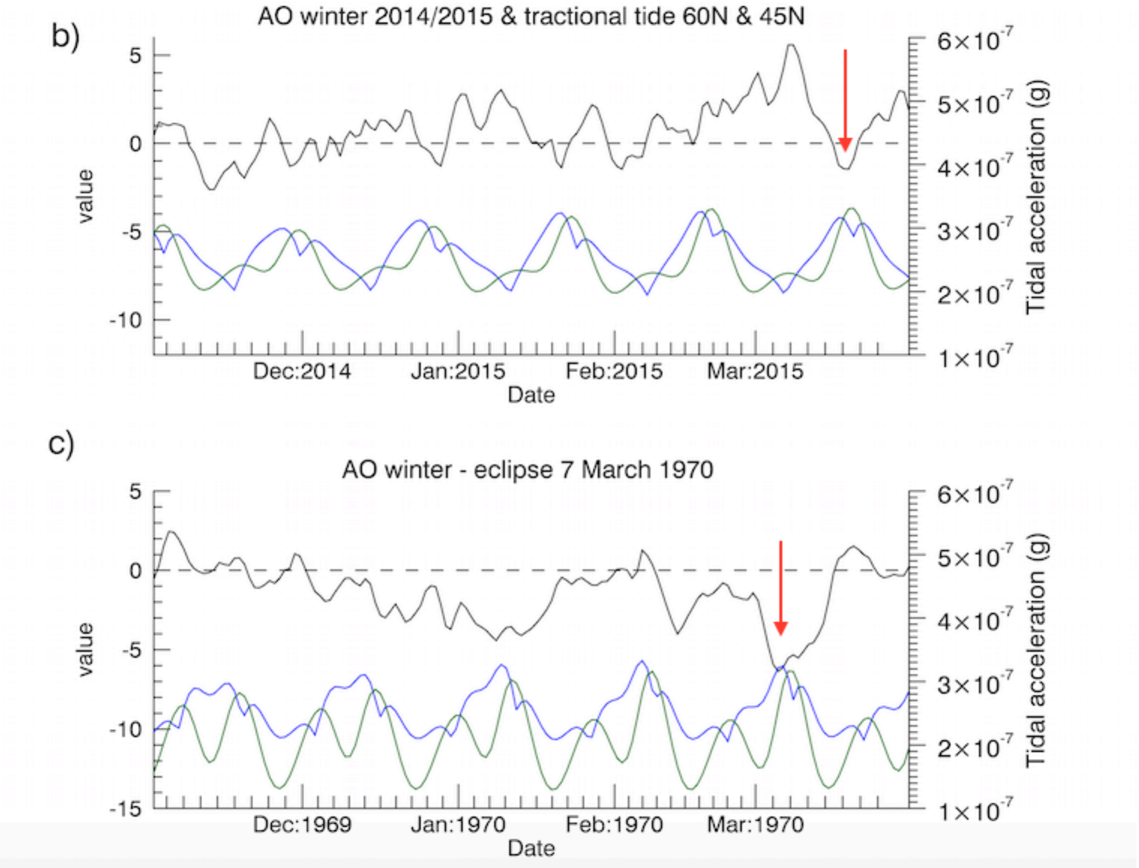


Figure 5: The lower graph is for 2015 and shows the strong reduction in AO which occurred at the eclipse on March 20th.

Are similar effects seen during other seasons ? Figure 15 shows 4 past total eclipses occurring at different seasons. All show negative trends in AO around the eclipse

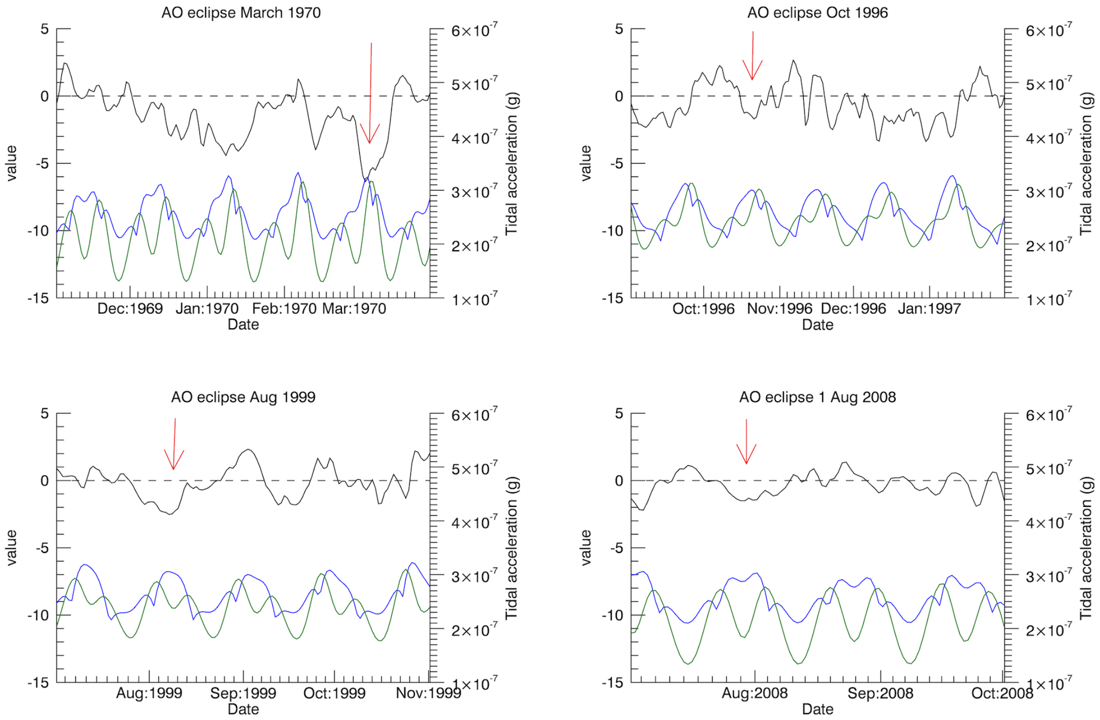


Figure 6: Four past total eclipses in different seasons all of which show a negative trend in the AO at the time of the eclipse.

Meteorologists have mostly ignored the effects of lunar tides mainly because their magnitude was considered to be negligible. We demonstrate here however that atmospheric tides at high latitudes can change the Polar Jet Stream flow as represented by the Arctic Oscillation.